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Executive functions and intraindividual variability following concussion

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The long-term outcomes of executive functions and intraindividual variability (IIV; i.e., trial-to-trial or across-task variability in cognitive performance) following concussion are unclear due to inconsistent and limited research findings, respectively. *Objective:* Responding to these gaps in scientific understanding, the current study aimed to assess the utility of both executive functions and IIV at predicting concussion history. *Method:* Altogether 138 self-identified athletes (M_{age} = 19.9 ± 1.91 years, 60.8% female, 19.6% with one concussion, 18.1% with two or more concussions) completed three executive-related cognitive tasks (i.e., n-back, go/no-go, global–local). Ordinal logistic regression analyses examined the joint effect of person-mean and IIV as predictors of concussion status. *Results:* Only mean response time for the global–local task predicted the number of past concussions, while no IIV variables reached unique significance. *Conclusions:* IIV research on concussion remains limited; however, the preliminary results do not indicate any additional value of IIV indices above mean performances at predicting past concussion. For executive functions, shifting appears most sensitive at detecting concussion group differences, with past researchers identifying post concussion impairment in attentional processing.

Keywords: Concussion; Mild traumatic brain injury; Executive function; Intraindividual variability.

Concussion, also referred to as mild traumatic brain injury (mTBI), has notable deleterious effects on brain functions shortly after injury (Grindel, 2003). However, as most symptoms subside after the acute recovery phase (i.e., three months post injury; Frencham, Fox, & Maybery, 2005; Rohling et al., 2011), the cognitive sequelae of concussion have been considered clinically insignificant (Binder, Rohling, & Larrabee, 1997; Schretlen & Shapiro, 2003). Athletes, in particular, exhibit more rapid recovery trajectories on average and return to baseline by seven days post injury, with no neuropsychological deficits observed past this timeframe (Belanger & Vanderploeg, 2005). Despite this positive prognosis, sports-related concussions have recently become a growing public health concern (Moser, 2007), due to the high frequency of concussive events among athletes (Coronado, McGuire, Faul, Sugerman, & Pearson, 2012) and the increased risk of neurodegeneration long after retiring from play (Guskiewicz et al., 2005; Lehman, Hein, Baron, & Gersic, 2012; McKee et al., 2009). However, based on past meta-analytic findings, the average post acute cognitive effect of concussion appears particularly small (Karr, Areshenkoff, & Garcia-Barrera, 2013).

Following these research conclusions, concussion in clinical practice has become synonymous with rapid symptom resolution. In the military, established concussion treatment algorithms involve expected recovery by seven days (Barth, Isler, Helmick, Wingler, & Jaffee, 2010); however, some researchers have posited that universal

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symptom resolution appears unlikely, with meta-analytic methods disguising individual differences in post concussion cognitive outcomes (Iverson, 2010). Termed the “miserable minority” (Ruff, Camenzuli, & Mueller, 1996; Ruff et al., 1994), a small group of patients may remain persistently symptomatic following concussion (Pertab, James, & Bigler, 2009), emphasizing the need for sensitive neuropsychological metrics to identify subtle subgroup impairments.

Although meta-analysts have reported swift cognitive recovery following concussion (Karr et al., 2013), criticism surrounds the sensitivity of neuropsychological tests at detecting long-term post concussion impairments, specifically among participants assessed long after injury. An early research group noted that, beyond three months post injury, clinicians assessing patients for concussion were “more likely to be correct when diagnosing no brain injury and less likely to be correct when diagnosing brain injury” (Binder et al., 1997, p. 428). Computerized and paper-and-pencil measures have shown limited utility at detecting subtle cognitive differences based on concussion history (Broglio, Ferrara, Piland, & Anderson, 2006), despite clear neurophysiological abnormalities remaining long after the concussive event (Broglio, Moore, & Hillman, 2011).

