Supplementary materials:

Athletes' age, sex and years of education moderate the acute neuropsychological impact of sports-related concussion: A meta-analysis

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Methodology and Data Checking

Meta-analysis is a quantitative review technique that may be used to aggregate results, and to quantify the influence of potential moderating variables, within a literature comprised of a variety of research samples and methodologies (Borenstein, Hedges, Higgins, & Rothstein, 2009; Lipsey & Wilson, 2001), such as that seen in the sports concussion literature (Comper, Hutchinson, Magrys, Mainwaring, & Richards, 2010). The current meta-analysis was conducted using procedures recommended by Lipsey and colleagues (Durlak & Lipsey, 1991; Lipsey & Wilson, 2001).

Literature Search and Inclusion Criteria

Online databases (PsychINFO, PUBMED, MEDLINE) were searched using the following keywords and their wild-card (*) variations: mild, minor, brain concussion, traumatic brain injury, head injury, brain injury, neuropsychology, assessment, cognitive, symptom, posture, balance, sport, athlete. The ISI Web of Science Citation Index and the reference lists of selected review and empirical papers were also examined. Unique citations (see Figure 1) were screened for relevance by the primary investigator (BKD), and those considered eligible for inclusion in the meta-analysis against *a priori* selection criteria were retrieved and reviewed in detail. In instances of ambiguity, a second investigator (MSH) reviewed the paper and consensus agreement was reached. Rates and reasons for study exclusion are summarised in Figure 2. Of the 78 papers judged eligible for inclusion in this meta-analysis, 38 had been analysed in previous meta-analyses of the concussion literature, while 40 papers had not been analysed previously. Seventy-eight additional papers that had been included in previous meta-analyses were excluded from analysis as they failed to meet current selection criteria.

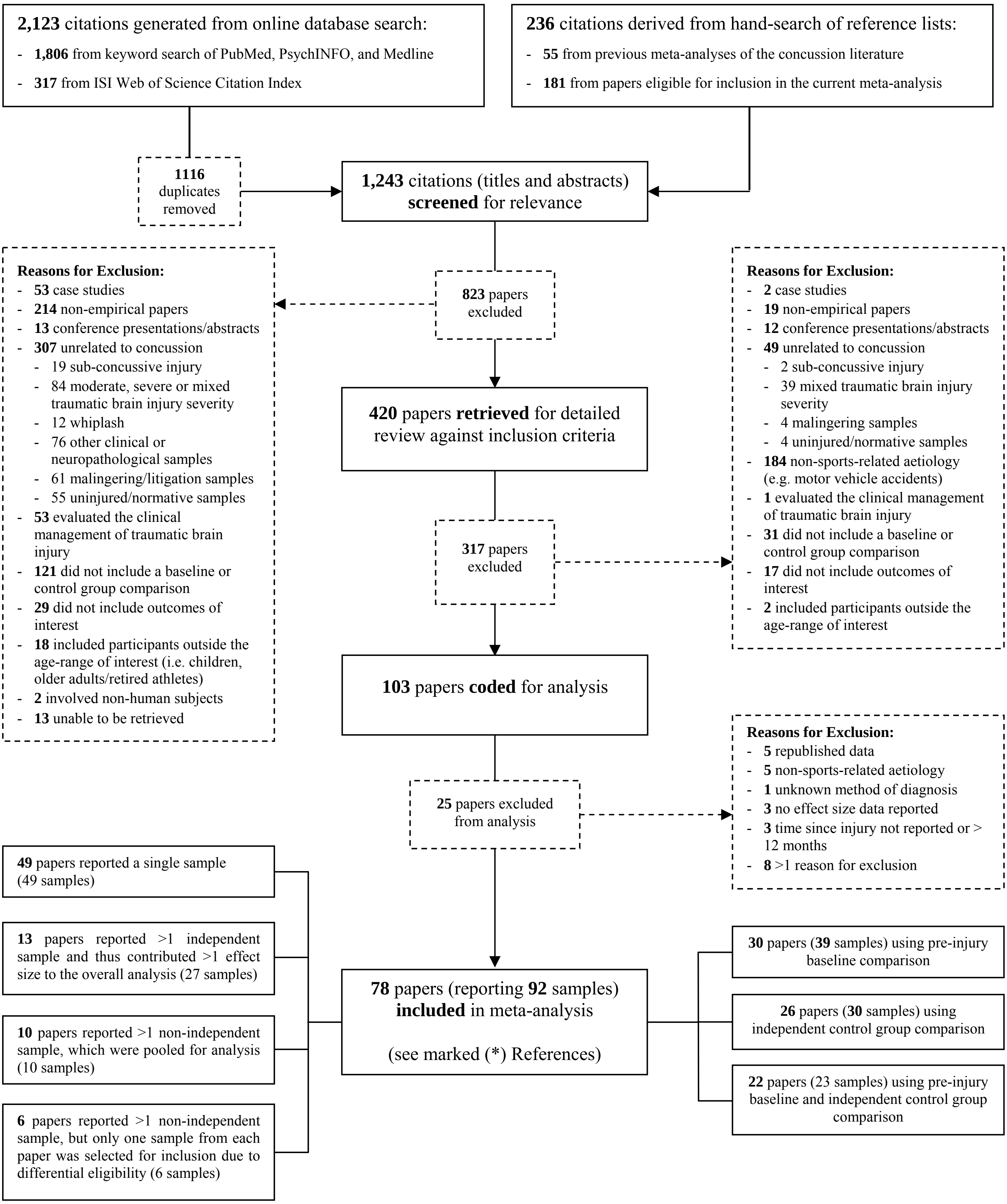

Figure 1. Literature search results and application of inclusion criteria.

Reasons for Exclusion:

- **410** did not assess outcomes from concussive injury (i.e. sub-concussive injury, mixed traumatic brain injury severity, other clinical diagnoses, or clinical management of injury)
- **326** presented commentary/literature reviews, conference presentations/abstracts only or case studies
- **189** included non-sports-related mechanisms of injury (e.g. motor vehicle accidents)
- **152** did not include a baseline or control group comparison
- **46** did not assess outcomes of interest (neuropsychological function, postural stability, post-concussion symptoms)
- **20** included participants outside the age range of interest (i.e. children or older adults no longer playing sport)
- **7** republished or reanalysed data from a paper already included in the meta-analysis
- **7** did not specify diagnostic classification criteria
- **3** did not report sufficient statistical information to calculate or estimate at least one relevant effect size
- **3** did not report the time elapsed since injury or the first post-injury assessment was beyond 12 months from injury
- **2** used non-human subjects

Figure 2. Summary of reasons for exclusion of published literature from the meta-analysis.

Selection criteria were developed from a preliminary examination of a random sample of retrieved papers, as well as previously published sports-related concussion literature reviews and meta-analyses. Liberal inclusion criteria were adopted, and extensive coding of sample characteristics and statistical information undertaken, to allow a detailed quantitative analysis of the potential moderators of sports-related concussion (Durlak & Lipsey, 1991). Studies were not automatically excluded on the grounds of limited methodological quality provided sufficient data were reported to enable coding and analysis of the moderating impact of the relevant features of study design and methodology.

From 78 papers a total of 92 independent samples of concussed athletes were deemed eligible for inclusion in analyses (see Figure 1). Where studies presented results separately for more than one independent sub-sample of concussed participants (e.g. males vs. females or high-school vs. college athletes), each sub-group was separately entered into the meta-analysis to increase sample size. Where sub-samples were clearly non-independent (e.g. multiple concussion sub-groups compared to a single control group) the concussion samples were pooled before analysis. In some instances, however, it was not sensible to pool dependent sub-samples due to significant differences in the timing of assessment (Cremona-Meteyard & Geffen, 1994; Killam, Cautin, & Santucci, 2005) or differences in the eligibility of separate sub-samples against inclusion criteria (Chen, Johnston, Petrides, & Ptito, 2008a; Guskiewicz, Perrin, & Gasneder, 1996; Lavoie, Dupuis, Johnston, Leclerc, & Lassonde, 2004; Macciocchi, Barth, Littlefield, & Cantu, 2001). In these instances, the most recently concussed sample and the samples that met eligibility criteria, respectively, were retained for analysis. For studies in which more than one control group was reported, those consisting of uninjured athletes or a normative athletic sample were given preference over non-athletes or other clinical groups to measure the impairment attributable to concussion relative to the state of healthy, uninjured athletes.

Further, to avoid artificial duplication of results, samples were excluded if they represented a clear republication or reanalysis of a data set already included in the meta-analysis. Where multiple studies reported on the same participant sample and research protocol, the study that reported methods and results in the greatest detail was included, while the other(s) was used to supplement and clarify any partially reported information. Because many studies did not clearly comment on this issue, the corresponding author of each eligible paper was contacted via email and invited to indicate whether their study sample represented a republication (in part or full) of any samples reported in other published papers (e.g. the sample had been re-drawn from a large research database). Authors were also asked to provide the relevant statistical data with which to calculate effect sizes if insufficient information had been reported in the published paper. Of those contacted, 12 authors (22%) provided supplementary data in relation to 15 papers (15%) while raw data were no longer available for 5 papers (5%), 10 authors (19%) expressed a willingness to cooperate in relation to 30 papers (29%) but subsequently failed to provide the requested information, 1 author (2%) declined to assist with respect to 3 papers (3%), and 27 authors (52%) failed to respond in any manner despite electronic confirmation of the validity of their listed email addresses. Consequently, the degree to which eligible participant samples drawn from large research databases may have overlapped with other included samples drawn from the same database remained ambiguous.

Data Extraction

Statistical information required for effect size calculation or estimation (dependent variables) as well as sample and methodological characteristics required for moderator analyses (independent variables) were coded in accordance with a detailed coding protocol[1]

[1] Available upon request from the corresponding author.

by the first author (BKD). Instances of study coding that presented significant ambiguity were also checked by the second author (MSH) and resolved by consensus.

Effect size data. Effect size data (group means, standard deviations, and sample sizes) were recorded separately for concussed and control groups from each independent sample, on each relevant outcome measure, at each assessment occasion (pre-injury and post-injury). All effects were coded such that a post-injury decline in concussed athletes' neuropsychological function or postural stability, or an increase in self-reported symptoms, relative to their pre-injury scores and/or that of a control group would produce a negative effect size.

As recommended by Lipsey and Wilson (2001, p. 45), separate coding and analysis was also performed for each of three research designs represented across the included samples, each of which required a distinct effect size formula (see Effect Size Calculation). The three research designs were as follows: the post-injury performance of a single group of concussed participants compared to their own pre-injury (baseline) performance; the post-injury performance of a group of concussed participants compared to the performance of an independent control group; and the change in performance of a group of concussed participants from pre-injury to post-injury, compared to the change in performance of an independent control group from baseline to retest. [2] Five included studies were described by their authors as using a pre-injury baseline comparison, but the baseline sample was not identical to the post-injury sample (Bruce & Echemendia, 2004; McCrea, Kelly, Randolph, Cisler, & Berger, 2002; Moser, Schatz, & Jordan, 2005; Pellman, Lovell, Viano, & Casson, 2006; Schatz, Pardini, Lovell, Collins, & Podell, 2006). These studies were reclassified as independent control group comparisons for this meta-analysis (a conservative strategy). Similarly, three studies were described by their authors as using both baseline and independent control group comparisons, but were reclassified; one as an independent control

[2] The latter design represents the most rigorous research design, as it controls for both premorbid functioning (pre-injury baseline) and the effect of repeat assessment (control group).

group comparison because baseline data were not reported (Fazio, Lovell, Pardini, & Collins, 2007), and two as pre-injury baseline comparisons because control data were not reported (Jantzen, Anderson, Steinberg, & Kelso, 2004; Van Kampen, Lovell, Pardini, Collins, & Fu, 2006).

Sample descriptors and moderator variables. A variety of participant sample descriptors and methodological characteristics were also systematically coded to facilitate planned moderator analyses. Coded variables included those pertaining to athlete characteristics (age, sex, level of competition, sport played, and premorbid functioning) and injury characteristics (diagnostic and severity criteria, signs and symptoms, and previous head injuries). In addition, for each outcome measure the type of test (neuropsychological, symptom, or postural stability assessment), cognitive domain assessed (e.g. attention/concentration, working memory, information processing speed), method of test administration (computerised or pen-and-paper), time elapsed between injury and assessment, and the number of pre- and post-injury assessments conducted, were recorded. The source of effect size data (descriptive or inferential statistics, or extrapolated from figures) and the method used to calculate or estimate each effect (including whether or not sufficient information had been reported by study authors), were also recorded in relation to each effect size entry.

Effect Size Calculation

Design-specific effect size formulae. Three design-specific effect size formulae were used to quantify the effects of sports-related concussion, as recommended by Lipsey and Wilson (2001). In addition, two effect size estimates were calculated for each effect included in the analysis – one using a pooled standard deviation term (d_{pooled}) to facilitate comparison to previously published meta-analyses, and the other using the standard deviation of the comparative (uninjured) group mean only ($d_{control}$) to evaluate change in post-concussion functioning relative to a healthy uninjured state.

For those studies that used an independent control group comparison, the magnitude of the effect was expressed in terms of the standardised mean difference between groups at each assessment occasion, by subtracting the control group mean from the concussed group mean and dividing by either (1) the pooled standard deviation of concussed (post-injury) and control group scores (Cooper & Hedges, 1994; Hedges & Olkin, 1985; Hunter & Schmidt, 1990; Hunter, Schmidt, & Jackson, 1982; Rosenthal, 1991), or (2) the standard deviation of control group scores only (Cohen, 1975; Glass, 1976; Glass, McGraw, & Smith, 1981). For those studies that used a pre-injury baseline comparison, the magnitude of the effect was expressed in terms of the standardised mean gain from pre- to post-injury, by subtracting the concussed group's pre-injury mean from their post-injury mean and dividing by either (1) the pooled standard deviation of pre- and post-injury scores (Becker, 1988); or (2) the standard deviation of pre-injury scores only (Morris & Deshon, 2002; Rohling, Beverly, Faust, & Demakis, 2009). For those studies that used both a pre-injury baseline and an independent control group comparison, the magnitude of the effect was expressed in terms of the difference between the concussed and control groups' standardised mean gain from baseline to follow-up assessment. Thus, the standardised mean gain of the control group was subtracted from the standardised mean gain of the concussed group, representing the magnitude of the concussed groups' change in performance after the control group's retest (practice) effects have been removed (Rohling et al., 2009). The denominator used for this equation was either (1) the pooled standard deviation of concussed (post-injury) and control group (follow-up) scores (Hedges & Olkin, 1985), i.e. $[(M_{\text{Concussed at Post-injury}} - M_{\text{Concussed at Pre-injury}}) - (M_{\text{Control at Follow-up}} - M_{\text{Control at Baseline}})] / SD_{\text{Pooled Control \& Concussed at Follow-up}}$; or (2) the standard deviation of each groups' baseline scores, respectively (Becker, 1988; Rohling et al., 2009), i.e. $[(M_{\text{Concussed at Post-injury}} - M_{\text{Concussed at Pre-injury}}) / SD_{\text{Concussed at Pre-injury}}] - [(M_{\text{Control at Follow-up}} - M_{\text{Control at Baseline}}) / SD_{\text{Control at Baseline}}]$. The results of the current study were found to be robust to the specific effect size formulae used (see below), consistent with previous meta-analyses of the mTBI literature (Binder, Rohling, & Larrabee, 1997; Pertab, James, & Bigler, 2009; Schretlen & Shapiro, 2003). While $d_{control}$ produced somewhat larger negative effect sizes than produced by d_{pooled}, the pattern of results and substantive interpretations did not differ across moderator analyses.

If the effect size could not be directly calculated from reported descriptive statistics (group means, standard deviations, and sample sizes), wherever possible the effect size was estimated from descriptive statistics extrapolated from figures, or derived from inferential statistics evaluating pre-post or group contrasts (i.e. *t*-test, F test, χ^2, reliable change indices, or *p*-values) according to formulae provided by Zakzanis (2001) and Lipsey & Wilson (2001). Those measures for which results were only described as ‘not statistically significant’, without accompanying statistics, were entered into the analysis conservatively as an effect size of zero (as per Frencham, Fox, & Maybery, 2005). If it was not possible to calculate or estimate an effect size from information reported in the published paper (i.e. results were not reported at all or reported only as ‘statistically significant’ without related statistics), and authors did not supply the necessary information upon request, such otherwise eligible effect sizes were excluded from analysis (see Table 1).

To avoid unduly biasing an individual sample’s impact on the overall results, multiple effects generated within a single sample (e.g. from multiple outcome measures, multiple cognitive domains and/or multiple assessment occasions) were aggregated by arithmetic mean to create a statistically independent set of effects relevant to each analysis. First, effects were averaged across all assessment occasions, and then across all individual outcome measures, to yield a single effect size per sample ($k = 92$ $d_{control}$ and $k = 91$ d_{pooled} effect sizes). Effect sizes were then adjusted by Hedge’s small-sample bias correction, weighted by the

Table 1

Number of Effect Sizes Extracted from Published Papers, by Number of Post-Injury Assessments and Method of Effect Size Estimation

Post-injury assessment	No. samples (*k*)	Number of individual effect sizes extracted from published papers (before aggregation for analysis)								*M* per sample (range)
		Described in design	Calculated [a]	Estimated [b]	Extrapolated [c]	Reported only as *ns*	Reported only as *sig.*	No data reported	Total quantifiable	
1st	91[de]	683	445	100	33	57	7	41	635	7.0 (1-27)
2nd	56	366	170	52	36	34	6	68	292	6.8 (1-23)
3rd	31	206	96	8	38	41	0	23	183	6.3 (1-23)
4th	17	133	45	1	21	45	0	21	112	6.6 (1-23)
5th	2	7	3	0	3	1	0	0	7	3.5 (3-4)
6th	1	3	3	0	0	0	0	0	3	3
7th	1	3	3	0	0	0	0	0	3	3
8th	1	3	0	0	3	0	0	0	3	3
Total	92[e]	1404	765	161	134	178	13	153	1238	13.5 (1-81)

Note. [a] Group means, standard deviations and samples sizes reported. [b] Estimated from inferential statistics (e.g. *t*-test, *F*-test). [c] Descriptive statistics extrapolated from figures. [d] A sub-sample from Lovell et al (2006) was excluded from the first post-injury assessment occasion as it represented republished data. [e] $d_{control}$ but not d_{pooled} effect sizes were able to be calculated for four effects derived from a single sample (Maddocks & Saling, 1996).

inverse of the sampling error variance, and aggregated across samples to compute the overall mean effect size. However, aggregation potentially obscures systematic variation across different sample characteristics and outcome measures (Durlak & Lipsey, 1991; Iverson, 2010). Therefore, effects were also grouped within each level of a given categorical moderator variable to create subsets of independent effects specific to each analysis.

Extreme scores. Frequency distributions of individual effect sizes (before aggregation) were examined by effect size estimate (d_{pooled} or $d_{control}$), comparison group (independent control group, pre-injury baseline, or both), type of outcome measure (neuropsychological measures, self-report symptoms, or postural stability assessment), and time since injury (<24 hours, 1-10 days, 10-30 days, or >30 days). Individual effect sizes more than 3 standard deviations from the mean of all relevant effect sizes and markedly separated from the majority of effects within that distribution were classified as extreme scores (Hedges & Olkin, 1985; Lipsey & Wilson, 2001; Schretlen & Shapiro, 2003). Less than 1% of individual effect sizes (10 from 1,238 quantifiable effects, see Table 1) were identified as extreme scores using this method, and all were $d_{control}$ estimates in the negative direction (i.e. representing a decline in functioning post-injury). Each of these 10 effects were generated by assessments conducted within 24 hours of injury and had been calculated using standard deviations which approached zero due to near-ceiling performance of the uninjured comparison group; generating unusually large effect size values ($d_{control}$ range: -584.87 to -19.68). To avoid losing important information represented by these effect sizes, but to reduce their disproportionate influence on meta-analytic results, these effects were retained for aggregation but truncated to less extreme values ($d_{control}$ range: -5.05 to -3.00) consistent with the next major cluster of effect sizes closer to the mean of the relevant distribution (see Lipsey & Wilson, 2001, p. 108; Schretlen & Shapiro, 2003). No extreme scores were identified from individual effects calculated using d_{pooled} effect size formulae.

Outlier analysis. Aggregated (sample-level) effect sizes calculated using either $d_{control}$ (see Figures 3a to 3d) or d_{pooled} (see Figures 4a to 4d) were checked for values more than 3 standard deviations from the relevant weighted mean effect size (Sterne, Becker, & Egger, 2005); overall and separately by comparison group. As shown in Figure 3a, one $d_{control}$ effect size was identified as an outlier in the negative direction relative to the overall mean effect ($d_{control}$ = -5.01, McCrory, Ariens, & Berkovic, 2000). Four $d_{control}$ effect sizes ($d_{control}$ range = -5.01 to -2.08, Bruce & Echemendia, 2004; Collins et al., 2003a; Daniel, Nassiri, Wilckens, & Land, 2002; McCrory, Ariens, & Berkovic, 2000) were also identified as outliers in the negative direction when compared to the weighted mean effect associated with each comparison group: none from samples using both an independent control group and pre-injury baseline comparison (Figure 3b), one from samples using an independent control group comparison (Figure 3c), and three from samples using a pre-injury baseline comparison (Figure 3d). As shown in Figure 4a, when calculated using the d_{pooled} statistic the same sample effect size was identified as an outlier in the negative direction relative to the overall mean effect (d_{pooled} = -2.68, McCrory et al., 2000), and as an outlier in the negative direction when compared to the weighted mean effect associated with each comparison group: none from samples using both an independent control group and pre-injury baseline comparison (Figure 4b), none from samples using an independent control group comparison (Figure 4c), and one from samples using a pre-injury baseline comparison (Figure 4d).