With limited long-term sensitivity to injury, neuropsychological assessments have often presented limited evidence for chronic effects of concussion on cognitive performance. However, the universal conclusion of rapid symptom resolution from concussion may be inaccurate due to two methodological considerations. First, meta-analyses draw inference from solely mean performances, ignoring variability in performance that may better detect neurobehavioral differences related to head injury (Hill & Rohling, 2011). Second, the small concussion-related effect sizes associated with neuropsychological testing often derive from collapsed estimates across different mental abilities, although cognitive domains vary in terms of post concussion outcomes (e.g., Belanger, Curtiss, Demery, Lebowitz, & Vanderploeg, 2005; Frencham et al., 2005). The separate evaluation of distinct cognitive abilities often produces diverse conclusions when compared to studies treating cognition as a global construct (Karr et al., 2013). These two considerations validate the further exploration of performance variability and specific cognitive constructs (e.g., executive functions) post concussion by future researchers.

Beginning with the assessment of constructs, effect sizes for specific cognitive domains vary across meta-analyses due to poor operational definitions of each construct, with independent researchers sometimes allocating the same neuropsychological tests to different domains (Karr et al., 2013). Among the cognitive abilities evaluated by past researchers, executive functions present the most notable variability across meta-analyses (range: $d = -0.11$ to 0.72; Belanger & Vanderploeg, 2005; Zakzanis, Leach, & Kaplan, 1999). These higher order cognitive constructs have historically eluded researchers, as they are difficult both to operationalize (Jurado & Rosselli, 2007) and to measure repeatedly (Bartels, Wegrzyn, Wiedl, Ackermann, & Ehrenreich, 2010). In turn, the variability in their associated effect sizes may derive from insufficient operational definitions of executive functions. As a result, future researchers must apply recently established cognitive models to ensure the accurate measurement of these constructs.

Executive functions

A lengthy history of theoretical and empirical work has established a foundational understanding of executive functions by psychological researchers (Jurado & Rosselli, 2007). A key study within the field identified three latent factors linked to frontal lobe functioning (i.e., updating, shifting, and inhibition) that overlapped in their predictive validity of more complex executive-related tasks, establishing both the diversity and unity of executive functions (Miyake et al., 2000). These three components derive largely from frontal lobe functioning; however, growing evidence supports their reliance on more posterior and subcortical substrates as well (Jurado & Rosselli, 2007). Associated with dorsolateral prefrontal functioning (D’Ardenne et al., 2012), the first component, updating, refers to the manipulation of information in working memory, actively trading old information for more pertinent information related to the current task. The second component, shifting, has been linked to the anterior cingulate cortex (ACC) and represents a function of the anterior attention network (Posner & Rothbart, 2007; Posner, Rothbart, Sheese, & Tang, 2007). This ability involves switching between multiple sets of task demands, overcoming the interference of concurrent or previous task demands to respond accurately to the current stimulus. Lastly, inhibition has been associated with lateral orbitofrontal activity (Rolls, 2004) and refers to the intentional suppression of a prepotent response, where an individual cognitively restricts a dominant response pattern in reaction to an unexpected change in task demands. Altogether, these three factors represent distinguishable, but interrelated, cognitive abilities that combine to predict performance on more complex executive-related tasks (Miyake et al., 2000). In turn, the universal term "executive functioning" refers to a collection of self-regulatory abilities that work both independently and conjunctively to produce and direct volitional behavior in response to novel cues or environmental requisites.

Although the exact number of executive components remains unclear (Jurado & Rosselli, 2007), the three factors identified by Miyake and colleagues (2000; i.e., updating, shifting, and inhibition) have become well established and highly cited within the field as replicable factors derived from executive-related tasks (Fisk & Sharp, 2004; Testa, Bennett, & Ponsford, 2012). In relation to concussion research, no past studies have used an established model of executive functions when selecting cognitive outcomes. Overall, the operational definitions of executive functions among concussion researchers appear particularly inconsistent, leading to fairly disparate findings (Karr et al., 2013). A recent systematic review rated concussion research based on scientific merit (Comper, Hutchison, Magrys, Mainwaring, & Richards, 2010), with one highly ranked study broadly operationalizing executive functions as performance on one sole measure (i.e., Trail Making Test, Part B; Collins et al., 1999).

An older meta-analysis originally conceptualized concussion as a frontal-executive pathology (Zakzanis et al., 1999), and, more recently, a high-profile autopsy of a retired American football safety showed significant frontal pathology (Roehr, 2012), likely deriving from a history of multiple sports-related concussions, but possibly resulting from the cumulative effects of multiple subconcussive impacts. Although some imaging evidence has linked concussion to executive dysfunction (Lipton et al., 2009; Niogi & Mukherjee, 2010), past meta-analyses have predominantly found minimal support for long-term executive-related deficits following concussion (e.g., Belanger et al., 2005; Belanger & Vanderploeg, 2005; Binder et al., 1997; Rohling et al., 2011); however, others have identified more adverse impacts of concussion on higher order cognitive functions (e.g., Belanger, Spiegel, & Vanderploeg, 2010; Frencham et al., 2005; Zakzanis et al., 1999). Multiple variables appear to moderate this effect, including time since injury (i.e., most athletes return to baseline by seven days post concussion; Belanger & Vanderploeg, 2005) and number of past concussions (i.e., multiple concussions have a greater impact on executive functions; Belanger et al., 2010; Belanger & Vanderploeg, 2005). As noted earlier, this inconsistency may derive from poor operational definitions of executive functions or inadequate sensitivity of neuropsychological tests at detecting long-term impairment.

Another potential conclusion concedes that concussion does not lead to long-term impairment in mean cognitive performance, as concluded by many past meta-analysts (Belanger et al., 2005; Belanger & Vanderploeg, 2005; Frencham et al., 2005; Rohling et al., 2011; Schretlen & Shapiro, 2003); however, meta-analytic findings derive fully from analyses of averaged performances, drawing clinical inference from solely mean outcomes. An alternative method for cognitive assessment involves the examination of intraindividual variability (IIV), or inconsistency in cognitive performance across time or different tests (Hultsch, Strauss, Hunter, & MacDonald, 2008). Past researchers have proposed IIV analysis as valuable for concussion assessment (Bleiberg, Halpern, Reeves, & Daniel, 1998), but only a limited body of existing research has explored IIV following concussion.

Intraindividual variability

IIV consists of increased response variability, often quantified through an intraindividual standard deviation (ISD) or a similar metric, such as the intraindividual coefficient of variation (ICV; Hultsch et al., 2008). Past researchers have identified many ways of assessing IIV, with inconsistency and dispersion standing as two common methods. Inconsistency quantifies variability in performance, often recruiting response time (RT) as a trial-to-trial outcome to evaluate variations in within-task performance. Dispersion refers to IIV within a battery of neuropsychological tests, calculated as the ISD of standardized performance scores across multiple cognitive tasks (e.g., Christensen et al., 1999; Hilborn, Strauss, Hultsch, & Hunter, 2009). A developing body of research has begun examining IIV indicators in relation to neuropsychological impairment following TBI, with past researchers positing that increased variability after brain injury represents "a compromised central nervous system struggling to maintain optimal and consistent performance" (Hill & Rohling, 2011, p. 164). Further, the neural substrates of IIV share involvement with executive functions, indicating a potential relationship between higher order cognitive deficits and increased IIV following head injury.

Multiple executive-related neurological structures and functions overlap with IIV (MacDonald, Nyberg, & Bäckman, 2006), with past researchers linking heightened IIV to frontal lobe lesions (Stuss, Murphy, Binns, & Alexander, 2003). During poor inhibitory performance (i.e., increased errors), IIV positively correlated with increased bilateral activity in the middle frontal gyri, linking IIV to increased executive-related demands (Bellgrove, Hester, & Garavan, 2004). Mild TBI appears to result in axonal injuries within the dorsolateral prefrontal cortex that correlate with deficits in executive-related performances (Lipton et al., 2009), and, in turn, researchers have linked frontal and temporal white matter damage to cognitive deficits post injury (Niogi & Mukherjee, 2010). Among a noninjured sample, heightened IIV tends to associate with less white matter in the brain (Walhovd & Fjell, 2007), indicating an overlap between myelin integrity and IIV. With some past researchers identifying frontal pathology (Lipton et al., 2009; Niogi & Mukherjee, 2010) and executive dysfunction following concussion (Belanger et al., 2010; Zakzanis et al., 1999), IIV may co-occur with executive-related deficits; however, only one past study has explored IIV in executive functions post concussion (Halterman et al., 2006), and overall few past concussion researchers have explored IIV for any cognitive outcome.