Outlying effect sizes were not removed from analyses, however, as they were considered to be representative of the acute concussion effect: all involved assessments within 48 hours of injury, a period when the greatest effect of concussion can be expected. In addition, each sample used only one or two outcome measures; consequently the size of the effect had not been diluted by aggregation across multiple outcome measures of varying degrees of

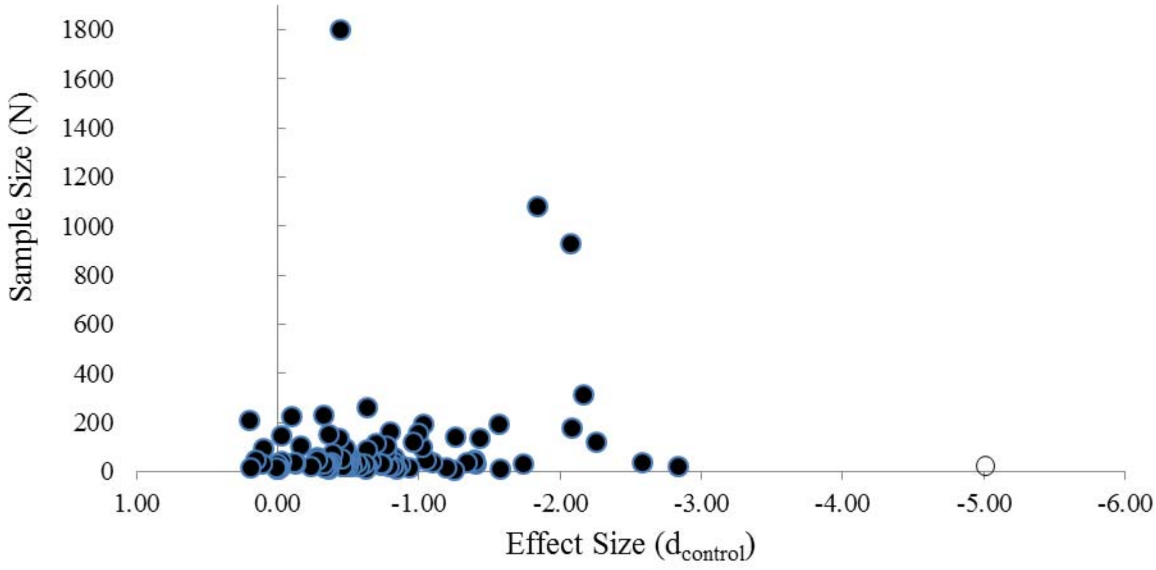

Figure 3a. Funnel plot of 92 independent aggregated effect sizes by total sample size, collapsed across all comparison groups (weighted mean effect size, $d_{control}$ = -0.72). Outlying effect sizes are indicated by unfilled data points. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988).

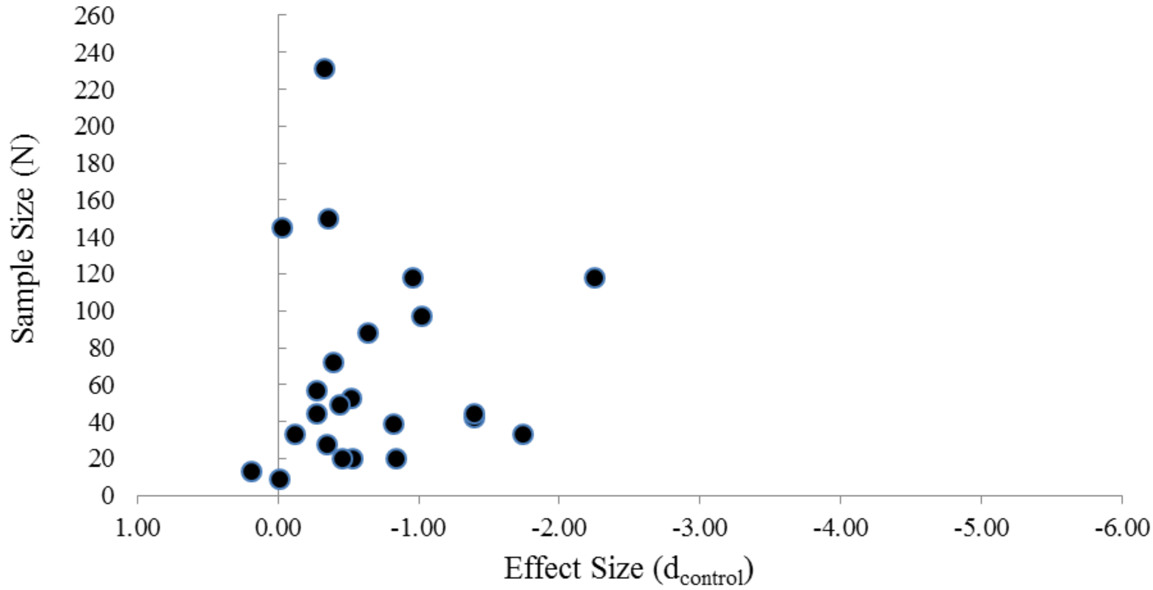

Figure 3b. Funnel plot of 23 independent aggregated effect sizes from samples using both an independent control group and pre-injury baseline comparison, by total sample size (weighted mean effect size, $d_{control}$ = -0.63). No outlying effect sizes were identified. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988).

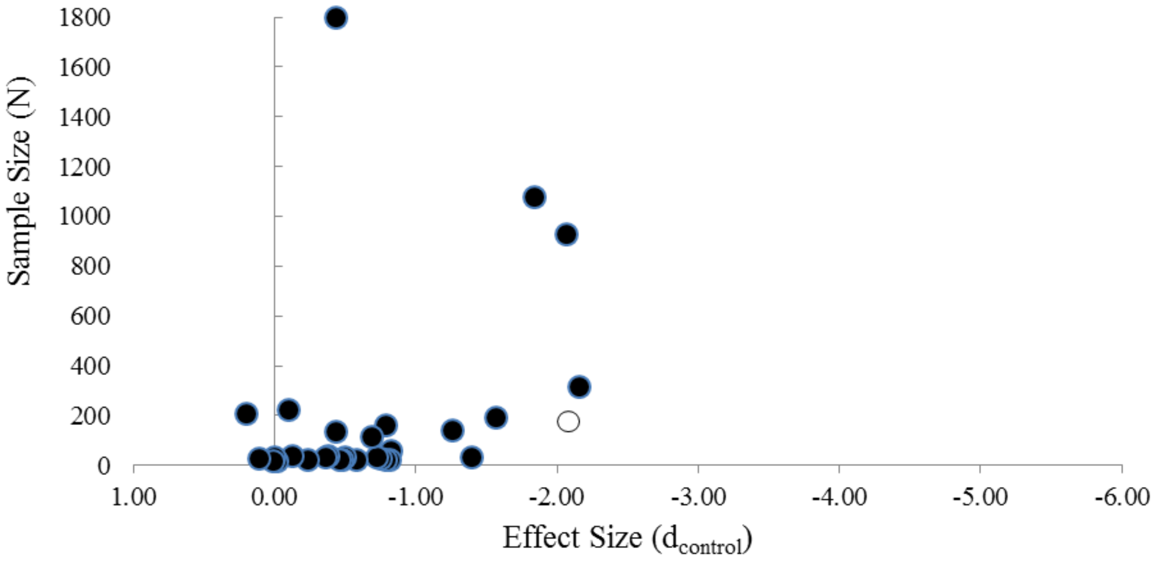

Figure 3c. Funnel plot of 30 independent aggregated effect sizes from samples using an independent control group comparison, by total sample size (weighted mean effect size, $d_{control}$ = -1.08). Outlying effect sizes are indicated by unfilled data points. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988).

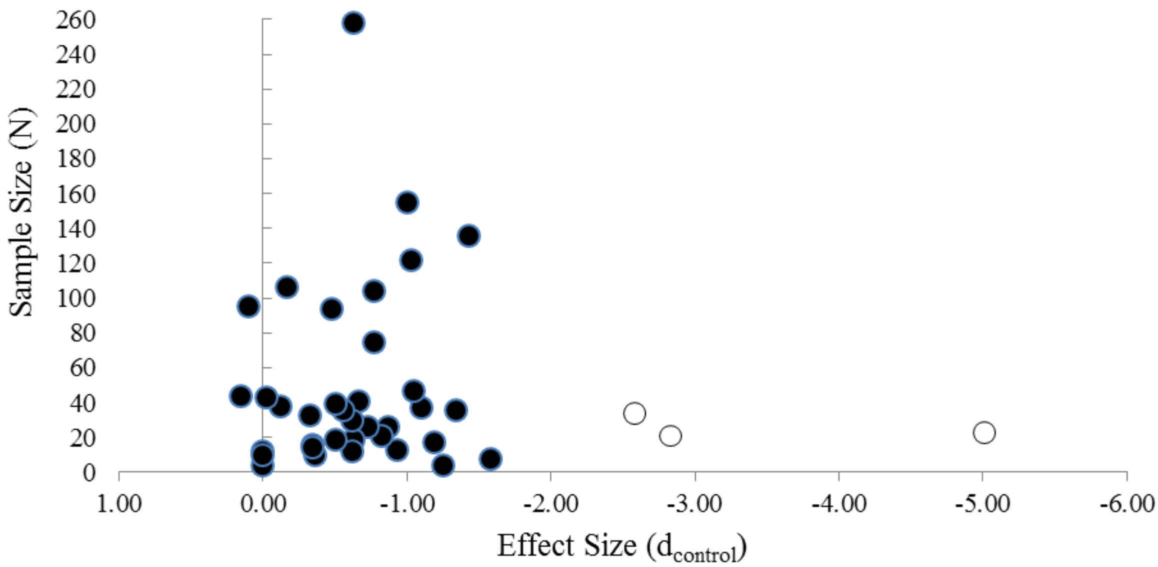

Figure 3d. Funnel plot of 39 independent aggregated effect sizes from samples using a pre-injury baseline comparison, by total sample size (weighted mean effect size, $d_{control}$ = -0.58). Outlying effect sizes are indicated by unfilled data points. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988).

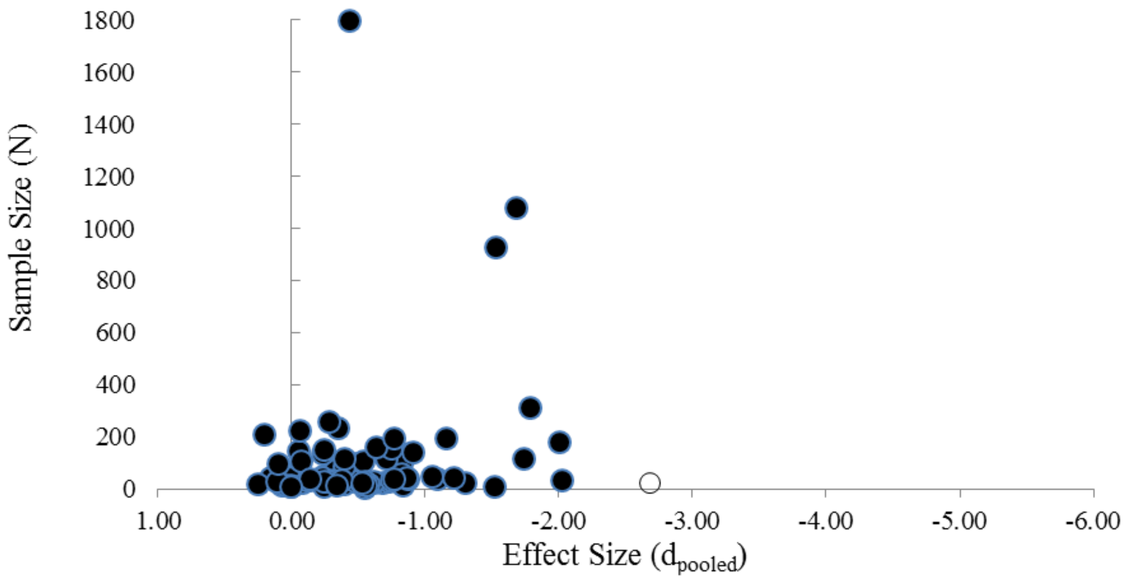

Figure 4a. Funnel plot of 91 independent aggregated effect sizes by total sample size, collapsed across all comparison groups (weighted mean effect size, d_{pooled} = -0.54). Outlying effect sizes are indicated by unfilled data points. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988).

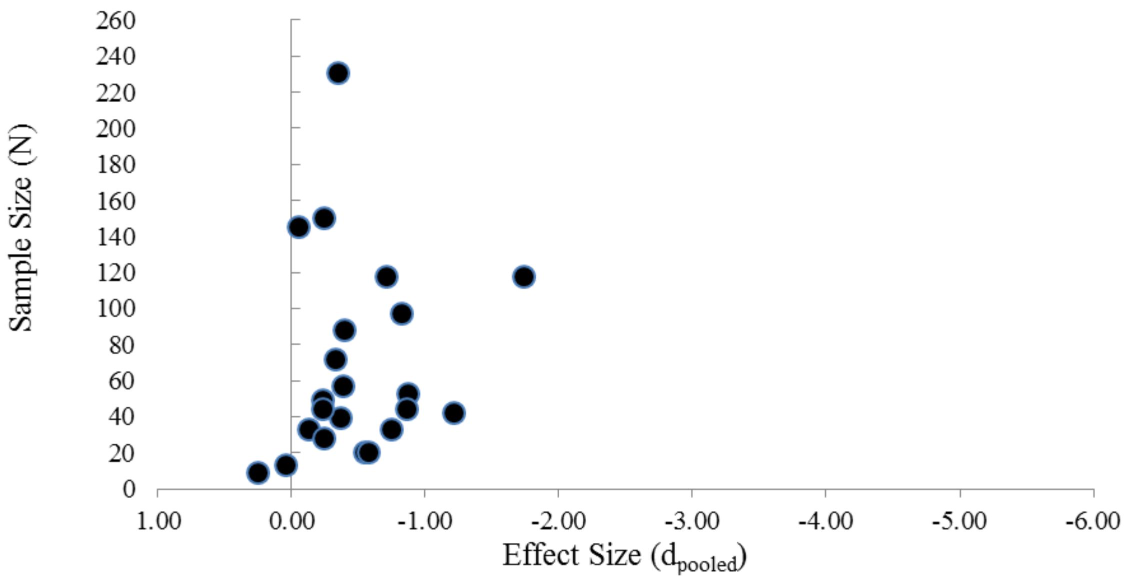

Figure 4b. Funnel plot of 22 independent aggregated effect sizes from samples using both an independent control group and pre-injury baseline comparison, by total sample size (weighted mean effect size, d_{pooled} = -0.51). No outlying effect sizes were identified. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988).

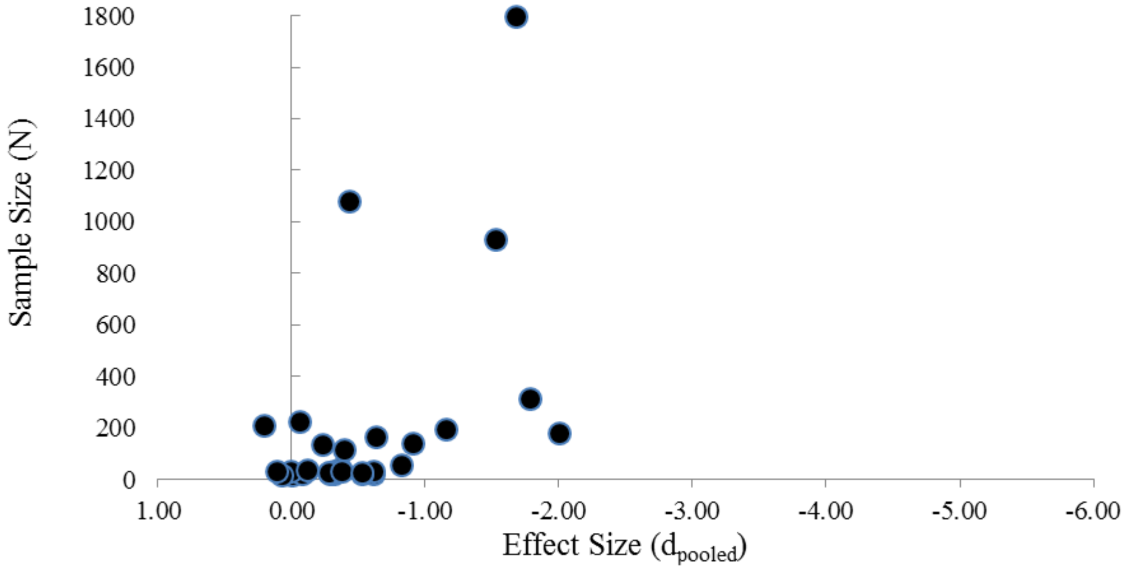

Figure 4c. Funnel plot of 30 independent aggregated effect sizes from samples using an independent control group comparison, by total sample size (weighted mean effect size, d_{pooled} = -0.85). No outlying effect sizes were identified. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988).

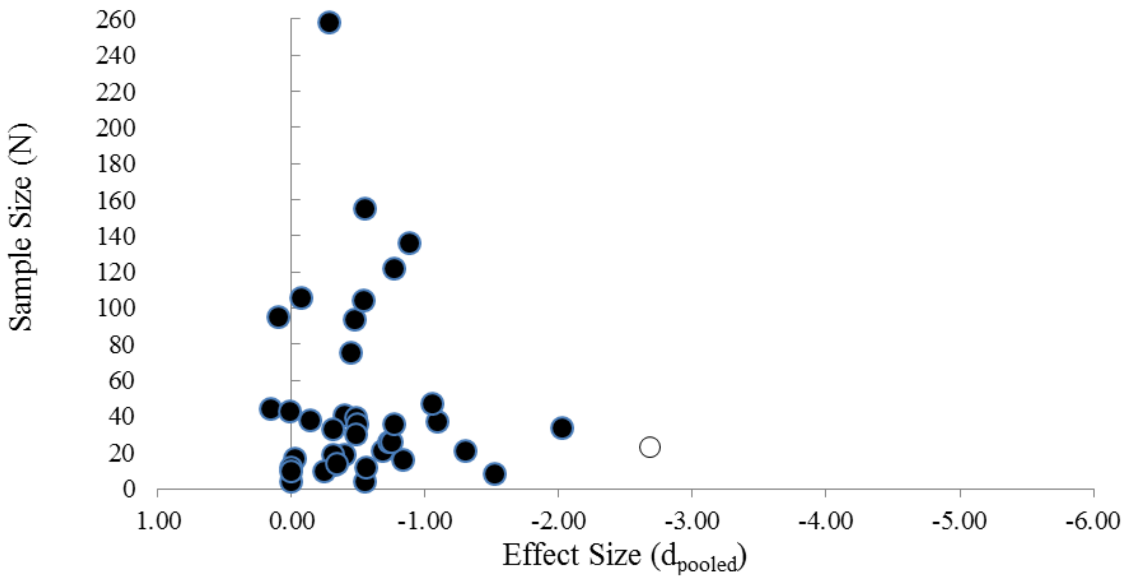

Figure 4d. Funnel plot of 39 independent aggregated effect sizes from samples using a pre-injury baseline comparison, by total sample size (weighted mean effect size, d_{pooled} = -0.43). Outlying effect sizes are indicated by unfilled data points. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988).

sensitivity to concussion or across multiple follow-up assessments beyond the period of typical recovery (see Table 2, notes d and e).

Moreover, exclusion of these outliers did not substantively alter the overall weighted mean effect size ($d_{control}$: outliers included = -0.72 (k = 92), 95% CI: -0.76, -0.68; outliers excluded = -0.70 (k = 88), 95% CI: -0.74, -0.66; d_{pooled}: outlier included = -0.54 (k = 91), 95% CI: -0.57, -0.50; outlier excluded = -0.53 (k = 90), 95% CI: -0.57, -0.50), the weighted mean effect size for samples using an independent control group comparison ($d_{control}$: outliers included = -1.08 (k = 30), 95% CI: -1.16, -0.99; outliers excluded = -1.05 (k = 29), 95% CI: -1.13, -0.96), the weighted mean effect size for samples using a pre-injury baseline comparison ($d_{control}$: outliers included = -0.58 (k = 39), 95% CI: -0.63, -0.53; outliers excluded = -0.56 (k = 36), 95% CI: -0.61, -0.51; d_{pooled}: outlier included = -0.43 (k = 39), 95% CI: -0.47, -0.39; outlier excluded = -0.42 (k = 38), 95% CI: -0.47, -0.38), the weighted mean effect size for the <24 hour time since injury interval ($d_{control}$: outliers included = -1.15 (k = 31), 95% CI: -1.23, -1.07; outliers excluded = -1.10 (k = 28), 95% CI: -1.19, -1.02; d_{pooled}: outlier included = -0.76 (k = 30), 95% CI: -0.82, -0.70; outlier excluded = -0.75 (k = 29), 95% CI: -0.81, -0.68) or the weighted mean effect size for the 1-10 day interval ($d_{control}$ = -0.56 (k = 68), 95% CI: -0.60, -0.52; outlier excluded = -0.55 (k = 67), 95% CI: -0.59, -0.51). Each effect size was therefore retained for further analysis.

Publication bias. An analysis of publication bias was undertaken to quantify the possible inflation of effect sizes due to the exclusion of unpublished studies from the meta-analytic sample. Although limiting the meta-analytic sample to published research suggests that a rigorous process of peer-review has been applied to the methodology and interpretation of these studies, the tendency for non-significant results to remain unpublished (known as the ‘file drawer’ problem), may lead to an overestimation of the overall effect of sports-related concussion (Rosenthal, 1991; Smith, 1980). Consequently, the trim and fill method was applied to funnel plots of independent sample-level effect sizes against standard error (see Figures 5a and 5b) to estimate the degree to which the observed global effect size may require adjustment to account for studies potentially missing from the analysis (Duval, 2005; Duval & Tweedie, 2000; Egger, Smith, Schneider, & Minder, 1997; Sterne et al., 2005).

Visual analysis of the funnel plots revealed an asymmetrical distribution of effects around the relevant aggregated mean effect size (d_{pooled} = -0.54, SE = 0.02, Figure 5a; $d_{control}$ = -0.72, SE = 0.02, Figure 5b). Trim and fill analysis confirmed the visual analysis. It indicated that all studies reporting a positive effect size (consistent with an improvement in function at post-injury assessment) were likely to have been included in the meta-analytic sample (whether estimated using $d_{control}$ or d_{pooled}). However, a number of studies reporting a negative effect size (consistent with a post-injury decrement in function associated with concussion) were likely to be missing from each distribution ($d_{control}$, k = 11; d_{pooled}, k = 20). If these missing studies were combined with the observed studies then, under the fixed effects model, the adjusted mean effect size was estimated as $d_{control}$ = -0.79 (95% CI: -0.82,-0.75), representing a 'large' decrement in functioning post-concussion, and d_{pooled} = -0.68 (95% CI: -0.71, -0.65), representing a 'moderate to large' decrement in functioning post-concussion. The absence of publication bias in the positive direction in this sample of the literature was further supported by cumulative meta-analyses conducted on sample-level effect sizes by concussed sample size (large to small), illustrated in Figure 6a (d_{pooled}) and Figure 6b ($d_{control}$). In the presence of publication bias the effect size would be expected to increase (in the negative direction) with the addition of small samples to the meta-analysis. In contrast, the cumulative global effect of concussion demonstrated a steady but marginal decrease in magnitude (in the positive direction) with the addition of effect sizes generated from studies recruiting relatively small concussion samples.