Research on IIV has steadily developed over the last two decades, focusing primarily on cognitive aging (Hultsch et al., 2008). Only one past meta-analysis has examined IIV, but it covered neither TBI nor executive functions (Dykiert, Der, Starr, & Deary, 2012). These authors examined age-related IIV increases in simple and choice RT tasks, identifying larger effect sizes for the more complex choice-based tasks. IIV research on aging has reached a greater overall maturity than IIV research on TBI, but IIV may provide a meaningful metric for assessing cognitive performance following TBI (Hill & Rohling, 2011). In turn, preliminary research has demonstrated some TBI-related increases in IIV across grades of injury (Hultsch et al., 2008). Although too few studies for a meta-analysis, several articles have examined IIV following concussion (Bleiberg, Garmoe, Halpern, Reeves, & Nadler, 1997; Burton, Hultsch, Strauss, & Hunter, 2002; Halterman et al., 2006; Hill & Rohling, 2011; MacFlynn, Montgomery, Fenton, & Rutherford, 1984; Makdissi et al., 2001; Sosnoff, Broglio, Hillman, & Ferrara, 2007; Stuss et al., 1989), described in detail in Table 1.

The first study examining concussion-related IIV identified significantly greater RT variability among concussed participants than in controls within 48 hours of injury, but this difference subsided by 6 weeks post concussion (MacFlynn et al., 1984). These authors used the ICV as their IIV index (i.e., ISD divided by individual mean RT), but this method does not fully control for main effects deriving from mean performance that may underlie IIV group differences (Hultsch et al., 2008). Similarly, Stuss et al. (1989) found significantly greater RT ISDs than in control participants; however, these researchers collapsed concussed participants with more severe TBI participants, blurring the interpretability of their results. These researchers also failed to account for mean confounds in their analyses, with their findings potentially deriving from mean group differences, as higher individual means (i.e., slower RT) are often significantly correlated with higher ISDs (Jensen, 1992).

Nearly a decade after these findings, Bleiberg et al. (1997) examined a small group of mild/moderate TBI participants, identifying increased variability for head-injured participants proportional to median slowing in RT. Sequential studies evaluating IIV have found similarly null results, including no increase in IIV—as measured by ICV—for an attentional task involving an executive component (Halterman et al., 2006) and no unique IIV group differences in RT once controlling for mean post concussion performance (Sosnoff et al., 2007). In a prospective study involving a small sample size ($N = 6$), researchers identified increased IIV post concussion and decreased IIV among noninjured control participants at follow-up, labeling RT variability as a noteworthy deficit following concussion (Makdissi et al., 2001). Notably, these researchers also failed to control for mean RTs in their repeated measures analyses. One additional study reported heightened IIV post concussion, assessing IIV in physical functioning, stress, and affect across weeks (Burton et al., 2002). Without adjusting for person-mean differences, these researchers identified greater variability in solely right-hand grip strength among concussion participants, a fairly trivial conclusion with limited clinical value.

Aside from trial-to-trial assessments of IIV, one research group examined dispersion within a database of TBI patients (i.e., IIV across standardized performance scores for a battery of cognitive tests), identifying increased IIV with greater TBI severity (Hill & Rohling, 2011). Across four TBI categorizations based on loss of consciousness (LOC) duration, brain injuries with LOC under an hour—the group most analogous to concussion—presented the lowest IIV and highest mean