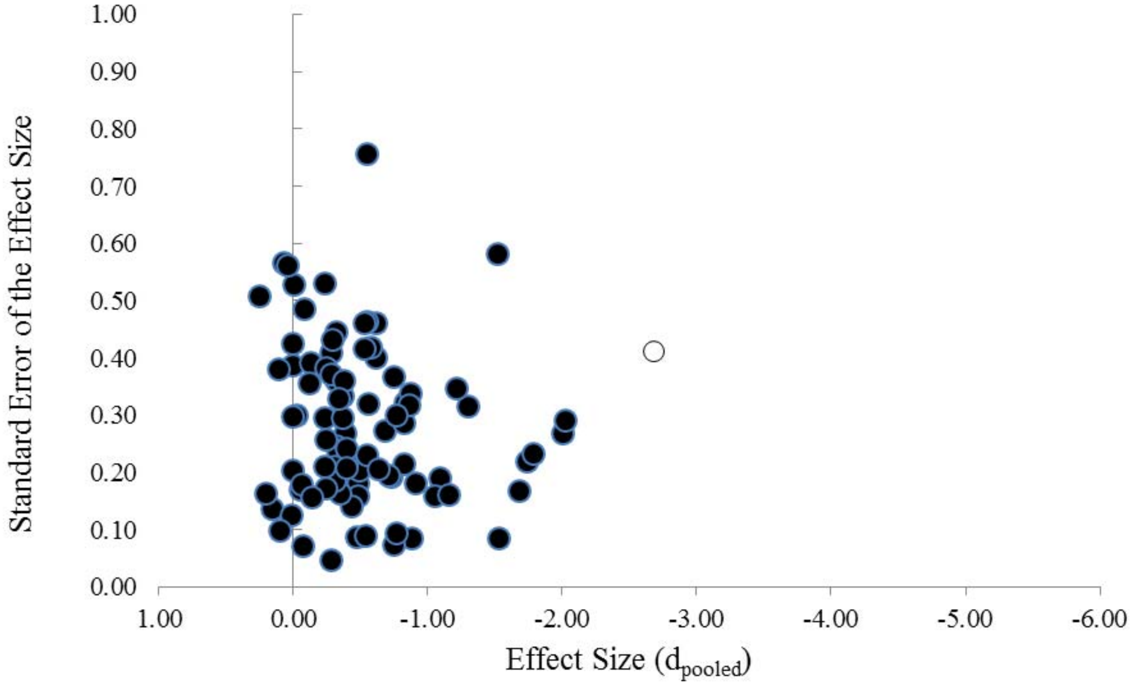

Figure 5a. Funnel plot of 91 independent aggregated effect sizes by the standard error of each effect size (weighted mean effect size, d_{pooled} = -0.54). Outlying effect sizes are indicated by unfilled data points.

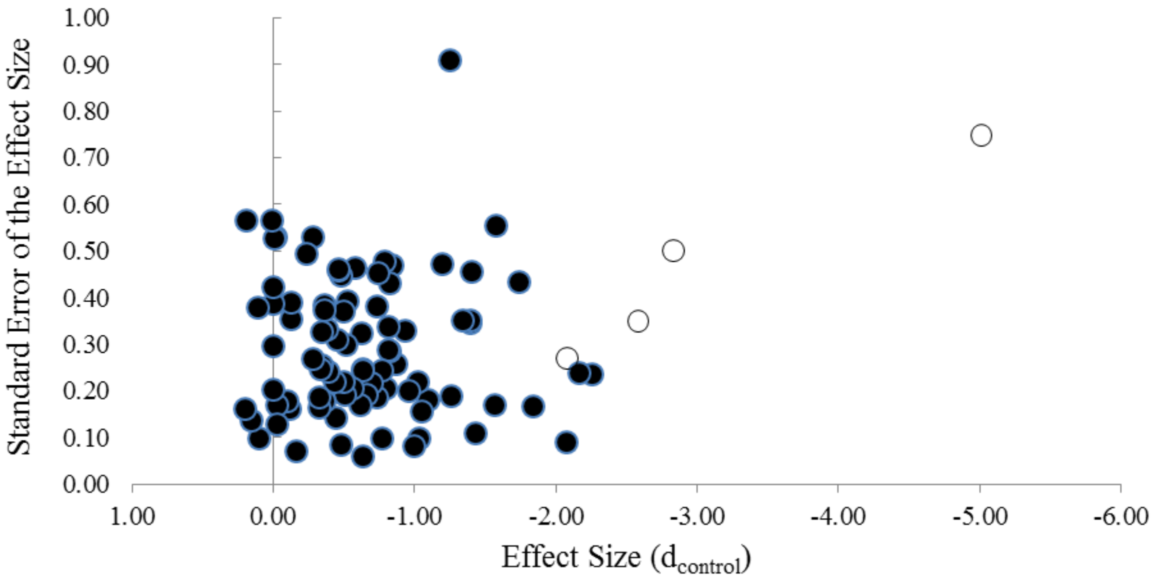

Figure 5b. Funnel plot of 92 independent aggregated effect sizes by the standard error of each effect size (weighted mean effect size, $d_{control}$ = -0.72). Outlying effect sizes are indicated by unfilled data points (see Table 2 for details).

Cumulative Meta-Analysis by Size of Concussed Sample

Study name	Point	Lower limit	Upper limit	p-Value	Outcome	Npm
Register-Mihalik et al., (2007) - no preseason headache	-0.28	-0.37	-0.19	0.00	Multiple	258
Lovell et al., (2006) - males	-0.66	-0.74	-0.59	0.00	Sx	217
Macciocchi et al., (1996)	-0.65	-0.72	-0.57	0.00	Multiple	183
Mihalik et al., (2007) - high school	-0.67	-0.74	-0.60	0.00	Multiple	155
Collins et al., (2006)	-0.70	-0.76	-0.64	0.00	Multiple	136
Van Kampen et al., (2006)	-0.71	-0.77	-0.65	0.00	Multiple	122
Fazio et al., (2007)	-0.72	-0.78	-0.67	0.00	NP	122
Register-Mihalik et al., (2007) - preseason headache	-0.63	-0.68	-0.57	0.00	Multiple	106
McClincy et al., (2006)	-0.62	-0.67	-0.57	0.00	Multiple	104
Pellman et al., (2004)	-0.57	-0.62	-0.52	0.00	NP	95
McCrea et al., (2003)	-0.57	-0.62	-0.52	0.00	Multiple	94
Broshek et al., (2005) - males	-0.56	-0.61	-0.51	0.00	NP	94
McCrea et al., (2002)	-0.56	-0.60	-0.51	0.00	NP	91
Broglio et al., (2007b)	-0.56	-0.60	-0.51	0.00	Multiple	75
Schatz et al., (2006)	-0.56	-0.61	-0.52	0.00	Multiple	72
Lovell et al., (2003)	-0.56	-0.60	-0.51	0.00	Multiple	64
McCrea (2001)	-0.56	-0.61	-0.52	0.00	NP	63
Collie et al., (2006)	-0.55	-0.60	-0.51	0.00	NP	61
Lovell et al., (2006) - repeat assessment	-0.55	-0.59	-0.51	0.00	Sx	52
Barr & McCrea (2001)	-0.56	-0.61	-0.52	0.00	NP	50
Ferguson et al., (1999)	-0.55	-0.59	-0.50	0.00	Sx	50
Pellman et al., (2006) - professional	-0.55	-0.59	-0.50	0.00	Multiple	48
Erlanger et al., (2003)	-0.56	-0.60	-0.51	0.00	Multiple	47
Collins et al., (2003) - asymptomatic	-0.54	-0.58	-0.50	0.00	Multiple	44
Lovell et al., (2004)	-0.52	-0.56	-0.48	0.00	Multiple	43
Lovell et al., (2006) - females	-0.54	-0.58	-0.50	0.00	Sx	43
Iverson et al., (2003)	-0.54	-0.58	-0.50	0.00	Multiple	41
Covassin et al., (2007) - males	-0.54	-0.58	-0.50	0.00	Multiple	41
Moser et al., (2005)	-0.53	-0.57	-0.49	0.00	Multiple	40
Covassin et al., (2007) - females	-0.53	-0.57	-0.49	0.00	Multiple	39
Slobounov et al., (2007)	-0.53	-0.57	-0.49	0.00	Multiple	38
Pellman et al., (2006) - high school	-0.53	-0.57	-0.49	0.00	Multiple	37
Broshek et al., (2005) - females	-0.54	-0.58	-0.50	0.00	NP	37
Guskiewicz et al., (2001)	-0.54	-0.57	-0.50	0.00	Multiple	36
Covassin et al., (2008) - no previous concussion	-0.53	-0.57	-0.50	0.00	Multiple	36
Sosnoff et al., (2008)	-0.54	-0.57	-0.50	0.00	Multiple	36
Field et al., (2003) - College	-0.54	-0.57	-0.50	0.00	Multiple	35
Collins et al., (2003) - symptomatic	-0.54	-0.58	-0.50	0.00	Multiple	34
McCrea et al., (1998)	-0.54	-0.58	-0.50	0.00	NP	33
Iverson et al., (2006)	-0.54	-0.58	-0.50	0.00	Multiple	30
Bruce & Echemendia (2004) - previous concussions	-0.55	-0.58	-0.51	0.00	Multiple	30
Echemendia et al., (2001)	-0.55	-0.58	-0.51	0.00	Multiple	29
Maddocks et al., (1995)	-0.55	-0.58	-0.51	0.00	NP	28
Cavanaugh et al., (2005)	-0.55	-0.58	-0.51	0.00	PS	27
Bruce & Echemendia (2004) - no previous concussions	-0.55	-0.59	-0.52	0.00	Multiple	27
Erlanger et al., (2001)	-0.56	-0.59	-0.52	0.00	Multiple	26
Mihalik et al., (2007) - college	-0.56	-0.59	-0.52	0.00	Multiple	26
Peterson et al., (2003)	-0.56	-0.60	-0.52	0.00	Multiple	24
McCrory et al., (2000)	-0.56	-0.60	-0.53	0.00	NP	23
Sosnoff et al., (2007)	-0.56	-0.60	-0.53	0.00	NP	22
Daniel et al., (2002)	-0.57	-0.60	-0.53	0.00	NP	21
Covassin et al., (2008) - 2+ previous concussion	-0.57	-0.60	-0.53	0.00	Multiple	21
Hinton-Bayre et al., (1999)	-0.57	-0.60	-0.53	0.00	NP	20
Dupuis et al., (2000)	-0.56	-0.60	-0.53	0.00	Multiple	20
Gosselin et al., (2006)	-0.56	-0.60	-0.53	0.00	Multiple	20
Iverson et al., (2004) - no previous concussions	-0.56	-0.60	-0.53	0.00	Multiple	19
Iverson et al., (2004) - 3+ previous concussions	-0.56	-0.60	-0.52	0.00	Multiple	19
Bruce & Echemendia (2003)	-0.56	-0.60	-0.52	0.00	NP	19
Field et al., (2003) - High School	-0.56	-0.60	-0.52	0.00	Multiple	19
Chen et al., (2007)	-0.56	-0.60	-0.52	0.00	Multiple	18
Piland et al., (2003)	-0.56	-0.60	-0.52	0.00	Multiple	17
Broglio et al., (2007a) - simple concussion	-0.56	-0.60	-0.52	0.00	Multiple	17
Riemann & Guskiewicz (2000)	-0.56	-0.60	-0.52	0.00	PS	16
Chen et al., (2008a)	-0.56	-0.59	-0.52	0.00	Multiple	16
Cavanaugh et al., (2006) - steady	-0.56	-0.59	-0.52	0.00	Multiple	16
Parker et al., (2006)	-0.56	-0.59	-0.52	0.00	PS	15
Moser & Schatz (2002)	-0.55	-0.59	-0.52	0.00	NP	14
Warden et al., (2001)	-0.55	-0.59	-0.52	0.00	NP	14
Parker et al., (2008)	-0.55	-0.59	-0.52	0.00	PS	14
Sim et al., (2008)	-0.55	-0.59	-0.51	0.00	NP	14
Cavanaugh et al., (2006) - unsteady	-0.55	-0.59	-0.52	0.00	Multiple	13
Slobounov et al., (2008)	-0.55	-0.59	-0.52	0.00	PS	12
Thompson et al., (2005)	-0.55	-0.59	-0.52	0.00	PS	12
Macciocchi et al., (2001)	-0.55	-0.58	-0.51	0.00	Multiple	12
Guskiewicz et al., (1997)	-0.55	-0.58	-0.51	0.00	Multiple	11
Guskiewicz et al., (1996)	-0.55	-0.58	-0.51	0.00	PS	10
Hinton-Bayre et al., (1997)	-0.55	-0.58	-0.51	0.00	NP	10
Lavoie et al., (2004)	-0.55	-0.58	-0.51	0.00	Multiple	10
Ellemberg et al., (2007)	-0.55	-0.58	-0.51	0.00	NP	10
Gosselin et al., (2009)	-0.55	-0.58	-0.51	0.00	Multiple	10
Parker et al., (2005)	-0.55	-0.58	-0.51	0.00	PS	10
Slobounov, Slobounov & Newell (2006)	-0.54	-0.58	-0.51	0.00	PS	10
Cremona-Meteyard & Geffen (1994) - Experiment 1	-0.54	-0.58	-0.51	0.00	Exp	9
Johnson et al., (2002)	-0.54	-0.58	-0.51	0.00	Multiple	9
Chen et al., (2008b)	-0.54	-0.58	-0.51	0.00	Multiple	9
Slobounov et al., (2006)	-0.54	-0.58	-0.51	0.00	PS	8
Makdissi (2001)	-0.54	-0.58	-0.51	0.00	NP	6
Killam et al., (2005)	-0.54	-0.58	-0.51	0.00	Multiple	5
Lovell & Collins (1998)	-0.54	-0.58	-0.51	0.00	NP	4
Broglio et al., (2007a) - complex concussion	-0.54	-0.58	-0.51	0.00	Multiple	4
Jantzen et al., (2004)	-0.54	-0.58	-0.51	0.00	Exp	4
	-0.54	-0.58	-0.51	0.00		

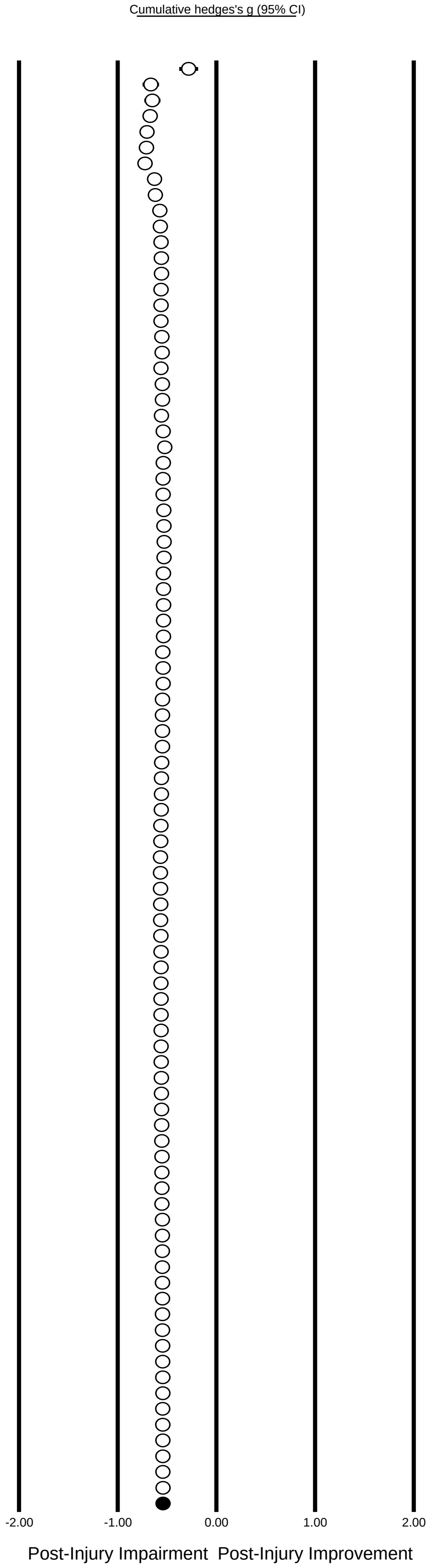

Figure 6a. Cumulative meta-analysis of d_{pooled} sample effect sizes by concussed sample size. Exp = experimental/ cognitive task; NP = neuropsychological assessment; Npm = number of concussed athletes at post-injury assessment; PS = postural stability assessment; Sx = self-report symptom severity.

Cumulative Meta-Analysis by Size of Concussed Sample

Study name	Point	Lower limit	Upper limit	p-Value	Outcome	Npm
Register-Mihalik et al., (2007) - no preseason headache	-0.63	-0.75	-0.51	0.000	Multiple	258
Lovell et al., (2006) - males	-1.22	-1.32	-1.13	0.000	Sx	217
Macciocchi et al., (1996)	-1.15	-1.24	-1.06	0.000	Multiple	183
Mihalik et al., (2007) - high school	-1.11	-1.19	-1.03	0.000	Multiple	155
Collins et al., (2006)	-1.15	-1.23	-1.08	0.000	Multiple	136
Van Kampen et al., (2006)	-1.14	-1.21	-1.07	0.000	Multiple	122
Fazio et al., (2007)	-1.16	-1.22	-1.09	0.000	NP	122
Register-Mihalik et al., (2007) - preseason headache	-0.97	-1.03	-0.91	0.000	Multiple	106
McClincy et al., (2006)	-0.95	-1.01	-0.89	0.000	Multiple	104
Pellman et al., (2004)	-0.86	-0.92	-0.81	0.000	NP	95
McCrea et al., (2003)	-0.85	-0.91	-0.80	0.000	Multiple	94
Broshek et al., (2005) - males	-0.81	-0.87	-0.76	0.000	NP	94
McCrea et al., (2002)	-0.81	-0.86	-0.76	0.000	NP	91
Broglio et al., (2007b)	-0.81	-0.86	-0.76	0.000	Multiple	75
Schatz et al., (2006)	-0.82	-0.87	-0.76	0.000	Multiple	72
Lovell et al., (2003)	-0.81	-0.86	-0.76	0.000	Multiple	64
McCrea (2001)	-0.82	-0.87	-0.77	0.000	NP	63
Collie et al., (2006)	-0.80	-0.85	-0.75	0.000	NP	61
Lovell et al., (2006) - repeat assessment	-0.79	-0.84	-0.74	0.000	Sx	52
Ferguson et al., (1999)	-0.76	-0.81	-0.72	0.000	Sx	50
Barr & McCrea (2001)	-0.78	-0.83	-0.73	0.000	NP	50
Pellman et al., (2006) - professional	-0.78	-0.83	-0.73	0.000	Multiple	48
Erlanger et al., (2003)	-0.79	-0.83	-0.74	0.000	Multiple	47
Collins et al., (2003) - asymptomatic	-0.76	-0.80	-0.71	0.000	Multiple	44
Lovell et al., (2004)	-0.73	-0.78	-0.69	0.000	Multiple	43
Lovell et al., (2006) - females	-0.75	-0.80	-0.71	0.000	Sx	43
Iverson et al., (2003)	-0.75	-0.80	-0.71	0.000	Multiple	41
Covassin et al., (2007) - males	-0.75	-0.80	-0.71	0.000	Multiple	41
Moser et al., (2005)	-0.74	-0.79	-0.70	0.000	Multiple	40
Covassin et al., (2007) - females	-0.74	-0.78	-0.69	0.000	Multiple	39
Slobounov et al., (2007)	-0.73	-0.77	-0.68	0.000	Multiple	38
Broshek et al., (2005) - females	-0.73	-0.78	-0.69	0.000	NP	37
Pellman et al., (2006) - high school	-0.73	-0.78	-0.69	0.000	Multiple	37
Guskiewicz et al., (2001)	-0.73	-0.77	-0.69	0.000	Multiple	36
Covassin et al., (2008) - no previous concussion	-0.73	-0.77	-0.69	0.000	Multiple	36
Sosnoff et al., (2008)	-0.73	-0.77	-0.69	0.000	Multiple	36
Field et al., (2003) - College	-0.73	-0.77	-0.69	0.000	Multiple	35
Collins et al., (2003) - symptomatic	-0.74	-0.78	-0.69	0.000	Multiple	34
McCrea et al., (1998)	-0.73	-0.77	-0.69	0.000	NP	33
Bruce & Echemendia (2004) - previous concussions	-0.74	-0.78	-0.70	0.000	Multiple	30
Iverson et al., (2006)	-0.74	-0.78	-0.70	0.000	Multiple	30
Echemendia et al., (2001)	-0.74	-0.78	-0.69	0.000	Multiple	29
Maddocks et al., (1995)	-0.74	-0.78	-0.70	0.000	NP	28
Bruce & Echemendia (2004) - no previous concussions	-0.75	-0.79	-0.71	0.000	Multiple	27
Cavanaugh et al., (2005)	-0.75	-0.79	-0.70	0.000	PS	27
Erlanger et al., (2001)	-0.75	-0.79	-0.70	0.000	Multiple	26
Mihalik et al., (2007) - college	-0.75	-0.79	-0.71	0.000	Multiple	26
Peterson et al., (2003)	-0.75	-0.79	-0.71	0.000	Multiple	24
McCrory et al., (2000)	-0.75	-0.79	-0.71	0.000	NP	23
Sosnoff et al., (2007)	-0.75	-0.79	-0.71	0.000	NP	22
Daniel et al., (2002)	-0.76	-0.80	-0.72	0.000	NP	21
Covassin et al., (2008) - 2+ previous concussion	-0.76	-0.80	-0.72	0.000	Multiple	21
Hinton-Bayre et al., (1999)	-0.76	-0.80	-0.72	0.000	NP	20
Dupuis et al., (2000)	-0.75	-0.79	-0.71	0.000	Multiple	20
Gosselin et al., (2006)	-0.76	-0.80	-0.71	0.000	Multiple	20
Bruce & Echemendia (2003)	-0.75	-0.79	-0.71	0.000	NP	19
Field et al., (2003) - High School	-0.75	-0.79	-0.71	0.000	Multiple	19
Iverson et al., (2004) - 3+ previous concussions	-0.75	-0.79	-0.71	0.000	Multiple	19
Iverson et al., (2004) - no previous concussions	-0.75	-0.79	-0.71	0.000	Multiple	19
Chen et al., (2007)	-0.75	-0.79	-0.71	0.000	Multiple	18
Piland et al., (2003)	-0.75	-0.79	-0.71	0.000	Multiple	17
Broglio et al., (2007a) - simple concussion	-0.75	-0.79	-0.71	0.000	Multiple	17
Riemann & Guskiewicz (2000)	-0.75	-0.79	-0.71	0.000	PS	16
Cavanaugh et al., (2006) - steady	-0.75	-0.79	-0.71	0.000	Multiple	16
Chen et al., (2008a)	-0.75	-0.79	-0.71	0.000	Multiple	16
Parker et al., (2006)	-0.75	-0.79	-0.71	0.000	PS	15
Warden et al., (2001)	-0.75	-0.79	-0.71	0.000	NP	14
Moser & Schatz (2002)	-0.75	-0.79	-0.71	0.000	NP	14
Parker et al., (2008)	-0.74	-0.78	-0.70	0.000	PS	14
Sim et al., (2008)	-0.74	-0.78	-0.70	0.000	NP	14
Cavanaugh et al., (2006) - unsteady	-0.74	-0.78	-0.70	0.000	Multiple	13
Macciocchi et al., (2001)	-0.73	-0.77	-0.70	0.000	Multiple	12
Thompson et al., (2005)	-0.73	-0.77	-0.70	0.000	PS	12
Slobounov et al., (2008)	-0.73	-0.77	-0.70	0.000	PS	12
Guskiewicz et al., (1997)	-0.73	-0.77	-0.70	0.000	Multiple	11
Guskiewicz et al., (1996)	-0.73	-0.77	-0.69	0.000	PS	10
Maddocks & Saling (1996)	-0.73	-0.77	-0.69	0.000	NP	10
Hinton-Bayre et al., (1997)	-0.73	-0.77	-0.69	0.000	NP	10
Lavoie et al., (2004)	-0.73	-0.77	-0.69	0.000	Multiple	10
Parker et al., (2005)	-0.73	-0.77	-0.69	0.000	PS	10
Slobounov, Slobounov & Newell (2006)	-0.73	-0.77	-0.69	0.000	PS	10
Ellemberg et al., (2007)	-0.73	-0.77	-0.69	0.000	NP	10
Gosselin et al., (2009)	-0.73	-0.77	-0.69	0.000	Multiple	10
Cremona-Meteyard & Geffen (1994) - Experiment 1	-0.73	-0.77	-0.69	0.000	Exp	9
Johnson et al., (2002)	-0.73	-0.76	-0.69	0.000	Multiple	9
Chen et al., (2008b)	-0.73	-0.76	-0.69	0.000	Multiple	9
Slobounov et al., (2006)	-0.73	-0.76	-0.69	0.000	PS	8
Makdissi (2001)	-0.73	-0.76	-0.69	0.000	NP	6
Killam et al., (2005)	-0.72	-0.76	-0.69	0.000	Multiple	5
Lovell & Collins (1998)	-0.72	-0.76	-0.69	0.000	NP	4
Jantzen et al., (2004)	-0.72	-0.76	-0.68	0.000	Exp	4
Broglio et al., (2007a) - complex concussion	-0.72	-0.76	-0.68	0.000	Multiple	4
	-0.72	-0.76	-0.68	0.000		

Cumulative point estimate (95% CI)

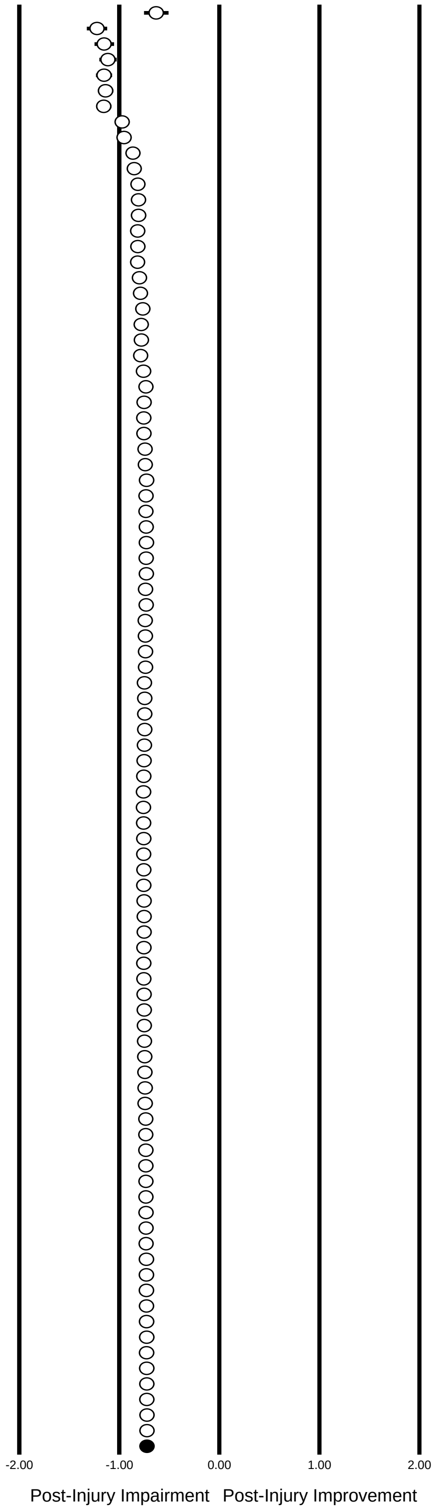

Figure 6b. Cumulative meta-analysis of $d_{control}$ sample effect sizes by concussed sample size. Exp = experimental/ cognitive task; NP = neuropsychological assessment; Npm = number of concussed athletes at post-injury assessment; PS = postural stability assessment; Sx = self-report symptom severity.

Selective reporting bias. An analysis of selective reporting bias was undertaken to quantify the possible inflation of the magnitude of aggregated effects associated with under-reporting of detailed descriptive statistics within published papers, and consequently, the inclusion of effect sizes in the meta-analysis estimated from inferential statistics or extrapolated from figures (see Table 1). It was noted during the process of coding studies for analysis that many authors failed to report detailed descriptive statistics for certain outcome measures, particularly those that failed to reach statistical significance. Like publication bias, selective reporting of results or selective inclusion in meta-analyses of only those results reported in detail may lead to a serious form of missing data and a biased overall effect size estimate (Sutton & Pigott, 2005). Automatically excluding these effect sizes would result in an overestimate of the true effect as findings too small to achieve statistical significance would be underrepresented in the analysis (Durlak & Lipsey, 1991, p. 304).

Additionally, those results reported only as statistically non-significant were entered into the analysis as an effect size of zero, as per Frencham and colleagues' treatment (2005). However, as the true effect associated with non-significant variables is unlikely to be exactly zero, this conservative strategy may underestimate the true magnitude of the overall effect. Consequently, excluding these effects may overestimate the magnitude of the overall effect (Durlak & Lipsey, 1991; Rosenthal & DiMatteo, 2001). Imputing the same value for each missing variable is also likely to inflate the precision of the estimate by underestimating the true variance of the data set and by providing a larger sample size for analysis (Sutton & Pigott, 2005).

Therefore, all outcome measures were coded to indicate whether or not sufficient data had been reported for effect size calculation and the nature of the data used to calculate (descriptive statistics) or estimate the effect size (inferential statistics, extrapolation from figures). A sensitivity analysis was then conducted to evaluate the robustness of results to the impact of selective reporting bias (i.e. the effect of excluding or including estimated effect sizes, and the effect of excluding results reported only as ‘non-significant’ or including a substituted value of zero). Table 1 details the number of effect sizes by assessment occasion, generated from each method of effect size derivation. Of the 1,404 individual effects described by study authors, 55% were able to be calculated directly from descriptive statistics, 21% were estimated from other reported statistical information (e.g. inferential statistics) or extrapolated from graphs, 13% were reported only as ‘not statistically significant’ and therefore entered into analyses as a value of zero, and 12% were unable to be estimated from the reported information because the effect was described only as statistically significant or not reported at all, leaving 1,238 quantifiable $d_{control}$ effects (or 1,234 d_{pooled} effects) for inclusion in analyses. Data required for effect size calculation were less likely to be reported as the number of post-injury assessments increased.

Overall, the magnitude of the global effect size was not substantively altered by the nature of the data used to calculate or estimate the effects. Across the meta-analytic sample a total of 178 individual effects were reported only as ‘not statistically significant’ by study authors and entered into analyses as a value of zero. The ‘moderate to large’ global effect ($d_{control}$ = -0.72; d_{pooled} = -0.54) was minimally increased when these highly estimated effects were excluded from analysis ($d_{control}$ = -0.74, p < .001, 95% CI -0.78, -0.70; $Q(87)$ = 900.62, p < .001; d_{pooled} = -0.57, p < .001, 95% CI -0.60, -0.53; $Q(86)$ = 654.62, p < .001) based on 88 $d_{control}$ or 87 d_{pooled} independent effect sizes of which 82 (93%) and 79 (91%) effects, respectively, were of a magnitude less than zero ($d_{control}$ range: -5.01 to 0.20; d_{pooled} range: -2.68 to 0.25). This change in magnitude was insufficient to alter substantive interpretations.

Results were also found to be robust to other methods of effect size estimation. A significant ‘moderate to large’ heterogeneous effect was produced when effects extrapolated from graphs were also excluded ($d_{control}$ = -0.73, p < .001, 95% CI -0.78, -0.69; $Q(77)$ =

891.08, $p < .001$; $d_{pooled} = -0.56$, $p < .001$, 95% CI -0.60, -0.52; $Q(76) = 635.56$, $p < .001$). Similarly, a significant 'moderate to large' heterogeneous effect was produced when effects that first required conversion from unconventional statistics to equivalent *t*-values were also excluded, leaving only those calculated directly from descriptive statistics or indirectly by conversion from *t*-tests or *F*-ratios ($d_{control} = -0.74$, $p < .001$, 95% CI -0.78, -0.70; $Q(72) = 843.93$, $p < .001$; $d_{pooled} = -0.55$, $p < .001$, 95% CI -0.59, -0.51; $Q(71) = 598.84$, $p < .001$), and a 'moderate to large' heterogeneous effect remained when only those effects calculated directly from descriptive statistics were retained ($d_{control} = -0.70$, $p < .001$, 95% CI -0.75, -0.65; $Q(61) = 691.43$, $p < .001$; $d_{pooled} = -0.52$, $p < .001$, 95% CI -0.56, -0.48; $Q(60) = 488.39$, $p < .001$). The difference between the global effect size generated from all methods of estimation ($d_{control} = -0.72$; $d_{pooled} = -0.54$) and the global effect size generated from direct calculation only ($d_{control} = -0.70$; $d_{pooled} = -0.52$) represented only 0.02 of a standard deviation; whereas the largest difference in global effect size magnitude between effects calculated directly from descriptive statistics ($d_{control} = -0.70$; $d_{pooled} = -0.52$) and inclusion of effects converted from *t*-tests or *F*-ratios ($d_{control} = -0.74$; $d_{pooled} = -0.57$), was only 0.04 to 0.05 of a standard deviation. The results of the sensitivity analysis therefore indicated that the magnitude of the global effect of concussion was not substantively altered by the inclusion of effect sizes estimated from inferential statistics or imputed as a value of zero. The results were therefore considered robust to the presence of selective reporting within the meta-analytic sample.

Comparison of $d_{control}$ and d_{pooled} Effect Size Statistics

The results of the fixed+systematic effects meta-analysis reported in Dougan, et al. (2012) were calculated by dividing the difference between the concussed group mean and the uninjured (pre-injury baseline or independent control group) group mean by the pooled standard deviation of the concussed (post-injury) and uninjured group means (d_{pooled}). However, as indicated above and displayed in Table 2, effect size estimates were also calculated in the form of a 'normative effect size' statistic by dividing the difference between the concussed group mean and the uninjured group mean by the standard deviation of the uninjured group mean only ($d_{control}$). The d_{pooled} statistic avoids skewed results when the two samples have disparate variances as it balances the typical variability often observed in patients with neuropsychological deficits against the reduced variability often observed in healthy controls upon retest (i.e. with practice). Consequently, the standard deviation term entered into the effect size equation is typically larger than if the comparison group standard deviation alone is used; d_{pooled} thus tends to produce a smaller effect size value than $d_{control}$ (Makdissi et al., 2001; Zakzanis, 2001).

However, Lipsey and Wilson recommend using only the standard deviation of the comparison group mean to estimate the effect size ($d_{control}$), if the standard deviation of the 'treatment' group (i.e. concussed participants) can reasonably be expected to be affected by the 'treatment' (i.e. concussive injury) (2001, p. 49). Research indicates that increased performance variability post-injury is indeed a characteristic of concussion (Bleiberg, Garmoe, Halpern, Reeves, & Nadler, 1997; Daniel, Nassiri, Wilckens, & Land, 2002; Makdissi et al., 2001; Stuss, Pogue, Buckle, & Bondar, 1994), and comparison of the standard deviations arising within this meta-analytic sample revealed a consistent pattern of greater variance in post-concussion scores relative to baseline and smaller variance in control scores upon retest relative to initial assessment (see below). Under these conditions, Lipsey and Wilson argue that the standard deviation of the comparison group mean (i.e. pre-injury baseline or healthy control group), while likely to be significantly smaller than the injured group's standard deviation (thus producing a larger effect size value), offers a better estimate of the population variance as it is untainted by the concussive injury.

While some meta-analysts have argued that the $d_{control}$ formula produces an overestimate of the effect (e.g. Frencham et al., 2005), quantifying the magnitude of the concussion effect in terms of deviation from uninjured performance allows for consideration of the magnitude of change in functioning associated with a recent concussion relative to the normal, healthy functioning of uninjured athletes. To this end, and to enable comparison with the d_{pooled} results reported in Dougan, et al. (2012), the results of a fixed+systematic effects meta-analysis conducted using $d_{control}$ effect size estimates are reported below.

As expected, $d_{control}$ typically produced somewhat larger effect sizes than d_{pooled}, overall and across all moderator analyses conducted. The largest difference between d_{pooled} and $d_{control}$ was associated with acute post-injury assessments (<24 hours since injury) and self-report symptom scales – i.e. variables that reflect the greatest contrast between the larger performance variability of concussed athletes (injury effects) and the smaller performance variability of uninjured athletes. Nonetheless, a similar *pattern* of effect sizes and statistical significance was observed across key moderator analyses irrespective of the effect size statistic (or meta-analytic model [3] [4]) used. Hence, the substantive interpretations and conclusions drawn in Dougan, et al. (2012) regarding the moderating effects of athlete characteristics are not specific to the use of the d_{pooled} effect size formulae or the fixed+systematic effects statistical model (as per Binder et al., 1997; Pertab et al., 2009; Schretlen & Shapiro, 2003).

[3] For further comparison of results using a "fixed+systematic effects" model see Appendix A ($d_{control}$) and Appendix B (d_{pooled}). For comparison of results using a "mixed effects" model see Appendix C ($d_{control}$) and Appendix D (d_{pooled}).

[4] With the exception of sport played (in particular, Australian Rules and ice hockey).

Comparison of concussed vs. uninjured comparison group standard deviations. First, the average standard deviations (SD) of concussed and control group means were compared. All distributions of standard deviations were severely positively skewed, but transformation did not alter substantive conclusions; untransformed data are therefore reported. As expected, concussed group post-injury standard deviations were significantly larger on average than comparison group (pre-injury baseline or independent control) standard deviations: within studies using both a pre-injury baseline and independent control group comparison, the mean concussed group post-injury standard deviation was significantly greater than that of the independent control group at retest, t (560) = 3.20, $p < .001$ (M = 7.16, SD = 9.67, and M = 5.04, SD = 5.94, respectively), despite their equivalence at baseline, t (560) = 0.19, *ns* (M = 6.23, SD = 7.58, and M = 6.10, SD = 8.10, respectively). Standard deviations also significantly increased from pre-injury to post-injury within concussed samples, t (280) = -3.24, $p < .001$, while independent control group standard deviations significantly decreased from baseline to retest, t (280) = 4.37, $p < .001$. Similarly, studies using only a pre-injury baseline comparison demonstrated significantly larger standard deviations at post-injury than at pre-injury, t (354) = -7.53, $p < .001$ (M = 5.88, SD = 7.11, and M = 4.27, SD = 4.91, respectively), and studies using only an independent control group comparison demonstrated a non-significant trend of larger concussed group post-injury standard deviations than independent control group standard deviations, t (625) = 1.34, *ns* (M = 14.67, SD = 53.65, and M = 10.43, SD = 31.58).

Results of the Meta-analysis Calculated Using the $d_{control}$ Effect Size Statistic

Characteristics of Included Samples

Thirty-one samples reported concussed athletes' average number of years of education (*n* = 1,516, range: 9.6 to 16.6 years) and 23 samples reported control athletes' average number of years of education (*n* = 2,699, range: 9.4 to 16.8 years). In contrast, only 18 samples reported rates of diagnosed learning disorders (*M* = 3% of concussed athletes, range: 0% to 20%; *M* = 3% of controls, range: 0% to 8%), 13 samples reported rates of diagnosed attention deficit/hyperactivity disorder (*M* = 4% of concussed athletes, range: 0% to 20%; *M* = 3% of controls, range: 0% to 7%), 5 samples reported nil drug or alcohol history, 4 samples recorded rates of special education (range: 0% to 3% of concussed athletes), 3 samples recorded rates of speech therapy (range: 0% to 7% of concussed athletes), 1 sample reported nil history of repeating a school grade, and 1 sample reported that 27% of athletes had received treatment for headache pre-injury. No athletes were reported to be involved in litigation and only one sample was clinic-referred (Chen, Johnston, Petrides, & Ptito, 2008b). Nine samples (*n* = 210 concussed; 457 controls) reported nil history of previous concussion, 56 samples (*n* = 2,537 concussed; 1,276 controls) reported a widely varied history of previous concussion within the concussed sample, and 27 samples did not report concussion history at all (*n* = 1,064 concussed; 3,908 controls). Consequently, the effect of concussion history could not be reliably controlled within the current meta-analytic sample.

Overall Effect of Sports-Related Concussion

Table 2 details the characteristics of the 92 independent samples of sports-related concussion included in analyses (*n* = 3,811 concussed athletes and 5,641 controls), while Tables 3 to 5 present the results of the meta-analysis calculated using the $d_{control}$ effect size statistic.

Table 2

Characteristics of the 92 Sports-Related Concussion Samples Included in the Meta-Analysis, Arranged by Comparison Group and Aggregated Effect Size ($d_{control}$).

Sample [a]	Concussed; Controls			Country	Sport	Level	Concussed athletes' history of previous concussions	TSI at each post-injury assessment [b]				Outcome measures			No. effects	$d_{control}$
	Sample size	% Male	Age (in years)					1st	2nd	3rd	4th	NP	SRS	PS		
							Pre-injury baseline and independent control group comparison									
Barr & McCrea (2001)	50; 68	100; 100	17.2; 18.1	USA	F	HS/C	-	0				S			1	-2.25
Piland et al. (2003)	17; 16	88; 88	19.8; 19.5	USA	M (F)	C	-	1	2	3	10		PnP		8	-1.74
Peterson et al. (2003)	24; 18	75; 75	20.2; 19.3	USA	M (F)	C	21% 1≤ (M = 5.0)	1	2	3	10	PnP	PnP	PC	20	-1.40
Sosnoff et al. (2007)	22; 22	91; -	19.8; -	USA	M (-)	C	59% 1≤	2				PC			7	-1.40
Iverson et al. (2003)	41; 56	90; 52	16.8; 17.6	USA	M (F)	A	-	1.3				PC	PC		5	-1.02
McCrea (2001)	63; 55	100; 100	18.2; 18.2	USA	F	HS/C	-	0	<2			S			10	-0.96
Maddocks & Saling (1996)	10; 10	100; 100	-; -	AUS	ARf	P	40% 1≤	5				PnP			4	-0.84
Field et al. (2003) – 1	19; 20	88; 88	15.2; 16.6	USA	M (F)	HS	M = 0.6 (0.7)	<1	3	5	7	PnP	PnP		20	-0.82
Lovell et al. (2003)	64; 24	94; 67	-; -	USA	M (F)	HS	Multiple (-)	1.5	4.2	7.6		PC	PC		6	-0.64
Hinton-Bayre et al. (1997)	10; 10	100; 100	22.1; 19.9	AUS	R	P	M = 2.6 (1.8)	1.5				PnP			5	-0.53
Field et al. (2003) – 2	35; 18	94; 94	19.9; 20.1	USA	M (F)	C	M = 1.5 (1.3)	<1	3	5	7	PnP	PnP		12	-0.52
Guskiewicz et al. (1996)	10; 10	100; 100	17.4; 18.6	USA	F	HS/C	-	1	3	5	10			PC	20	-0.46
Echemendia et al. (2001)	29; 20	92; 92	-; -	USA	M	C	-	2hrs	2	7	30	PnP	PnP		81	-0.44
Guskiewicz et al. (2001)	36; 36	69; 69	19.5; 20.0	USA	M	C	-	1	3	5		PnP		C; PC	36	-0.39
McCrea et al. (2003)	94; 56	100; 100	20.0; 19.2	USA	F	C	M = 0.6 (0.8)	0 2	<3hrs 7	1 90	2	S; PnP	PnP	C	45	-0.36
Sim et al. (2008)	14; 14	79; 77	15.5; 15.7	USA	M (-)	HS	43% 1≤	2.5	6.3	9.9	45	PC			24	-0.35
Macciocchi et al. (1996)	183; 48	100; 100	19.0; 19.0	USA	F	C	42% 1≤	1	5	10	84	PnP	PnP		22	-0.33
Cavanaugh et al. (2005)	27; 30	78; 50	19.5; 21.7	USA	M (F)	C	26% 1≤	<2						PC	15	-0.28
Lovell & Collins (1998)	4; 40	100; 100	-; 19.6	USA	F	M	M = 1.0 (range 0-6)	<1	180			PnP			20	-0.28
Hinton-Bayre et al. (1999)	20; 13	100; 100	21.1; 19.6	AUS	R	P	M = 2.4 (2.4)	2	10.5	28		PnP			9	-0.12
Collie et al. (2006)	61; 84	100; 100	22.9; 23.4	AUS	ARf	A	M = 2.7 (2.4)	3				PnP; PC			9	-0.03
Johnson et al. (2002)	9; 9	44; 60	-; -	USA	M (R)	C	-	1	3	5	10		PnP	PC	8	-0.01
Makdissi (2001)	6; 7	100; 100	20.5; 20.3	AUS	ARf	C	-	2				PnP; PC			3	0.19

Sample [a]	Concussed; Controls			Country	Sport	Level	Concussed athletes' history of previous concussions	TSI at each post-injury assessment [b]				Outcome measures			No. effects	$d_{control}$
	Sample size	% Male	Age (in years)					1st	2nd	3rd	4th	NP	SRS	PS		
							Independent control group comparison only									
Bruce & Echemendia (2004) – 1	27; 286	100; 100	20.2; 18.8	USA	M	C	None	2hrs					PnP		1	-2.16
Bruce & Echemendia (2004) – 2	30; 147	100; 100	20.2; 19.0	USA	M	C	100% 1≤	2hrs					PnP		1	-2.08 [d]
Lovell et al. (2006) – 1 [c]	221; 707	-; 83	16.5; -	USA	M (-)	HS	-	2					PC		1	-2.07
Lovell et al. (2006) – 2 [c]	39; 1,039	-; 77	-; -	USA	M (-)	C	-	2					PC		1	-1.84
Fazio et al. (2007)	122; 70	81; 47	16.7; 17.3	USA	M (F)	HS/C	24% 1≤	1.9				PC			4	-1.57
Gosselin et al. (2006)	20; 10	95; 90	25.9; 22.0	CAN	M (IH)	C/P	*M* = 4.3 (3.6)	71.4				PnP;Exp	PnP		12	-1.40
Schatz et al. (2006)	72; 66	79; 44	16.5; 17.3	USA	M (F)	HS	100% 1≤	2				PC	PC		6	-1.26
Maddocks et al. (1995)	28; 28	100; 100	-; -	AUS	ARf	P	-	10mins				S			14	-0.83
Thompson et al. (2005)	12; 12	100; 100	21.0; 21.0	USA	M (-)	C	*M* = 1.0 (0.0)	89						PC	2	-0.82
Ellemberg et al. (2007)	10; 12	0; 0	22.7; 22.3	CAN	S	C	None	246				PnP; PC			19	-0.79
Pellman et al. (2006) – 1	37; 125	100; 100	15.8; 15.6	USA	F	HS	*M* = 0.9 (range 0-3)	1.5	5			PC	PC		10	-0.79
Chen et al. (2007)	18; 10	100; 100	28.9; 21.9	CAN	M (IH)	C/P	*M* = 3.4 (1.4)	156				PC; Exp	PnP		25	-0.75
Riemann & Guskiewicz (2000)	16; 16	94; 94	19.2; 22.5	USA	-	C	-	1	3	5	10			C; PC	36	-0.73
Pellman et al. (2006) – 2	48; 68	100; 100	26.3; 24.3	USA	F	P	*M* = 1.2 (range 0-4)	1.2	2.9			PC	PC		10	-0.69
Parker et al. (2005)	10; 10	40; 40	20.2; 19.9	USA	M (-)	C	-	1.6						G	20	-0.58
Chen et al. (2008a)	16; 16	100; 100	26.0; 20.0	CAN	M (-)	C/P	*M* = 3.4 (1.8)	219				Exp	PnP		6	-0.50
Guskiewicz et al. (1997)	11; 11	73; 73	18.6; 20.2	USA	-	C	-	1	3	5	10	PnP		PC	37	-0.48
Gosselin et al. (2009)	10; 11	70; 64	24.3; 22.6	CAN	M	C/P	*M* = 4.6 (2.1)	132				PnP; PC	PnP		26	-0.46
Lovell et al. (2006) – 3	52; 1,746	90; 80	-; -	USA	M (-)	HS/C	-	-	5.6	11.7			PC		2	-0.44
McCrea et al. (2002)	91; 45	100; 100	17.3; 17.5	USA	F	HS/C	-	-	15mins	2	90	S			20	-0.44
Bruce & Echemendia (2003)	19; 19	100; 100	20.1; 19.9	USA	M (F)	C	53% 1≤	2hrs	2	7	30	PnP			24	-0.38
Parker et al., (2006)	15; 15	60; 60	20.6; 20.6	USA	M (-)	C	-	1.6	5	14	28			G	80	-0.36
Cremona-Meteyard & Geffen (1994) – Experiment 1	9; 12	100; 100	23.0; 22.1	AUS	ARf	P	67% 1≤	<14	365			Exp			12	-0.24
Moser & Schatz (2002)	14; 21	79; 81	16.4; 16.8	USA	M (-)	HS	97% 1≤	4				PnP			18	-0.13
Moser et al. (2005)	40; 183	-; -	15.8; 15.7	USA	M (-)	HS	80% 1≤	3.5				PnP	PnP		9	-0.10
Chen et al. (2008b)	9; 6	100; 100	31.5; 20.0	CAN	M (IH)	C	*M* = 4.2 (1.4)	90	547			Exp			4	-0.02
Dupuis et al. (2000)	20; 10	100; 100	21.5; 21.5	CAN	M (F)	C	100% 1≤ (*M* = 2.9)	171.8				PnP;Exp			11	0.00
Killam et al. (2005)	5; 9	60; 67	22.6; 22.0	USA	M (-)	C	100% 1≤	73				PnP	PnP		10	0.01

Sample [a]	Concussed; Controls			Country	Sport	Level	Concussed athletes' history of previous concussions	TSI at each post-injury assessment [b]				Outcome measures			No. effects	$d_{control}$
	Sample size	% Male	Age (in years)					1st	2nd	3rd	4th	NP	SRS	PS		
Parker et al. (2008)	14; 14	-; -	20.7; 20.6	USA	M (-)	C	-	1.4	5	14	28			G	32	0.11
Ferguson et al. (1999)	50; 159	100; 100	20.2; 19.6	USA	M (IH)	HS/P	None	180					PnP		1	0.20
Pre-injury baseline comparison only																
McCrory et al. (2000)	23	100	-	AUS	ARf	P	-	15mins				PnP			1	-5.01 [d]
Daniel et al. (2002)	21	100	-	USA	F	C	Multiple (-)	0				S			1	-2.83 [e]
Collins et al. (2003a) – 1	34 (poor post-injury)	85	17.4	USA	M (F)	HS/C	90% 1≤	1.4				PC	PC		2	-2.58 [e]
Slobounov, Tutwiler, et al. (2006)	8	100	21.0	USA	M (-)	C	None	3	10	30				PC	15	-1.58
Collins et al. (2006)	136	100	16.1	USA	F	HS	28% 1≤	2.2				PC	PC		5	-1.43
Sosnoff et al. (2008)	36	81	21.2	USA	M (-)	C	-	<1				PC	PnP	PC	16	-1.34
Broglio et al. (2007a) – 1	4 (complex concussion)	76	19.8	USA	M (F)	C	*M* = 1.8 (2.0)	1.2	18.8			PC	PnP		12	-1.25
Broglio et al. (2007a) – 2	17 (simple concussion)	76	19.8	USA	M (F)	C	*M* = 1.8 (2.0)	1.2	5.6			PC	PnP		12	-1.19
Broshek et al. (2005) – 1	37	0	17.5	USA	M	HS/C	46% 1≤	3.8				PC			3	-1.10
Erlanger et al. (2003)	47	57	17.6	USA	M	HS/C	68% 1≤	2.1				PC			3	-1.05
Van Kampen et al. (2006)	122	82	16.6	USA	M (F)	HS/C	24% 1≤	2				PC	PC		5	-1.03
Mihalik et al. (2007) – 1	155	84	15.6	USA	M (-)	HS	Multiple (-)	3.3				PC	PC		5	-1.00
Cavanaugh et al. (2006) – 1	13 (unsteady post-injury)	-	-	USA	M	C	Multiple (-)	<2	3				PnP	PC	46	-0.93
Mihalik et al. (2007) – 2	26	89	22.1	USA	M (-)	C	Multiple (-)	3.3				PC	PC		5	-0.87
Covassin et al. (2008) – 1	21	67	21.1	USA	M	C	100% 2≤	1.2	5.1			PC	PC		10	-0.82
Broglio et al. (2007b)	75	83	-	USA	M (F)	C	-	<1				PnP; PC	PnP	PC	27	-0.77
McClincy et al. (2006)	104	88	16.1	USA	M (F)	HS/C	33% 1≤	2.4	7.6	14.4		PC	PC		15	-0.77
Erlanger et al. (2001)	26	65	18.6	USA	M (-)	HS/C	-	1.8				PC			3	-0.73
Covassin et al. (2007) – 1	41	100	-	USA	M	C	52% 1≤	1.9	8.1			PC	PC		10	-0.66
Iverson et al. (2004) – 1	19	95	17.9	USA	M (F)	A	None	1.8				PC	PC		4	-0.63
Register-Mihalik et al. (2007) – 1	258 (no headache)	-	16.7	USA	M (-)	HS/C	31% 1≤	1	3	7		S	PnP	C	12	-0.63
Iverson et al. (2006)	30	93	16.1	USA	M (F)	A	27% 1≤	1.5	5.2	10.3		PC	PC		15	-0.62
Slobounov et al. (2008)	12	53	21.2	USA	R	C	None	-	-	30				PC	11	-0.62

Sample [a]	Concussed; Controls			Country	Sport	Level	Concussed athletes' history of previous concussions	TSI at each post-injury assessment [b]				Outcome measures			No. effects	$d_{control}$
	Sample size	% Male	Age (in years)					1st	2nd	3rd	4th	NP	SRS	PS		
Covassin et al. (2008) – 2	36	47	20.6	USA	M	C	None	1.2	5.1			PC	PC		10	-0.56
Covassin et al. (2007) – 2	39	0	-	USA	M	C	52% 1≤	1.9	8.1			PC	PC		10	-0.50
Iverson et al. (2004) – 2	19	90	17.8	USA	M (F)	A	100% 3≤	1.6				PC	PC		4	-0.50
Broshek et al. (2005) – 2	94	100	19.2	USA	M (F)	HS/C	46% 1≤	2.8				PC			3	-0.48
Lavoie et al. (2004)	10	100	21.5	CAN	M	C	100% 1≤ (*M* = 3.2)	51				PnP	PnP		14	-0.36
Cavanaugh et al. (2006) – 2	16 (steady post-injury)	-	-	USA	M	C	Multiple (-)	<2	3				PnP	PC	46	-0.34
Warden et al. (2001)	14	100	19.0	USA	B	C	-	-	4			PC			7	-0.34
McCrea et al. (1998)	33	100	-	USA	F	HS/C	-	0	2			S			10	-0.33
Register-Mihalik et al. (2007) – 2	106 (preseason headache)	-	16.7	USA	M (-)	HS/C	40% 1≤	1	3	7		S	PnP	C	12	-0.17
Slobounov et al. (2007)	38	55	21.2	USA	R	C	None	10	17	30		PnP		PC	11	-0.12
Lovell et al. (2004)	43	81	15.6	USA	M (F)	HS	Multiple (-)	1.4	6.3			PC	PC		8	-0.02
Jantzen et al. (2004)	4	100	20.0	USA	F	C	-	3.5				Exp			4	0.00
Macciocchi et al. (2001)	12	100	19.1	USA	F	C	*M* = 1.0 (0.0)	-	-	10	84		PnP		2	0.00
Slobounov, Slobounov & Newell (2006)	10	100	19.5	USA	M (-)	C	None	-	-	30				PC	3	0.00
Pellman et al. (2004)	95	100	25.4	USA	F	C/P	-	2.2				PnP			10	0.10
Collins et al. (2003a) – 2	44 (good post-injury)	91	15.5	USA	M (F)	HS/C	80% 1≤	2				PC	PC		2	0.15

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator – aggregated across all post-injury assessments and all outcome measures; TSI = time since injury. Country: AUS = Australia; CAN = Canada; USA = United States of America. Sport: ARf = Australian Rules football; B = Boxing; F = American football; IH = ice hockey; M = multiple sports at risk of concussive injury (specify if >50% sample from single sport); R = Rugby; S = soccer. Level of competition: A = amateur/non-professional club; HS = high school; C = college; P = professional/elite; M = mixed levels. Outcome Measures: C = Clinical assessment of postural stability; Exp = Experimental/cognitive tasks; G = computerised assessment of gait stability under single and dual-task conditions; NP = neuropsychological tests; PC = computerised assessment; PnP = traditional pen-and-paper assessment; PS = postural stability assessment; S = sideline assessment of mental status; SRS = self-report symptoms.

[a] For full reference see asterisked (*) citations in References section. [b] The four columns (1st, 2nd, 3rd, 4th) represent the first four post-injury assessment occasions potentially conducted by a given study, while the number presented within each column represents the time elapsed between injury and that specific assessment occasion (TSI), reported as the average TSI, or mid-point of a reported TSI range; in days unless otherwise indicated. [c] Data also presented separately for 217 males (1,391 controls), $d_{control}$ = -2.43 and 43 females (355 controls), $d_{control}$ = -1.74. [d] Identified as an outlier relative to the overall mean effect size and the mean effect size for that comparison group. [e] Identified as an outlier relative to the mean effect size for that comparison group.

Aggregated across all outcome measures and post-injury assessments, the overall weighted mean effect size ($d_{control}$) represented a statistically significant 'moderate to large'[5] decrement in general functioning following sports-related concussion (-0.72; 95% CI: -0.76, -0.68); based on 92 independent effects (range: -5.01 to 0.20), 89% of which represented a decline in post-injury functioning, and 62% of which were 'moderate' or 'large' in magnitude. The overall effect was significantly heterogeneous ($Q(91) = 932$, $p < .001$); investigation of moderator variables was therefore considered appropriate.

The overall effect was comprised of a 'moderate' decrement in neuropsychological functioning (-0.47; 95% CI: -0.51, -0.43; $Q(70) = 571$, $p < .001$), a 'large' increase in self-reported symptoms (-0.99; 95% CI: -1.03, -0.94; $Q(49) = 1011$, $p < .001$), and a 'small' but significant decrement in postural stability (-0.14; 95% CI: -0.21, -0.07; $Q(21) = 66$, $p < .001$), when collapsed over all follow-up assessments. Neuropsychological outcomes varied by comparison group: a 'small to moderate' effect was derived from samples using a pre-injury baseline (-0.43; 95% CI: -0.47, -0.38; $Q(32) = 395$, $p < .001$), while a 'moderate to large' effect was derived from samples using an independent control group (-0.60; 95% CI: -0.73, -0.48; $Q(18) = 74$, $p < .001$), and from samples using both comparisons (-0.60; 95% CI: -0.71, -0.48; $Q(18) = 91$, $p < .001$). Postural stability outcomes also varied by comparison group: a 'small' effect was derived from samples using a pre-injury baseline (-0.08; 95% CI: -0.16, -0.01; $Q(9) = 32$, $p < .001$), while a 'moderate' effect was derived from samples using an independent control group (-0.53; 95% CI: -0.86, -0.20; $Q(5) = 5$, *ns*), and from samples using both comparisons (-0.47; 95% CI: -0.69, -0.26; $Q(5) = 12$, $p < .05$). In contrast, a 'large' effect was derived from samples using a pre-injury baseline (-0.83; 95% CI: -0.89, -0.77; $Q(24) = 550$, $p < .001$), and from samples using both comparisons to assess self-report symptoms (-0.80; 95% CI: -0.96, -0.63; $Q(9) = 54$, $p < .001$), while a very 'large' effect was derived from samples using an independent control group only (-1.48; 95% CI: -1.58, -1.38; $Q(14) = 282$, $p < .001$).

[5] By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988).

Effect size diminished rapidly with increasing time since injury: a ‘large’ effect was derived from all assessments conducted within 24 hours of injury (-1.15; 95% CI: -1.23, -1.07; $Q(30) = 212$, $p < .001$; $M = 12$ hours post-injury), a ‘moderate to large’ effect was observed between 1 and 10 days post-injury (-0.56; 95% CI: -0.60, -0.52; $Q(67) = 922$, $p < .001$; $M = 3.7$ days), while a ‘small’ homogenous effect was observed between 10 and 30 days post-injury (-0.16; 95% CI: -0.26, -0.05; $Q(11) = 7$, *ns*; $M = 23.3$ days), which was not significantly different from zero beyond 30 days (-0.10; 95% CI: -0.23, 0.03; $Q(18) = 28$, *ns*; $M = 143.5$ days). Effect size also diminished with repeat assessment: from ‘large’ effects at first post-injury assessment (-0.94; 95% CI: -0.99, -0.90; $Q(87) = 907$, $p < .001$; $M = 18.2$ days post-injury), to ‘small to moderate’ effects at second assessment (-0.36; 95% CI: -0.42, -0.31; $Q(42) = 185$, $p < .001$; $M = 35.3$ days), non-significant effects at third assessment (-0.03; 95% CI: -0.08, -0.03; $Q(28) = 96$, $p < .001$; $M = 13.2$ days), and ‘small’ homogenous effects at fourth assessment (-0.18; 95% CI: -0.31, -0.06; $Q(16) = 26$, *ns*; $M = 29.1$ days).

Consequently, to control for the confound of recovery over time with the effect of repeat assessment, time since injury was re-analysed including only first post-injury assessments: revealing a ‘large’ effect within 24 hours of injury (-1.20; 95% CI: -1.28, -1.12; $Q(30) = 229$, $p < .001$; $M = 12$ hours post-injury) which remained ‘large’ 1 to 10 days post-injury (-0.89; 95% CI: -0.94, -0.83; $Q(46) = 610$, $p < .001$; $M = 2.4$ days), but was non-significant and homogenous beyond 30 days (-0.20; 95% CI: -0.41, 0.01; $Q(10) = 20$, *ns*; $M = 126.5$ days).[6] A regression analysis of first assessments conducted within 10 days post-injury confirmed a significant reduction in effect size magnitude with an increasing number of days since injury ($\beta = 0.11$; 95% CI: 0.08, 0.14, $p < .001$, $\alpha = -1.19$, $k = 77$). Extrapolating from the model, concussed athletes first assessed 24 hours following injury produced a ‘large’ effect ($d_{control} = -1.20$), while athletes first assessed 10 days following injury produced a ‘small’ effect ($d_{control} = -0.10$). The relationship between time and concussion effect was

[6] Nil first assessments were conducted between 10 and 30 days from injury in the current meta-analytic sample.

stronger than would be expected by chance (Q_M (1) = 53, $p < .001$), yet significant between-study variability remained unexplained by this model (Q_R (75) = 776, $p < .001$).

When first post-injury assessments were further analysed by outcome, a ‘moderate’ decrement in neuropsychological functioning (-0.46; 95% CI: -0.53, -0.40; $Q(21) = 275$, $p < .001$), a ‘large’ increase in self-reported symptoms (-1.31; 95% CI: -1.40, -1.22; $Q(14) = 438$, $p < .001$), and a ‘moderate to large’ decrement in postural stability (-0.58; 95% CI: -0.65, -0.50; $Q(13) = 59$, $p < .001$) were observed within 24 hours of injury, while a ‘moderate to large’ decrement in neuropsychological functioning (-0.64; 95% CI: -0.69, -0.59; $Q(40) = 340$, $p < .001$), a ‘large’ increase in self-reported symptoms (-1.69; 95% CI: -1.77, -1.61; $Q(24) = 372$, $p < .001$), and a ‘large’ decrement in postural stability (-1.09; 95% CI: -1.42, -0.76; $Q(4) = 22$, $p < .001$) were observed 1 to 10 days post-injury (see Table 3). Further, when only samples using both a baseline and control group comparison were included in the analysis (i.e. the most rigorous research design), a ‘large’ decrement in neuropsychological functioning (-1.15; 95% CI: -1.31, -1.00; $Q(9) = 60$, $p < .001$), a ‘large’ increase in self-reported symptoms (-2.71; 95% CI: -3.03, -2.40; $Q(5) = 52$, $p < .001$), and a ‘large’ decrement in postural stability (-0.94; 95% CI: -1.16, -0.71; $Q(5) = 61$, $p < .01$) were observed within 24 hours of injury, while a ‘moderate’ decrement in neuropsychological functioning (-0.50; 95% CI: -0.67, -0.34; $Q(9) = 29$, $p < .001$) and a ‘large’ increase in self-reported symptoms (-1.43; 95% CI: -1.77, -1.09; $Q(1) = 0$, *ns*) remained at 1 to 10 days post-injury.[7]

With the exception of self-report symptoms within 1-10 days, and outcomes assessed beyond 10 days from injury, significant heterogeneity remained unexplained by these moderator analyses; additional analyses were therefore required. Insufficient samples were available for further analysis of outcomes within 24 hours of injury (e.g. $k = 1$ adolescent or high school athletes, $k = 0$ female athletes). Consequently, subsequent moderator analyses include outcomes first assessed during the 1-10 day follow-up interval only.

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[7] Nil postural stability assessments first assessed 1-10 days post-injury were compared to both a baseline and control group in the current meta-analytic sample.

Athlete Characteristics

Age group. At first assessments conducted 1-10 days following injury, adolescent athletes demonstrated larger post-concussion neuropsychological deficits, on average, than adult athletes (Table 3: $d_{control}$ = -0.78 and -0.28, respectively), and reported comparable symptoms (Table 3: $d_{control}$ = -1.86 and -1.85, respectively), but were not assessed for postural stability. The significant difference in neuropsychological outcomes was not better accounted for by differences between adolescents and adults in average time since injury (Table 4: *M* = 2.4 and 2.8 days, respectively), type of comparison group (Table 4), or sample sex (Table 5). When only samples using both a baseline and control group comparison were included in analysis, adolescents demonstrated greater neuropsychological impairment than adults ($d_{control}$ = -0.90 and -0.30, respectively). Adolescent males also demonstrated substantially larger neuropsychological deficits than adult males ($d_{control}$ = -1.11 and -0.16, respectively). Adolescent females were not available for comparison to adult females in the current sample.

Age in years. Regression analyses confirmed that each additional year of concussed athletes' average age (range: 15.2 to 31.5 years) corresponded to a significant reduction in the magnitude of the overall effect of concussion (β = 0.07; 95% CI: 0.05, 0.08, $p < .001$, α = -1.90, $k = 76$), and the effect size magnitude when only neuropsychological outcomes, first post-injury assessments conducted 1-10 days from injury, and studies using both baseline and control group comparisons were included in analyses (β = 0.14; 95% CI: 0.06, 0.21 , $p <.001$, α = -3.18, $k = 8$). Holding these variables constant, the relationship between age and concussion effect was stronger than would be expected by chance ($Q_M(1) = 12$, $p < .001$), while residual between-study variability was not significant ($Q_R(6) = 11$, *ns*). Extrapolating from the model, athletes at 15 years of age could be expected to demonstrate a 'large' decrement in neuropsychological functioning at first assessment within 1-10 days post-concussion ($d_{control}$ = -1.14), while adult athletes over the age of 24 years could be expected to demonstrate minimal change within the same interval ($d_{control}$ = 0.09).

Years of education. Regression analyses also indicated that each additional year of concussed athletes' education (range: 9.6 to 16.6 years) corresponded to a significant reduction in the magnitude of the overall effect of concussion (β = 0.21; 95% CI: 0.17, 0.25, $p < .001$, α = -3.35, $k = 31$), and the effect size magnitude when only neuropsychological outcomes, first post-injury assessments conducted 1-10 days from injury, and studies using both baseline and control group comparisons were included in analyses (β = 0.25; 95% CI: 0.07, 0.43, $p < .01$, α = -4.22, $k = 5$). Holding these variables constant, the relationship between years of education and concussion effect was stronger than would be expected by chance ($Q_M(1) = 8$, $p < .01$) although significant between-study variability remained unexplained by the model ($Q_R(3) = 17$, $p < .001$). Extrapolating from the model, athletes with 10 years of education could be expected to demonstrate a 'large' decrement in neuropsychological functioning upon first assessment within 1-10 days post-concussion ($d_{control}$ = -1.68), while those with 16 years of education could be expected to demonstrate a 'small' effect within the same interval ($d_{control}$ = -0.15). Insufficient samples were available for analysis of the interaction between age, sex and years of education.

Sex. At first assessments conducted 1-10 days following injury, female athletes demonstrated larger post-concussion neuropsychological deficits, on average, than male athletes (Table 3: $d_{control}$ = -0.90 and -0.49, respectively), though males reported more symptoms than females (Table 3: $d_{control}$ = -2.43 and -1.62, respectively); females were not assessed for postural stability. The significant difference in neuropsychological outcomes was not better accounted for by differences between females and males in average time since injury (Table 4: M = 2.9 and 2.7 days, respectively), type of comparison group (Table 4), or age group (Table 5). When only samples using a baseline comparison were included in analysis, females demonstrated greater neuropsychological impairment than males ($d_{control}$ = -0.90 and -0.53, respectively); females were not assessed using both a baseline and control group comparison or control group only. Female adults also demonstrated substantially larger neuropsychological deficits than male adults ($d_{control}$ = -0.67 and -0.16, respectively). Female adolescents were not available for comparison to male adolescents in the current meta-analytic sample.

Level of competition. At first assessments conducted 1-10 days following injury, athletes injured during high school competition demonstrated larger post-concussion neuropsychological deficits, on average, than athletes concussed at other levels of competition (Table 3: $d_{control}$ = -0.78 and -0.47, respectively), though professional/elite athletes reported more symptoms than high school, college or amateur athletes (Table 3: $d_{control}$ = -3.14, -1.86, -1.71 and -1.54, respectively); only college athletes were assessed for postural stability. The significant difference in neuropsychological outcomes was not better accounted for by differences between levels of competition in average time since injury (Table 4: M = 2.4 and range: 1.8 to 2.8 days, respectively) or type of comparison group (Table 4). When only samples using both a baseline and control group comparison were included in analysis, high school athletes demonstrated greater neuropsychological impairment than other levels of competition ($d_{control}$ = -0.99 and range: -0.59 to -0.37, respectively). Insufficient samples were available for analysis of the moderating effect of level of competition by sample age, sex, or years of education.

Sport played. At first assessments conducted 1-10 days following injury, samples predominantly recruiting American footballer players demonstrated 'moderate to large' neuropsychological deficits and a 'large' increase in self-report symptoms (Table 3: $d_{control}$ = -0.64 and -1.57, respectively), comparable in magnitude to the overall meta-analytic sample. A single sample of Rugby union players demonstrated 'large' postural stability deficits within 1-10 days following concussion ($d_{control}$ = -1.79). However, samples of Australian Rules and Rugby union football players did not demonstrate a statistically significant change in neuropsychological function within the same period of assessment. As the majority of samples included in this meta-analysis recruited athletes from a variety of sports, other sports such as ice hockey, soccer, and boxing were not sufficiently represented within the sample to support individual analysis.

Table 3

Effect Size Presented as a Function of Athlete Characteristics and Type of Outcome Measure: administered at first post-injury assessments conducted 1-10 days following a sports-related concussion.

Athlete characteristics	Sample size		Outcome measures at first assessment 1-10 days post-injury								
			Neuropsychological tests			Self-report symptom scales			Postural stability assessment		
	Concussed	Controls	$d_{control}$	*k*	*Q*	$d_{control}$	*k*	*Q*	$d_{control}$	*k*	*Q*
Aggregated effect at 1-10 days	2,222	2,626	-0.64 ***	41	340.05 ***	-1.69 ***	25	372.34 ***	-1.09 ***	5	21.62 ***
Adolescent (≤18 years)	641	1,140	-0.78 ***	9	61.61 ***	-1.86 ***	8	65.80 ***	-	-	-
Adult (≥19 years)	687	1,360	-0.28 ***	19	64.15 ***	-1.85 ***	9	59.88 ***	-1.09 ***	5	21.62 ***
100% Female	119	355	-0.90 ***	2	2.28	-1.62 ***	2	1.14	-	-	-
100% Male	890	1,776	-0.49 ***	14	104.62 ***	-2.43 ***	5	16.78 **	-2.61 ***	1	-
High school	796	1,140	-0.78 ***	9	61.61 ***	-1.86 ***	8	65.80 ***	-	-	-
Professional/Elite	97	113	-0.47 ***	5	0.87	-3.14 ***	1	-	-	-	-
College	408	1,156	-0.47 ***	11	36.62 ***	-1.71 ***	8	36.09 ***	-1.09 ***	5	21.62 ***
Amateur	170	140	-0.47 ***	5	25.27 ***	-1.54 ***	4	8.37 *	-	-	-
American football	1,243	465	-0.64 ***	21	260.69 ***	-1.57 ***	16	328.46 ***	-	-	-
Australian Rules	86	113	-0.12	4	3.04	-	-	-	-	-	-
Rugby union	68	23	-0.11	3	2.74	-	-	-	-1.79 ***	1	-

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); *k* = number of independent sample effect sizes; *Q* = test of homogeneity of effect size variance.

* p < .05, ** p < .01, *** p < .001

Table 4

Effect Size Presented as a Function of Athlete Characteristics and Comparison Group: neuropsychological outcome measures administered at first post-injury assessments conducted 1-10 days following sports-related concussion.

Athlete characteristics	Aggregated over comparison groups				Comparison group [a] at first assessment 1-10 days post-injury (neuropsychological outcomes only)								
					Both baseline and control group			Independent control group only			Pre-injury baseline only		
	$d_{control}$	k	Q	TSI	$d_{control}$	k	Q	$d_{control}$	k	Q	$d_{control}$	k	Q
Aggregated effect at 1-10 days	-0.64 ***	41	340.05 ***		-0.50 ***	10	28.66 **	-0.79 ***	7	56.29 ***	-0.64 ***	24	248.52 ***
Adolescent (≤18 years)	-0.78 ***	9	61.61 ***	2.4	-0.99 ***	2	0.00	-0.64 ***	4	28.65 ***	-0.80 ***	3	30.06 ***
Adult (≥19 years)	-0.28 ***	19	64.15 ***	2.8	-0.30 **	7	15.62 *	-0.41 *	2	0.09	-0.25 ***	10	47.70 ***
100% Female	-0.90 ***	2	2.28	2.9	-	-	-	-	-	-	-0.90 ***	2	2.28
100% Male	-0.49 ***	14	104.62 ***	2.7	-0.20 *	6	4.63	-0.68 ***	3	5.61	-0.53 ***	5	84.07 ***
High school	-0.78 ***	9	61.61 ***	2.4	-0.99 ***	2	0.00	-0.64 ***	4	28.65 ***	-0.80 ***	3	30.06 ***
Professional/Elite	-0.47 ***	5	0.87	2.4	-0.59 *	3	0.37	-0.41 *	2	0.09	-	-	-
College	-0.47 ***	11	36.62 ***	2.8	-0.43 **	2	9.66 **	-	-	-	-0.47 ***	9	26.91 ***
Amateur	-0.47 ***	5	25.27 ***	1.8	-0.37 **	2	10.56 ***	-	-	-	-0.56 ***	3	13.61 ***

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); k = number of independent sample effect sizes; Q = test of homogeneity of effect size variance; TSI = average time elapsed since injury (in days).

[a] For a full break-down of results by athlete characteristics, time since injury, and comparison group see Appendix A, Table A2.

* $p < .05$, ** $p < .01$, *** $p < .001$

Table 5

Effect Size Presented as a Function of Athlete Age and Sex: neuropsychological outcome measures administered at first post-injury assessments conducted 1-10 days following sports-related concussion.

Sex of sample	Age group at first assessment 1-10 days post-injury (neuropsychological outcomes only)							
	Adolescent (≤18 years)				Adult (≥19 years)			
	$d_{control}$	k	Q	TSI	$d_{control}$	k	Q	TSI
100% Female	-	-	-	-	-0.67 ***	1	-	1.9
100% Male	-1.11 ***	2	0.20	1.9	-0.15 *	11	21.70 *	2.8 [a]

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); k = number of independent sample effect sizes; Q = test of homogeneity of effect size variance; TSI = average time elapsed since injury (in days).

[a] If adult male samples are matched to adolescent male and adult female samples on TSI (≥3 days excluded): adult male $d_{control}$ = -0.16 *, k = 7, Q = 18.82 **, TSI M = 1.8 days.

* p < .05, ** p < .01, *** p < .001

Summary of Results

Aggregation across all research designs, outcome measures and post-injury assessments yielded a moderate to large global effect of sports-related concussion (d_{pooled} = -0.54; $d_{control}$ = -0.72), comprised of moderate neuropsychological deficits (d_{pooled} = -0.40; $d_{control}$ = -0.47), a large increase in self-reported symptoms (d_{pooled} = -0.66; $d_{control}$ = -0.99), and small but significant postural stability deficits (d_{pooled} = -0.11; $d_{control}$ = -0.14). When these outcomes were re-analysed including only first post-injury assessments, conducted within 10 days of injury, and compared to both a pre-injury baseline and independent control group (to control for the confound of repeat assessment), large effect sizes were demonstrated across all outcomes within 24 hours of injury (neuropsychological outcomes: d_{pooled} = -0.90; $d_{control}$ = -1.15; symptoms: d_{pooled} = -1.49; $d_{control}$ = -2.71; postural stability: d_{pooled} = -0.76; $d_{control}$ = -0.94), while reductions in effect size magnitude were observed at 1-10 days post-injury (neuropsychological outcomes: d_{pooled} = -0.41; $d_{control}$ = -0.50; symptoms: d_{pooled} = -0.91; $d_{control}$ = -1.43; postural stability (all comparisons): d_{pooled} = -1.10; $d_{control}$ = -1.09).

These results vary from that previously reported by meta-analyses of the sports-related concussion and general mTBI literatures. The post-concussion deficit in neuropsychological functioning, collapsed across all follow-up assessments, was marginally smaller in magnitude than previously associated with sports-related concussion (d_{pooled} = -0.49, Belanger & Vanderploeg, 2005), but larger than that associated with mixed-mechanism mTBI (e.g. d_{pooled} = -0.28, Rohling et al., 2011; $d_{control}$ = -0.31, d_{pooled} = -0.24, Schretlen & Shapiro, 2003), with one exception (d_{pooled} = -0.54, Belanger, Curtiss, Demery, Lebowitz, & Vanderploeg, 2005). In contrast, neuropsychological outcomes first assessed within 10 days of injury were larger than previously associated with the first 14 days following a sports-related concussion ($d_{control}$ = -0.81 at first assessment and -0.26 at follow-up, Broglio & Puetz, 2008), likely due to the current study's larger sample size and separate analysis of outcomes first assessed within 24 hours and first assessed between 1 and 10 days post-injury.

Athletes' symptom reports, derived predominantly from concussion-specific scales (e.g. Graded Symptom Checklist, Lovell & Collins, 1998), produced an overall effect substantially larger than that derived from non-mTBI-specific symptom inventories used to assess mTBI in the general population (e.g. Beck Depression Inventory; see Panayiotou, Jackson, & Crowe, 2010, d_{pooled} = -0.05). However, the effect sizes derived from post-concussion symptoms first assessed within 10 days of injury were smaller than that produced at first assessments conducted within 14 days of sports-related concussion, though comparable in magnitude to follow-up assessments conducted within the same period (Broglio & Puetz, 2008, $d_{control}$ = -3.31 and -1.09, respectively). Additionally, this is the first meta-analysis to demonstrate statistically significant post-concussion impairment of postural stability, when collapsed across all follow-up assessments, when only first assessments conducted within 24 hours of injury, and when only first assessments conducted 1-10 days following injury, were included in analyses. This lies in contrast to a previous report by Broglio and Puetz (2008) of non-significant postural deficits at both first and follow-up assessments conducted within 14 days of injury.

As expected, effect sizes diminished with increasing time since injury: from large adverse effects an average of 12 hours post-injury (d_{pooled} = -0.76; $d_{control}$ = -1.15), to moderate effects an average of 3.7 days post-injury (d_{pooled} = -0.44; $d_{control}$ = -0.56), and small homogenous effects at approximately three weeks post-injury (d_{pooled} = -0.13; $d_{control}$ = -0.16), with non-significant effects beyond 30 days. This pattern of recovery over time is consistent with previous meta-analyses (Belanger & Vanderploeg, 2005; Rohling et al., 2011; Schretlen & Shapiro, 2003), and with neurometabolic and neurophysiologic recovery periods (Giza & Hovda, 2001, 2004), and was echoed by each type of outcome measure and control group comparison (see Appendices A to D). However, the current study was the first meta-analysis of the concussion literature to also clearly demonstrate that recovery over time is confounded with the attenuating effects of repeat assessment, such that, when repeat assessment was held constant moderate to large effect sizes persisted from the first 24 hours (d_{pooled} = -0.79; $d_{control}$ = -1.20) into the 1-10 day follow-up period (d_{pooled} = -0.71; $d_{control}$ = -0.89). Regression analysis also confirmed a significant inverse relationship between days since injury and the effect size magnitude associated with post-concussion sequelae, such that small to moderate effects persisted at first assessments conducted on day 10 post-injury.

Together with the above results (indicating a persistent small deficit upon repeat follow-up assessment between 10 and 30 days post-injury, and non-significant effects beyond 30 days), these results suggest that, for at least some athletes, resolution of post-concussion sequelae may not occur for up to one month after sustaining a concussion. This is significantly longer than previously reported for the resolution of neuropsychological impairment following a sports-related concussion (i.e. 7 to 10 days, Belanger & Vanderploeg, 2005), though comparable with the timing of resolution of neuropsychological deficits following mTBI in the general population (i.e. beyond 30 days, Rohling et al., 2011). This result emphasises the importance of measuring post-concussion symptoms and postural stability in addition to neuropsychological outcomes to accurately monitor duration to recovery. However, in the current study, an absence in the extant literature of first assessments conducted between 10 and 30 days prevented identification of the specific timing of resolution of these residual post-concussion deficits. While for the majority of athletes post-concussion deficits are likely to be small to minimal beyond 10 days, and negligible beyond 30 days, there are likely to be individual differences between athletes in the trajectory of their recovery during this period; individualised assessment of neuropsychological, symptomatic, and postural stability outcomes is therefore essential to inform safe return-to-play decision-making during this early post-injury period.

Consistent with previous reports (Belanger & Vanderploeg, 2005; Broglio & Puetz, 2008), larger effect sizes were derived from studies using control group comparisons, than from studies using pre-injury baseline comparisons. However, the current study was the first meta-analysis to also distinguish samples using *both* baseline and control group comparisons (a more rigorous research design which controls for both premorbid group differences and practice arising from repeat assessment) from those that used only one type of comparison group, when calculating effect sizes and when conducting moderator analyses. This revealed that while effect sizes for neuropsychological and postural stability outcomes derived from studies using both comparisons were comparable in magnitude to those derived from studies using only control group comparisons, effect sizes for self-reported symptoms derived from studies using both comparisons were comparable in magnitude to studies using only baseline comparisons. This pattern of results suggests that in the presence of inadequately controlled practice effects arising from repeat neuropsychological or postural stability assessment, the magnitude of the post-concussion effect size may be attenuated. Conversely, in the presence of inadequately controlled premorbid group differences in symptom reporting, the magnitude of the post-concussion effect size may be inflated. This also indicates that measures of self-reported symptoms are most sensitive to the presence of premorbid group differences in rates of symptom reporting; while measures of neuropsychological function, and particularly measures of postural stability, are most sensitive to the attenuating effects of repeat assessment. The latter result may arise due to the common use of alternate forms of neuropsychological instruments to mitigate practice effects (less readily available to postural stability assessment), and that practice effects are typically greater on measures of psychomotor performance (Calamia, Markon, & Tranel, 2012; Lezak, 2004; Valovich, Perrin, & Gansneder, 2003).

In summary, during the first 10 days following concussion, outcomes appeared to be differentially sensitive to the impact of concussion, to the confounding effect of repeat assessment and to the type of control comparison used. We therefore recommend that to minimise the confound of practice arising from repeat assessment with recovery over time, clinical assessment of post-concussion neuropsychological functioning and postural stability to determine an athletes' rate of recovery and readiness for return-to-play should only commence following the resolution of self-reported post-concussion symptoms, and be compared to both a pre-injury baseline and an independent control group. This is consistent with recommendations previously issued at the second International Conference on Concussion in Sport (McCrory et al., 2009), and by the National Athletic Trainers' Association (Guskiewicz et al., 2004).

While the *pattern* of results observed in this study were broadly consistent with that of previously published meta-analyses, deviations of effect size *magnitude* from those previously reported may be attributable to (1) the increased sample size (and therefore statistical power) of the current analysis, (2) variation across meta-analyses with respect to the specific formulae (e.g. d_{pooled} vs. $d_{control}$) used to calculate effect sizes derived from each of the three research designs distinguished in the current analysis, (3) calculation of effect sizes weighted by the inverse variance rather than sample size as per previous sports-related concussion meta-analyses (the latter method has been demonstrated to inflate the magnitude of the effect, Panayiotou et al., 2010), (4) control in the current analysis of the confounding effect of practice arising from repeat assessment and the nature of the comparison group used, (5) differences in the specific assessment and sample characteristics captured by each meta-analysis, e.g. the frequent assessment of athletes within minutes to hours of a sports-related concussive injury, when deficits are at their most dramatic, rather than hours to days following mTBI in the general population, or Belanger and colleagues' inclusion of litigation/clinic-referred cases of mTBI, which were demonstrated to be associated with larger effect sizes than non-referred cases (Belanger et al., 2005), and (6) greater inclusion of outcome measures specifically designed for the sensitive assessment of sports-related concussion in recently published studies (e.g. use of concussion-specific symptom inventories, assessment of concussion-sensitive cognitive domains such as attention and memory, or inclusion of computerised vs. pen-and-paper assessment tools). For example, with ongoing developments in the assessment of sports-related concussion, recently published studies in this field are more likely to include immediate post-concussion assessments conducted at the sideline within the very acute phase of injury, or assessed using concussion-specific symptom scales, postural stability assessments and computerised neuropsychological assessment; therefore potentially producing larger effect sizes than earlier studies conducted days or weeks following injury using traditional neuropsychological assessment instruments only. In this regard, we refer the reader to a thorough discussion of the limitations common to meta-analyses in the field of sports-related concussion, presented by Belanger and Vanderploeg (2005).

Nonetheless, the significant differences identified between athletic subgroups on neuropsychological outcomes first assessed in the acute (1-10 days) post-injury interval were not well explained by differences between these sub-groups with regard to the timing of assessment, the number of follow-up assessments, the outcomes assessed, or the control group comparison made. Moreover, the observed pattern of results is unlikely to simply be an artefact of variation in meta-analysis methodology, as we deliberately selected methodology that was consistent with that of previous meta-analyses in the field (e.g. study inclusion criteria, formulae for effect size calculation, estimation of effect sizes from inferential statistics, and adoption of a fixed+systematic effects model), and/or could be expected to produce the most reliable effect size as per procedures recommended by Lipsey and colleagues (Durlak & Lipsey, 1991; Lipsey & Wilson, 2001). We have also presented the results of both d_{pooled} and $d_{control}$ effect size calculations, as well as both “fixed+systematic” effects and “mixed effects” statistical models (see Appendices A to D), for the reader’s consideration. We note that while $d_{control}$ effect sizes were found to be marginally larger than d_{pooled} effect sizes, the pattern of effect sizes observed across key moderator analyses held regardless of the specific effect size formulae or statistical model adopted. Finally, although this study was subject to the usual publication bias concerns (i.e. that included studies may have been more likely to achieve publication by demonstrating surprising or distinctive results, Rothstein, Sutton, & Borenstein, 2005), we argue that this was unlikely to be a major cause for concern here, as results were found to be robust to the influence of both publication and selective reporting biases. Nonetheless, to minimise the potential for selective reporting biases within the sports-related concussion literature, future research should consider the recommendations of Comper et al. (2010).

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Appendix A

Meta-analytic results calculated using a $d_{control}$ effect size statistic

and a fixed+systematic effects statistical model

Table A1

Results of the Meta-Analysis of Sports-Related Concussion Presented as a Function of Athlete Characteristics and Outcome Measures.

Athlete characteristics	Sample size		Aggregated across outcomes			Outcome measures: Neuropsychological tests			Self-report symptom scales			Postural stability assessment		
	Concussed	Controls	$d_{control}$	*k*	*Q*	$d_{control}$	*k*	*Q*	$d_{control}$	*k*	*Q*	$d_{control}$	*k*	*Q*
Overall effect of sports concussion	3,811	5,641	-0.72 ***	92	932.42 ***	-0.47 **	71	571.28 ***	-0.99 ***	50	1011.33 ***	-0.14 ***	22	66.46 ***
Age group														
Adolescent (≤18 years)	815	1,160	-1.11 ***	11	243.95 ***	-0.68 ***	10	92.50 ***	-1.65 ***	9	150.32 ***	-	-	-
Adult (≥19 years)	1,544	2,202	-0.54 ***	59	323.02 ***	-0.32 ***	42	142.81 ***	-0.90 ***	29	345.31 ***	-0.43 ***	19	31.55 *
Sex														
100% Female	129	367	-1.14 ***	4	23.31 ***	-0.75 ***	3	6.71 *	-1.37 ***	2	9.33 **	-	-	-
100% Male	1,643	2,735	-0.84 ***	39	769.47 ***	-0.52 ***	30	224.76 ***	-1.60 ***	14	473.03 ***	-0.35 **	5	7.05
Level of competition														
High school	815	1,160	-1.11 ***	11	243.95 ***	-0.68 ***	10	92.50 ***	-1.65 ***	9	150.32 ***	-	-	-
Professional/Elite	148	141	-0.76 ***	7	36.50 ***	-0.58 ***	7	40.46 ***	-2.45 ***	1	-	-	-	-
College	1,167	1,920	-0.67 ***	45	217.87 ***	-0.42 ***	28	67.92 ***	-0.82 ***	24	249.81 ***	-0.43 ***	19	31.55 *
Amateur	170	140	-0.50 ***	5	14.10 **	-0.39 ***	5	13.31 **	-1.17 ***	4	9.93 *	-	-	-
Sport played														
American football	1,946	862	-0.64 ***	38	360.92 ***	-0.58 ***	34	338.66 ***	-1.07 ***	24	382.60 ***	-0.31 **	5	14.68 **
Australian Rules	137	141	-0.40 **	6	47.08 ***	-0.40 **	6	47.08 ***	-	-	-	-	-	-
Rugby union	89	32	-0.22	5	2.62	-0.06	3	1.48	0.09	1	-	-0.52 ***	3	0.88
Ice hockey	97	185	-0.04	4	12.79 **	-0.60 *	3	3.64	-0.19	3	77.35 ***	-	-	-
Soccer	10	12	-0.79	1	-	-0.79	1	-	-	-	-	-	-	-
Boxing	14	-	-0.34	1	-	-0.34	1	-	-	-	-	-	-	-

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); *k* = number of independent sample effect sizes; *Q* = test of homogeneity of effect size variance.

* p < .05, ** p < .01, *** p < .001

Table A2

Results of the Meta-Analysis of Sports-Related Concussion Presented as a Function of Athlete Characteristics, Comparison Group, and Time Since Injury.

Comparison group	Aggregated over time			Time since injury [a]											
				<24 hours			1 – 10 days			10 – 30 days			>30 days		
Athlete characteristics	$d_{control}$	*k*	*Q*	$d_{control}$	*k*	*Q*	$d_{control}$	*k*	*Q*	$d_{control}$	*k*	*Q*	$d_{control}$	*k*	*Q*
Overall effect of sports concussion	-0.72 ***	92	932.42 ***	-1.15 ***	31	211.75 ***	-0.56 ***	68	921.99 ***	-0.16 **	12	7.19	-0.10	19	27.93
Adolescent (≤18 years)	-1.11 ***	11	243.95 ***	-1.49 ***	1	-	-1.11 ***	11	242.79 ***	-	-	-	0.00	1	-
Adult (≥19 years)	-0.54 ***	59	323.02 ***	-1.16 ***	23	157.29 ***	-0.42 ***	38	155.37 ***	-0.23 *	9	6.03	-0.26 ***	15	14.73
100% Female	-1.14 ***	4	23.31 ***	-	-	-	-1.16 ***	3	22.75 ***	-	-	-	-0.79	1	-
100% Male	-0.84 ***	39	769.47 ***	-1.27 ***	15	124.28 **	-0.76 ***	23	624.91 ***	-0.10	4	1.59	-0.06	14	16.86
High school	-1.11 ***	11	243.95 ***	-1.49 ***	1	-	-1.11 ***	11	242.79 ***	-	-	-	0.00	1	-
Professional/Elite	-0.76 ***	7	36.50 ***	-1.36 ***	2	27.27 ***	-0.61 ***	5	1.06	0.06	1	-	-0.20	1	-
College	-0.67 ***	45	217.87 ***	-1.15 ***	21	129.41 ***	-0.56 ***	30	110.24 ***	-0.25 **	8	5.49	-0.19 *	10	6.43
Amateur	-0.50 ***	5	14.10 **	-	-	-	-0.56 ***	5	17.36 **	-0.07	1	-	-	-	-
Both baseline and control group	-0.63 ***	23	97.61 ***	-1.13 ***	14	85.69 ***	-0.45 ***	19	38.02 **	0.00	2	0.03	-0.13	5	1.92
Adolescent (≤18 years)	-0.58 ***	3	1.22	-1.49 ***	1	-	-0.58 ***	3	0.20	-	-	-	0.00	1	-
Adult (≥19 years)	-0.42 ***	16	34.04 **	-0.98 ***	10	58.84 ***	-0.37 ***	14	29.13 **	0.00	2	0.03	-0.18	3	1.20
100% Female	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
100% Male	-0.56 ***	11	71.80 ***	-1.14 ***	6	47.00 ***	-0.25 **	8	4.97	0.06	1	-	-0.18	4	1.21
High school	-0.58 ***	3	1.22	-1.49 ***	1	-	-0.58 ***	3	0.20	-	-	-	0.00	1	-
Professional/Elite	-0.46	3	1.41	-	-	-	-0.59 **	3	0.37	0.06	1	-	-	-	-
College	-0.52 ***	11	24.76 **	-0.98 ***	10	58.84 ***	-0.44 ***	9	22.20 **	-0.03	1	-	-0.18	3	1.20
Amateur	-0.40 **	2	12.81 ***	-	-	-	-0.30 **	2	12.81 ***	-	-	-	-	-	-

Comparison group / Athlete characteristics	Aggregated over time			Time since injury [a] <24 hours			1 – 10 days			10 – 30 days			>30 days		
	$d_{control}$	k	Q	$d_{control}$	k	Q	$d_{control}$	k	Q	$d_{control}$	k	Q	$d_{control}$	k	Q
Independent control group only	-1.08 ***	30	363.28 ***	-1.43 ***	7	35.72 ***	-1.16 ***	17	259.41 ***	-0.08	4	1.10	-0.08	12	25.17 **
Adolescent (≤18 years)	-1.46 ***	5	128.72 ***	-	-	-	-1.46 ***	5	128.72 ***	-	-	-	-	-	-
Adult (≥19 years)	-1.05 ***	21	104.93 ***	-1.52 ***	6	33.60 ***	-0.94 ***	9	48.71 ***	-0.06	3	1.08	-0.51 ***	10	8.53
100% Female	-1.63 ***	2	3.39	-	-	-	-1.74 ***	1	-	-	-	-	-0.79	1	-
100% Male	-1.43 ***	15	347.27 ***	-1.42 ***	5	32.03 ***	-1.66 ***	6	227.35 ***	0.00	1	-	0.05	8	12.84
High school	-1.46 ***	5	128.72 ***	-	-	-	-1.46 ***	5	128.72 ***	-	-	-	-	-	-
Professional/Elite	-0.69 ***	3	1.06	-0.83 **	1	-	-0.62 **	2	0.68	-	-	-	-0.20	1	-
College	-1.20 ***	14	91.32 ***	-1.69 ***	5	26.25 ***	-1.04 ***	7	44.56 ***	-0.06	3	1.08	-0.34	5	3.64
Amateur	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pre-injury baseline only	-0.58 ***	39	369.20 ***	-1.09 ***	10	82.68 ***	-0.43 ***	32	439.35 ***	-0.19 **	6	4.99	-0.08	2	0.65
Adolescent (≤18 years)	-0.91 ***	3	67.06 ***	-	-	-	-0.91 ***	3	67.06 ***	-	-	-	-	-	-
Adult (≥19 years)	-0.36 ***	22	120.40 ***	-1.15 ***	7	52.72 ***	-0.28 ***	15	44.06 ***	-0.36 **	4	2.26	-0.08	2	0.65
100% Female	-0.80 ***	2	4.75 *	-	-	-	-0.80 ***	2	4.75 *	-	-	-	-	-	-
100% Male	-0.51 ***	13	176.18 ***	-1.42 ***	4	40.87 ***	-0.43 ***	9	129.92 ***	-0.20	2	1.15	-0.08	2	0.65
High school	-0.91 ***	3	67.06 ***	-	-	-	-0.91 ***	3	67.06 ***	-	-	-	-	-	-
Professional/Elite	-5.01 *** [b]	1	-	-5.01 *** [b]	1	-	-	-	-	-	-	-	-	-	-
College	-0.51 ***	20	54.42 ***	-1.02 ***	6	25.22 ***	-0.47 ***	14	21.86	-0.36 **	4	2.26	-0.08	2	0.65
Amateur	-0.59 ***	3	0.23	-	-	-	-0.70 ***	3	1.89	-0.07	1	-	-	-	-

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); k = number of independent sample effect sizes; Q = test of homogeneity of effect size variance.

[a] Time since injury intervals were selected for consistency with documented neurometabolic and neurophysiologic recovery periods (Giza & Hovda, 2001, 2004).

[b] Observed effect size identified as an outlier but considered a genuine representation of the data: single effect size (i.e. no aggregation) derived from assessment conducted within 15 minutes of injury using a single test score (Digit Symbol Substitution Test).

* $p < .05$, ** $p < .01$, *** $p < .001$

Table A3

Effect Size Presented as a Function of Athlete Characteristics and Comparison Group: Neuropsychological outcome measures administered at first post-injury assessments conducted 1-10 days following sports-related concussion.

Athlete characteristics	Aggregated over comparisons				Comparison group								
					Both baseline and control group			Independent control group only			Pre-injury baseline only		
	$d_{control}$	k	Q	TSI	$d_{control}$	k	Q	$d_{control}$	k	Q	$d_{control}$	k	Q
Adolescent (≤18 years)	-0.78 ***	9	61.61 ***	2.4	-0.99 ***	2	0.00	-0.64 ***	4	28.65 ***	-0.80 ***	3	30.06 ***
Adult (≥19 years)	-0.28 ***	19	64.15 ***	2.8	-0.30 **	7	15.62 *	-0.41 *	2	0.09	-0.25 ***	10	47.70 ***
100% Female	-0.90 ***	2	2.28	2.9	-	-	-	-	-	-	-0.90 ***	2	2.28
100% Male	-0.49 ***	14	104.62 ***	2.7	-0.20 *	6	4.63	-0.68 ***	3	5.61	-0.53 ***	5	84.07 ***
High school	-0.78 ***	9	61.61 ***	2.4	-0.99 ***	2	0.00	-0.64 ***	4	28.65 ***	-0.80 ***	3	30.06 ***
Professional/Elite	-0.47 ***	5	0.87	2.4	-0.59 *	3	0.37	-0.41 *	2	0.09	-	-	-
College	-0.47 ***	11	36.62 ***	2.8	-0.43 **	2	9.66 **	-	-	-	-0.47 ***	9	26.91 ***
Amateur	-0.47 ***	5	25.27 ***	1.8	-0.37 **	2	10.56 ***	-	-	-	-0.56 ***	3	13.61 ***

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); k = number of independent sample effect sizes; Q = test of homogeneity of effect size variance; TSI = average time elapsed since injury (in days).

* $p < .05$, ** $p < .01$, *** $p < .001$

Table A4

Effect Size Presented as a Function of Athlete Age and Sex: Neuropsychological outcome measures administered at first post-injury assessments conducted 1-10 days following sports-related concussion.

Sex of sample	Age group							
	Adolescent (≤18 years)				Adult (≥19 years)			
	$d_{control}$	*k*	*Q*	TSI	$d_{control}$	*k*	*Q*	TSI
100% Female	-	-	-	-	-0.67 ***	1	-	1.9
100% Male	-1.11 ***	2	0.20	1.9	-0.15 *	11	21.70 *	2.8 [a]

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); *k* = number of independent sample effect sizes; *Q* = test of homogeneity of effect size variance; TSI = average time elapsed since injury (in days).

[a] If adult male samples matched to adolescent male and adult female samples on TSI (≥3 days excluded): adult male $d_{control}$ = -0.16 *, *k* = 7, *Q* = 18.82 **, TSI *M* = 1.8 days.

* p < .05, ** p < .01, *** p < .001

Appendix B

Meta-analytic results calculated using a d_{pooled} effect size statistic

and a fixed+systematic effects statistical model

Table B1

Results of the Meta-Analysis of Sports-Related Concussion Presented as a Function of Athlete Characteristics and Outcome Measures.

Athlete characteristics	Sample size		Aggregated across outcomes			Outcome measures: Neuropsychological tests			Self-report symptom scales			Postural stability assessment		
	Concussed	Controls	d_{pooled}	k	Q	d_{pooled}	k	Q	d_{pooled}	k	Q	d_{pooled}	k	Q
Overall effect of sports concussion	3,801	5,631	-0.54 ***	91	667.63 ***	-0.40 ***	70	405.37 ***	-0.66 ***	50	602.95 ***	-0.11 **	22	54.69 ***
Age group														
Adolescent (≤18 years)	815	1,160	-0.81 ***	11	146.55 ***	-0.54 ***	10	57.70 ***	-1.17 ***	9	78.39 ***	-	-	-
Adult (≥19 years)	1,534	2,192	-0.45 ***	58	238.42 ***	-0.28 ***	41	99.04 ***	-0.66 ***	29	190.37 ***	-0.37 ***	19	24.19
Sex														
100% Female	129	367	-1.02 ***	4	20.81 ***	-0.72 ***	3	7.52 *	-0.99 ***	2	17.45 ***	-	-	-
100% Male	1,633	2,725	-0.69 ***	38	488.78 ***	-0.45 ***	29	142.88 ***	-1.16 ***	14	274.34 ***	-0.31 *	5	6.18
Level of competition														
High school	815	1,160	-0.81 ***	11	146.55 ***	-0.54 ***	10	57.70 ***	-1.17 ***	9	78.39 ***	-	-	-
Professional/Elite	138	131	-0.69 ***	6	29.18 ***	-0.63 ***	6	31.30 ***	-0.93 ***	1	-	-	-	-
College	1,167	1,920	-0.54 ***	45	162.79 ***	-0.36 ***	28	39.78	-0.63 ***	24	166.89 ***	-0.37 ***	19	24.19
Amateur	170	140	-0.39 ***	5	8.41	-0.33 ***	5	9.41	-0.76 ***	4	3.33	-	-	-
Sport played														
American football	1,946	862	-0.51 ***	38	223.29 ***	-0.48 ***	34	223.67 ***	-0.74 ***	24	181.69 ***	-0.29 **	5	11.44 *
Australian Rules	127	131	-0.46 ***	5	37.71 ***	-0.46 ***	5	37.71 ***	-	-	-	-	-	-
Rugby union	89	32	-0.22	5	2.99	-0.07	3	1.75	0.73	1	-	-0.57 ***	3	0.63
Ice hockey	97	185	0.04	4	4.37	-0.29	3	0.84	-0.18	3	37.75 ***	-	-	-
Soccer	10	12	-0.61	1	-	-0.61	1	-	-	-	-	-	-	-
Boxing	14	-	-0.34	1	-	-0.34	1	-	-	-	-	-	-	-

Note. d_{pooled} = weighted mean effect size calculated using the pooled standard deviations of the concussed group and the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); k = number of independent sample effect sizes; Q = test of homogeneity of effect size variance.

* $p < .05$, ** $p < .01$, *** $p < .001$

Table B2

Results of the Meta-Analysis of Sports-Related Concussion Presented as a Function of Athlete Characteristics, Comparison Group, and Time Since Injury.

Comparison group / Athlete characteristics	Aggregated over time			Time since injury [a] <24 hours			1 – 10 days			10 – 30 days			>30 days		
	d_{pooled}	k	Q	d_{pooled}	k	Q	d_{pooled}	k	Q	d_{pooled}	k	Q	d_{pooled}	k	Q
Overall effect of sports concussion	-0.54 ***	91	667.63 ***	-0.76 ***	30	118.63 ***	-0.44 ***	67	670.82 ***	-0.13 **	12	7.16	-0.06	19	18.18
Adolescent (≤18 years)	-0.81 ***	11	146.55 ***	-1.21 ***	1	-	-0.82 ***	11	144.75 ***	-	-	-	0.00	1	-
Adult (≥19 years)	-0.45 ***	58	238.42 ***	-0.88 ***	22	84.67 ***	-0.34 ***	37	119.74 ***	-0.23 *	9	5.67	-0.19 *	15	6.64
100% Female	-1.02 ***	4	20.81 ***	-	-	-	-1.04 ***	3	20.01 ***	-	-	-	-0.61	1	-
100% Male	-0.69 ***	38	488.78 ***	-1.04 ***	14	75.78 ***	-0.63 ***	22	381.30 ***	-0.10	4	1.53	-0.03	14	14.14
High school	-0.81 ***	11	146.55 ***	-1.21 ***	1	-	-0.82 ***	11	144.75 ***	-	-	-	0.00	1	-
Professional/Elite	-0.69 ***	6	29.18 ***	-1.43 ***	2	13.59 ***	-0.41 **	4	0.69	0.06	1	-	-0.06	1	-
College	-0.54 ***	45	162.79 ***	-0.85 ***	20	65.28 ***	-0.46 ***	30	88.82 ***	-0.25 *	8	5.16	-0.16	10	5.05
Amateur	-0.39 ***	5	8.41	-	-	-	-0.44 ***	5	11. 00 *	-0.05	1	-	-	-	-
Both baseline and control group	-0.51 ***	22	60.15 ***	-0.86 ***	14	34.55 ***	-0.37 ***	18	23.86	-0.01	2	0.04	-0.13	5	2.94
Adolescent (≤18 years)	-0.44 **	3	2.20	-1.21 ***	1	-	-0.46 **	3	1.07	-	-	-	0.00	1	-
Adult (≥19 years)	-0.33 ***	15	16.10	-0.73 ***	10	14.16	-0.30 ***	13	17.02	-0.01	2	0.04	-0.17	3	2.21
100% Female	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
100% Male	-0.49 ***	10	45.64 ***	-0.90 ***	6	23.59 ***	-0.24 **	7	3.25	0.06	1	-	-0.18	4	2.26
High School	-0.44 **	3	2.20	-1.21 ***	1	-	-0.46 **	3	1.07	-	-	-	0.00	1	-
Professional/Elite	-0.34	2	0.62	-	-	-	-0.53 *	2	0.02	0.06	1	-	-	-	-
College	-0.40 ***	11	11.62	-0.73 ***	10	14.16	-0.35 ***	9	13.53	-0.04	1	-	-0.17	3	2.21
Amateur	-0.35 **	2	7.85 **	-	-	-	-0.35 **	2	7.85 **	-	-	-	-	-	-

Comparison group / Athlete characteristics	Aggregated over time			Time since injury [a] <24 hours			1 – 10 days			10 – 30 days			>30 days		
	d_{pooled}	k	Q	d_{pooled}	k	Q	d_{pooled}	k	Q	d_{pooled}	k	Q	d_{pooled}	k	Q
Independent control group only	-0.85 ***	30	251.02 ***	-1.14 ***	7	31.12 ***	-0.93 ***	17	165.01 ***	-0.08	4	0.92	0.02	12	13.76
Adolescent (≤18 years)	-1.11 ***	5	73.59 ***	-	-	-	-1.11 ***	5	73.59 ***	-	-	-	-	-	-
Adult (≥19 years)	-0.85 ***	21	98.36 ***	-1.26 ***	6	27.23 ***	-0.78 ***	9	46.89 ***	-0.05	3	0.88	-0.30 *	10	2.92
100% Female	-1.41 ***	2	3.41	-	-	-	-1.52 ***	1	-	-	-	-	-0.61	1	-
100% Male	-1.12 ***	15	239.13 ***	-1.20 ***	5	28.95 ***	-1.29 ***	6	145.26 ***	0.00	1	-	0.11	8	8.06
High school	-1.11 ***	5	73.59 ***	-	-	-	-1.11 ***	5	73.59 ***	-	-	-	-	-	-
Professional/Elite	-0.50 **	3	2.30	-0.83 **	1	-	-0.34	2	0.34	-	-	-	-0.06	1	-
College	-1.04 ***	14	80.31 ***	-1.36 ***	5	24.41 ***	-0.94 ***	7	39.33 ***	-0.05	3	0.88	-0.24	5	2.01
Amateur	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pre-injury baseline only	-0.43 ***	39	277.08 ***	-0.67 ***	9	33.75 ***	-0.34 ***	32	352.62 ***	-0.15 **	6	5.60	-0.05	2	0.32
Adolescent (≤18 years)	-0.67 ***	3	36.78 ***	-	-	-	-0.67 ***	3	36.78 ***	-	-	-	-	-	-
Adult (≥19 years)	-0.31 ***	22	81.60 ***	-0.84 ***	6	30.37 ***	-0.23 ***	15	31.42 **	-0.36 **	4	2.02	-0.05	2	0.32
100% Female	-0.74 ***	2	6.88 **	-	-	-	-0.74 ***	2	6.88 **	-	-	-	-	-	-
100% Male	-0.47 ***	13	106.94 ***	-1.18 ***	3	18.15 ***	-0.40 ***	9	81.12 ***	-0.20	2	1.11	-0.05	2	0.32
High school	-0.67 ***	3	36.78 ***	-	-	-	-0.67 ***	3	36.78 ***	-	-	-	-	-	-
Professional/Elite	-2.68 *** [b]	1	-	-2.68 *** [b]	1	-	-	-	-	-	-	-	-	-	-
College	-0.40 ***	20	28.55	-0.68 ***	5	8.71	-0.38 ***	14	15.10	-0.36 **	4	2.02	-0.05	2	0.32
Amateur	-0.42 ***	3	0.41	-	-	-	-0.51 ***	3	2.34	-0.05	1	-	-	-	-

Note. d_{pooled} = weighted mean effect size calculated using the pooled standard deviations of the concussed group and the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); k = number of independent sample effect sizes; Q = test of homogeneity of effect size variance.

[a] Time since injury intervals were selected for consistency with documented neurometabolic and neurophysiologic recovery periods (Giza & Hovda, 2001, 2004). [b] Observed effect size identified as an outlier but considered a genuine representation of the data: single effect size (i.e. no aggregation) derived from assessment conducted within 15 minutes of injury using a single test score (Digit Symbol Substitution Test).

* $p < .05$, ** $p < .01$, *** $p < .001$

Table B3

Effect Size Presented as a Function of Athlete Characteristics and Comparison Group: Neuropsychological outcome measures administered at first post-injury assessments conducted 1-10 days following sports-related concussion.

Athlete characteristics	Aggregated over comparisons				Comparison group: Both baseline and control group			Comparison group: Independent control group only			Comparison group: Pre-injury baseline only		
	d_{pooled}	k	Q	TSI	d_{pooled}	k	Q	d_{pooled}	k	Q	d_{pooled}	k	Q
Adolescent (≤18 years)	-0.60 ***	9	33.41 ***	2.4	-0.69 ***	2	0.09	-0.44 ***	4	15.38 **	-0.63 ***	3	14.75 ***
Adult (≥19 years)	-0.25 ***	18	48.78 ***	2.7	-0.25 *	6	6.53	-0.39 *	2	0.46	-0.23 ***	10	41.06 ***
100% Female	-0.87 ***	2	2.96	2.9	-	-	-	-	-	-	-0.87 ***	2	2.96
100% Male	-0.42 ***	13	59.29 ***	2.5	-0.18	5	2.39	-0.48 ***	3	1.08	-0.45 ***	5	50.23 ***
High school	-0.60 ***	9	33.41 ***	2.4	-0.69 ***	2	0.09	-0.44 ***	4	15.38 **	-0.63 ***	3	14.75 ***
Professional/Elite	-0.43 **	4	0.69	2.4	-0.53	2	0.02	-0.39 *	2	0.46	-	-	-
College	-0.41 ***	11	26.88 **	2.8	-0.34 *	2	3.48	-	-	-	-0.43 ***	9	23.13 **
Amateur	-0.42 ***	5	18.16 ***	1.8	-0.34 *	2	7.17 **	-	-	-	-0.48 ***	3	10.32 **

Note. d_{pooled} = weighted mean effect size calculated using the pooled standard deviations of the concussed group and the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); k = number of independent sample effect sizes; Q = test of homogeneity of effect size variance; TSI = average time elapsed since injury (in days).

* p < .05, ** p < .01, *** p < .001

Table B4

Effect Size Presented as a Function of Athlete Age and Sex: Neuropsychological outcome measures administered at first post-injury assessments conducted 1-10 days following sports-related concussion.

Sex of sample	Age group							
	Adolescent (≤18 years)				Adult (≥19 years)			
	d_{pooled}	*k*	*Q*	TSI	d_{pooled}	*k*	*Q*	TSI
100% Female	-	-	-	-	-0.62 **	1	-	1.9
100% Male	-0.75 ***	2	0.78	1.9	-0.13 *	10	15.71	2.6 [a]

Note. d_{pooled} = weighted mean effect size calculated using the pooled standard deviations of the concussed group and the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); *k* = number of independent sample effect sizes; *Q* = test of homogeneity of effect size variance; TSI = average time elapsed since injury (in days).

[a] If adult male samples matched to adolescent male and adult female samples on TSI (≥3 days excluded): adult male d_{pooled} = -0.15 *, *k* = 7, *Q* = 15.37 *, TSI *M* = 1.8 days.

* p < .05, ** p < .01, *** p < .001

Appendix C

Meta-analytic results calculated using a $d_{control}$ effect size statistic

and a mixed effects statistical model

Table C1

Results of the Meta-Analysis (Mixed Effects Model) of Sports-Related Concussion Presented as a Function of Athlete Characteristics and Outcome Measures.

Athlete characteristics	Sample size		Aggregated across outcomes		Outcome measures					
					Neuropsychological tests		Self-report symptom scales		Postural stability assessment	
	Concussed	Controls	$d_{control}$	*k*	$d_{control}$	*k*	$d_{control}$	*k*	$d_{control}$	*k*
Overall effect of sports concussion	3,811	5,641	-0.73 ***	92	-0.59 ***	71	-1.30 ***	50	-0.41 ***	22
Age group										
Adolescent (≤18 years)	815	1,160	-1.00 ***	11	-0.94 *	10	-1.42 ***	9	-	-
Adult (≥19 years)	1,544	2,202	-0.69 ***	59	-0.49 ***	42	-1.41 ***	29	-0.49 ***	19
Sex										
100% Female	129	367	-1.06 ***	4	-0.75 **	3	-1.36 ***	2	-	-
100% Male	1,643	2,735	-0.76 ***	39	-0.58 ***	30	-1.72 ***	14	-0.44 **	5
Level of competition										
High school	815	1,160	-1.00 ***	11	-0.94 *	10	-1.42 ***	9	-	-
Professional/Elite	148	141	-0.80 ***	7	-0.56 ***	7	-2.45 ***	1	-	-
College	1,167	1,920	-0.70 ***	45	-0.49 ***	28	-1.17 ***	24	-0.49 ***	19
Amateur	170	140	-0.55 **	5	-0.40 **	5	-1.24 ***	4	-	-
Sport played										
American football	1,946	862	-0.76 ***	38	-0.66 ***	34	-1.35 ***	24	-0.47 *	5
Australian Rules	137	141	-0.99 *	6	-0.98 *	6	-	-	-	-
Rugby union	89	32	-0.22	5	-0.06	3	0.09	1	-0.52 ***	3
Ice hockey	97	185	-0.44	4	-0.59	3	-3.62 *	3	-	-
Soccer	10	12	-0.79	1	-0.79	1	-	-	-	-
Boxing	14	-	-0.34	1	-0.34	1	-	-	-	-

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); *k* = number of independent sample effect sizes.

* $p < .05$, ** $p < .01$, *** $p < .001$

Table C2

Results of the Meta-Analysis (Mixed Effects Model) of Sports-Related Concussion Presented as a Function of Athlete Characteristics, Comparison Group, and Time Since Injury.

Comparison group / Athlete characteristics	Aggregated over time		Time since injury [a] <24 hours		1 – 10 days		10 – 30 days		>30 days	
	$d_{control}$	k	$d_{control}$	k	$d_{control}$	k	$d_{control}$	k	$d_{control}$	k
Overall effect of sports concussion	-0.73 ***	92	-1.34 ***	31	-0.62 ***	68	-0.16 **	12	-0.16	19
Adolescent (≤18 years)	-1.00 ***	11	-1.49 ***	1	-0.79 ***	11	-	-	0.00	1
Adult (≥19 years)	-0.69 ***	59	-1.42 ***	23	-0.51 ***	38	-0.23 *	9	-0.27 **	15
100% Female	-1.06 ***	4	-	-	-1.12 **	3	-	-	-0.79	1
100% Male	-0.76 ***	39	-1.49 ***	15	-0.52 *	23	-0.10	4	-0.08	14
High school	-1.00 ***	11	-1.49 ***	1	-0.79 ***	11	-	-	0.00	1
Professional/Elite	-0.80 ***	7	-1.36 ***	2	-0.61 ***	5	0.06	1	-0.20	1
College	-0.70 ***	45	-2.86***	21	-0.57 ***	30	-0.25 *	8	-0.19 *	10
Amateur	-0.55 **	5	-	-	-0.61 ***	5	-0.07	1	-	-
Both baseline and control group	-0.67 ***	23	-1.31 ***	14	-0.51 ***	19	0.00	2	-0.13	5
Adolescent (≤18 years)	-0.58 ***	3	-1.49 ***	1	-0.58 ***	3	-	-	0.00	1
Adult (≥19 years)	-0.50 ***	16	-1.24 ***	10	-0.45 ***	14	0.00	2	-0.18	3
100% Female	-	-	-	-	-	-	-	-	-	-
100% Male	-0.58 **	11	-1.20 ***	6	-0.25 **	8	0.06	1	-0.18	4
High school	-0.58 ***	3	-1.49 ***	1	-0.58 ***	3	-	-	0.00	1
Professional/Elite	-0.46	3	-	-	-0.59 *	3	0.06	1	-	-
College	-0.61 ***	11	-1.24 ***	10	-0.52 ***	9	-0.03	1	-0.18	3
Amateur	-0.52	2	-	-	-0.52	2	-	-	-	-

Comparison group / Athlete characteristics	Aggregated over time		Time since injury [a]							
			<24 hours		1 – 10 days		10 – 30 days		>30 days	
	$d_{control}$	*k*	$d_{control}$	*k*	$d_{control}$	*k*	$d_{control}$	*k*	$d_{control}$	*k*
Independent control group only	-0.75 ***	30	-1.37 ***	7	-0.71 ***	17	-0.08	4	-0.28	12
Adolescent (≤18 years)	-0.89 *	5	-	-	-0.89 *	5	-	-	-	-
Adult (≥19 years)	-0.76 ***	21	-1.41 ***	6	-0.58 *	9	-0.06	3	-0.51 ***	10
100% Female	-1.37 **	2	-	-	-1.74 ***	1	-	-	-0.79	1
100% Male	-0.82 **	15	-1.33 ***	5	-0.79	6	0.00	1	-0.09	8
High school	-0.89 *	5	-	-	-0.89 ***	5	-	-	-	-
Professional/Elite	-0.69 ***	3	-0.83 **	1	-0.62 **	2	-	-	-0.20	1
College	-0.78 ***	14	-1.54 ***	5	-0.59 ***	7	-0.06	3	-0.34	5
Amateur	-	-	-	-	-	-	-	-	-	-
Pre-injury baseline only	-0.71 ***	39	-1.36 ***	10	-0.62 ***	32	-0.19 **	6	-0.08	2
Adolescent (≤18 years)	-0.82 ***	3	-	-	-0.82 *	3	-	-	-	-
Adult (≥19 years)	-0.71 ***	22	-1.75 ***	7	-0.46 ***	15	-0.36 **	4	-0.08	2
100% Female	-0.80 ***	2	-	-	-0.80 **	2	-	-	-	-
100% Male	-0.79 ***	13	-2.48 ***	4	-0.47 *	9	-0.21	2	-0.08	2
High school	-0.82 ***	3	-	-	-0.82 ***	3	-	-	-	-
Professional/Elite	-5.01 *** [b]	1	-5.01 *** [b]	1	-	-	-	-	-	-
College	-0.62 ***	20	-1.31 ***	6	-0.50 ***	14	-0.36 **	4	-0.08	2
Amateur	-0.59 ***	3	-	-	-0.70 ***	3	-0.07	1	-	-

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); *k* = number of independent sample effect sizes.

[a] Time since injury intervals were selected for consistency with documented neurometabolic and neurophysiologic recovery periods (Giza & Hovda, 2001, 2004).

[b] Observed effect size identified as an outlier but considered a genuine representation of the data: single effect size (i.e. no aggregation) derived from assessment conducted within 15 minutes of injury using a single test score (Digit Symbol Substitution Test).

* $p < .05$, ** $p < .01$, *** $p < .001$

Table C3

Effect Size (Mixed Effects Model) Presented as a Function of Athlete Characteristics and Comparison Group: Neuropsychological outcome measures administered at first post-injury assessments conducted 1-10 days following sports-related concussion.

Athlete characteristics	Aggregated over comparisons			Comparison group					
				Both baseline and control group		Independent control group only		Pre-injury baseline only	
	$d_{control}$	k	TSI	$d_{control}$	k	$d_{control}$	k	$d_{control}$	k
Adolescent (≤18 years)	-0.73 ***	9	2.4	-0.99 ***	2	-0.60 *	4	-0.75 ***	3
Adult (≥19 years)	-0.44 ***	19	2.8	-0.44 *	7	-0.41 *	2	-0.47 **	10
100% Female	-0.90 ***	2	2.9	-	-	-	-	-0.90 ***	2
100% Male	-0.44 **	14	2.7	-0.20 *	6	-0.64 **	3	-0.47	5
High school	-0.73 ***	9	2.4	-0.99 ***	2	-0.60 *	4	-0.75 ***	3
Professional/Elite	-0.47 ***	5	2.4	-0.59 *	3	-0.41 *	2	-	-
College	-0.58 ***	11	2.8	-0.76	2	-	-	-0.55 ***	9
Amateur	-0.52 *	5	1.8	-0.47	2	-	-	-0.55 *	3

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); k = number of independent sample effect sizes; TSI = average time elapsed since injury (in days).

* p < .05, ** p < .01, *** p < .001

Table C4

Effect Size (Mixed Effects Model) Presented as a Function of Athlete Age and Sex: Neuropsychological outcome measures administered at first post-injury assessments conducted 1-10 days following sports-related concussion.

Sex of sample	Age group					
	Adolescent (≤18 years)			Adult (≥19 years)		
	$d_{control}$	*k*	TSI	$d_{control}$	*k*	TSI
100% Female	-	-	-	-0.67 ***	1	1.9
100% Male	-1.11 ***	2	1.9	-0.26 *	11	2.8 [a]

Note. $d_{control}$ = weighted mean effect size calculated using the standard deviation of the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); *k* = number of independent sample effect sizes; TSI = average time elapsed since injury (in days).

[a] If adult male samples matched to adolescent male and adult female samples on TSI (≥3 days excluded):
adult male $d_{control}$ = -0.30 *, *k* = 7, TSI *M* = 1.8 days.

* p < .05, ** p < .01, *** p < .001

Appendix D

Meta-analytic results calculated using a d_{pooled} effect size statistic

and a mixed effects statistical model

Table D1

Results of the Meta-Analysis (Mixed Effects Model) of Sports-Related Concussion Presented as a Function of Athlete Characteristics and Outcome Measures.

Athlete characteristics	Sample size		Aggregated across outcomes		Outcome measures					
					Neuropsychological tests		Self-report symptom scales		Postural stability assessment	
	Concussed	Controls	d_{pooled}	k	d_{pooled}	k	d_{pooled}	k	d_{pooled}	k
Overall effect of sports concussion	3,801	5,631	-0.55 ***	91	-0.47 ***	70	-0.80 ***	50	-0.34 ***	22
Age group										
Adolescent (≤18 years)	815	1,160	-0.78 *	11	-0.75 *	10	-1.03 ***	9	-	-
Adult (≥19 years)	1,534	2,192	-0.51 ***	58	-0.39 ***	41	-0.81 ***	29	-0.40 ***	19
Sex										
100% Female	129	367	-0.94 ***	4	-0.70 *	3	-1.04 *	2	-	-
100% Male	1,633	2,725	-0.58 ***	38	-0.45 ***	29	-1.11 ***	14	-0.38 *	5
Level of competition										
High school	815	1,160	-0.78 *	11	-0.75 *	10	-1.03 ***	9	-	-
Professional/Elite	138	131	-0.60 ***	6	-0.43 ***	6	-0.93 ***	1	-	-
College	1,167	1,920	-0.52 ***	45	-0.39 ***	28	-0.72 ***	24	-0.40 ***	19
Amateur	170	140	-0.40 ***	5	-0.34 **	5	-0.76 ***	4	-	-
Sport played										
American football	1,946	862	-0.54 ***	38	-0.52 ***	34	-0.75 ***	24	-0.42 *	5
Australian Rules	127	131	-0.73	5	-0.73	5	-	-	-	-
Rugby union	89	32	-0.22	5	-0.07	3	0.73	1	-0.57 ***	3
Ice hockey	97	185	-0.07	4	-0.29	3	-1.30	3	-	-
Soccer	10	12	-0.61	1	-0.61	1	-	-	-	-
Boxing	14	-	-0.34	1	-0.34	1	-	-	-	-

Note. d_{pooled} = weighted mean effect size calculated using the pooled standard deviations of the concussed group and the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); k = number of independent sample effect sizes.

* $p < .05$, ** $p < .01$, *** $p < .001$

Table D2

Results of the Meta-Analysis (Mixed Effects Model) of Sports-Related Concussion Presented as a Function of Athlete Characteristics, Comparison Group, and Time Since Injury.

Comparison group Athlete characteristics	Aggregated over time		Time since injury [a]							
			<24 hours		1 – 10 days		10 – 30 days		>30 days	
	d_{pooled}	*k*	d_{pooled}	*k*	d_{pooled}	*k*	d_{pooled}	*k*	d_{pooled}	*k*
Overall effect of sports concussion	-0.55 ***	91	-0.91 ***	30	-0.48 ***	67	-0.13 **	12	-0.06	19
Adolescent (≤18 years)	-0.78 *	11	-1.21 ***	1	-0.60 ***	11	-	-	0.00	1
Adult (≥19 years)	-0.51 ***	58	-0.94 ***	22	-0.39 ***	37	-0.23 *	9	-0.19 *	15
100% Female	-0.94 ***	4	-	-	-1.01 **	3	-	-	-0.61	1
100% Male	-0.58 ***	38	-1.12 ***	14	-0.42 **	22	-0.10	4	-0.03	14
High school	-0.78 *	11	-1.21 ***	1	-0.60 ***	11	-	-	0.00	1
Professional/Elite	-0.60 ***	6	-1.73	2	-0.41 **	4	0.06	1	-0.06	1
College	-0.52 ***	45	-0.87 ***	20	-0.44 ***	30	-0.25 *	8	-0.16	10
Amateur	-0.40 ***	5	-	-	-0.45 **	5	-0.05	1	-	-
Both baseline and control group	-0.52 ***	22	-0.89 ***	14	-0.39 ***	18	-0.01	2	-0.13	5
Adolescent (≤18 years)	-0.45 **	3	-1.21 ***	1	-0.46 **	3	-	-	0.00	1
Adult (≥19 years)	-0.35 ***	15	-0.75 ***	10	-0.33 ***	13	-0.01	2	-0.17	3
100% Female	-	-	-	-	-	-	-	-	-	-
100% Male	-0.49 **	10	-0.93 ***	6	-0.24 **	7	0.06	1	-0.18	4
High School	-0.45 **	3	-1.21 ***	1	-0.46 **	3	-	-	0.00	1
Professional/Elite	-0.34	2	-	-	-0.53	2	0.06	1	-	-
College	-0.41 ***	11	-0.75 ***	10	-0.37 **	9	-0.04	1	-0.17	3
Amateur	-0.43	2	-	-	-0.43	2	-	-	-	-

Comparison group / Athlete characteristics	Aggregated over time		Time since injury [a]							
			<24 hours		1 – 10 days		10 – 30 days		>30 days	
	d_{pooled}	*k*	d_{pooled}	*k*	d_{pooled}	*k*	d_{pooled}	*k*	d_{pooled}	*k*
Independent control group only	-0.57 ***	30	-1.06 ***	7	-0.57 ***	17	-0.08	4	-0.05	12
Adolescent (≤18 years)	-0.68 *	5	-	-	-0.68 *	5	-	-	-	-
Adult (≥19 years)	-0.58 ***	21	-1.10 ***	6	-0.47	9	-0.05	3	-0.30 *	10
100% Female	-1.17 **	2	-	-	-1.52 ***	1	-	-	-0.61	1
100% Male	-0.63 *	15	-1.15 ***	5	-0.60	6	0.00	1	0.08	8
High school	-0.68 *	5	-	-	-0.68 *	5	-	-	-	-
Professional/Elite	-0.50 **	3	-0.83 **	1	-0.34	2	-	-	-0.06	1
College	-0.65 **	14	-1.16 ***	5	-0.52	7	-0.05	3	-0.24	5
Amateur	-	-	-	-	-	-	-	-	-	-
Pre-injury baseline only	-0.52 ***	39	-0.80 ***	9	-0.47 ***	32	-0.16 **	6	-0.05	2
Adolescent (≤18 years)	-0.55 *	3	-	-	-0.55 *	3	-	-	-	-
Adult (≥19 years)	-0.49 ***	22	-1.05 ***	6	-0.33 ***	15	-0.36 **	4	-0.05	2
100% Female	-0.74 *	2	-	-	-0.74 *	2	-	-	-	-
100% Male	-0.55 ***	13	-1.51 **	3	-0.34 *	9	-0.20	2	-0.05	2
High school	-0.55 *	3	-	-	-0.55 *	3	-	-	-	-
Professional/Elite	-2.68 *** [b]	1	-2.68 *** [b]	1	-	-	-	-	-	-
College	-0.42 ***	20	-0.74 ***	5	-0.38 ***	14	-0.36 **	4	-0.05	2
Amateur	-0.42 ***	3	-	-	-0.50 ***	3	-0.05	1	-	-

Note. d_{pooled} = weighted mean effect size calculated using the pooled standard deviations of the concussed group and the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); *k* = number of independent sample effect sizes.

[a] Time since injury intervals were selected for consistency with documented neurometabolic and neurophysiologic recovery periods (Giza & Hovda, 2001, 2004). [b] Observed effect size identified as an outlier but considered a genuine representation of the data: single effect size (i.e. no aggregation) derived from assessment conducted within 15 minutes of injury using a single test score (Digit Symbol Substitution Test).

* $p < .05$, ** $p < .01$, *** $p < .001$

Table D3

Effect Size (Mixed Effects Model) Presented as a Function of Athlete Characteristics and Comparison Group: Neuropsychological outcome measures administered at first post-injury assessments conducted 1-10 days following sports-related concussion.

Athlete characteristics	Aggregated over comparisons			Comparison group					
				Both baseline and control group		Independent control group only		Pre-injury baseline only	
	d_{pooled}	*k*	TSI	d_{pooled}	*k*	d_{pooled}	*k*	d_{pooled}	*k*
Adolescent (≤18 years)	-0.53 ***	9	2.4	-0.69 ***	2	-0.41 *	4	-0.57 ***	3
Adult (≥19 years)	-0.37 ***	18	2.7	-0.29 *	6	-0.39 *	2	-0.42 **	10
100% Female	-0.86 ***	2	2.9	-	-	-	-	-0.86 ***	2
100% Male	-0.35 ***	13	2.5	-0.18	5	-0.48 ***	3	-0.38 *	5
High school	-0.53 ***	9	2.4	-0.69 ***	2	-0.41	4	-0.57 ***	3
Professional/Elite	-0.43 **	4	2.4	-0.53	2	-0.39	2	-	-
College	-0.49 ***	11	2.8	-0.47	2	-	-	-0.50 ***	9
Amateur	-0.43 *	5	1.8	-0.41	2	-	-	-0.44	3

Note. d_{pooled} = weighted mean effect size calculated using the pooled standard deviations of the concussed group and the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); *k* = number of independent sample effect sizes; TSI = average time elapsed since injury (in days).

* p < .05, ** p < .01, *** p < .001

Table D4

Effect Size (Mixed Effects Model) Presented as a Function of Athlete Age and Sex: Neuropsychological outcome measures administered at first post-injury assessments conducted 1-10 days following sports-related concussion.

Sex of sample	Age group					
	Adolescent (≤18 years)			Adult (≥19 years)		
	d_{pooled}	*k*	TSI	d_{pooled}	*k*	TSI
100% Female	-	-	-	-0.62 **	1	1.9
100% Male	-0.75 ***	2	1.9	-0.21 *	10	2.6 [a]

Note. d_{pooled} = weighted mean effect size calculated using the pooled standard deviations of the concussed group and the uninjured comparison group as the denominator. By convention, effect size magnitudes ≥ .80 are considered large, .50 moderate and ≤ .20 small (Cohen, 1988); *k* = number of independent sample effect sizes; TSI = average time elapsed since injury (in days).

[a] If adult male samples matched to adolescent male and adult female samples on TSI (≥3 days excluded): adult male d_{pooled} = -0.28 *, *k* = 7, *Q* = 15.37 *, TSI *M* = 1.8 days.

* p < .05, ** p < .01, *** p < .001