TABLE 1
Summary of past concussion studies examining IIV

		Concussion group			*Control group*			*Study characteristics*			*Notable results*
Authors	*Year*	*N*	$\bar{x}$ *Age (SD), years*	*% Male*	*N*	$\bar{x}$ *Age (SD), years*	*% Male*	*Design*	*Outcome measures*	*IIV metric*	*IIV conclusions*
Bleiberg et al.	1997	6	31.83 (3.66)	50.00	6	29.5 (3.73)	50.00	Tested 30 times over 4 days, about 2 days apart. IIV quantified within-day	Procedural RT, running memory, Sternberg, math processing, spatial processing	IQR and semi-IQR to median ratio	Increased IIV on first three tests for TBI group proportionate to slowing mean performance
Burton et al.	2002	19	35.26 (9.72)	78.95	26	32.77 (10.0)	46.15	Ten testing sessions about one week apart	Physical functions (e.g., gait, grip strength, pulse), stress, & affect	Res. ISD	Greater right grip strength IIV for concussion, but did not control for mean confounds
Halterman et al.	2006	20	21.00 (1.74)	60.00	20	21.00 (1.81)	60.00	Four testing sessions over one month post concussion with matched control	Attentional network test: alerting, orienting and executive function	CV	No IIV differences across groups
Hill & Rohling[a]	2011	152						Secondary analysis of TBI patient database	Cognitive test battery (tests not listed)	Dispersion-based ISD	More IIV with increased TBI severity, with concussion having the lowest IIV
Makdissi et al.	2001	6	20.50 (3.10)	100	6	20.30 (4.20)	100	Prospective design with baseline and follow-up within 72 hours of concussion	CogState simple RT	ISD	Decreased IIV for controls at follow-up and increased IIV for concussion group at follow-up proportional to increases in slow RT responses
MacFlynn et al.	1984	45	30.90 (15.9)	62.22	45	30.90 (15.9)[c]	62.22	Patients tested within 48 hours of concussion, and 6 weeks and 6 months post injury, compared to matched controls	Four-choice RT test	CV	Greater IIV for concussion patients at first assessment, but no difference by 6 weeks
Rabinowitz & Arnett	2013	71	18.60 (0.80)	21.00	42	18.50 (0.80)	51.00	Athletes tested at baseline and between 0 and 210 days post concussion (within 1 week on average). Control participants were tested at baseline and 1 month later	Comprehensive Trail Making, ImPACT, Visuo-spatial Memory Test, Verbal Learning Test, Symbol Digit Modalities, Stroop Color–Word	Dispersion-based ISD	IIV did not increase post concussion. Athletes with higher baseline IIV trended toward IIV increases post concussion. IIV correlated with mean performance
Sosnoff et al.	2007	22	19.80 (2.20)	90.91	22	19.80 (2.20)[c]	90.91	Prospective design with baseline and follow-up within 48 hours of concussion	RT, cued RT, visual recognition, animal decoding, and symbol scanning	ISD	No concussion-related IIV differences once controlling for mean RT
Stuss et al.[b]	1989	22	29.50 (12.6)	68.18	22	27.70 (11.6)	68.18	Compared TBI group IIV at baseline with controls.TBI included concussion group, but also more severe TBI	Simple and multiple choice RT tests	ISD	Greater IIV for head-injured group with varying severities, but did not control for mean confounds

Note. CV = coefficient of variation; IIV = intraindividual variability; IQR = interquartile range; ISD = intraindividual standard deviation; res. = residualized; RT = response time; TBI = traumatic brain injury; ImPACT = Immediate Post Concussion Assessment and Cognitive Test.

[a] Hill and Rohling (2011) conducted a secondary dispersion analysis on an existing TBI database, with no noninjured control group reported. As well, age and gender composition were not reported. [b] Stuss et al. (1989) collapsed all TBI participants into one group for IIV analyses. [c] Denotes estimated mean age and standard deviations, as authors reported using age- and gender-matched controls. The concussion demographics listed include only concussed participants, not the additional TBI participants.

performance for the neuropsychological test battery; however, without a noninjured control group for comparison, it remains unclear whether the observed concussion-related dispersion levels differ from normally occurring performance variability across cognitive tasks. Another study explored dispersion among athletes both before and after concussion (Rabinowitz & Arnett, 2013), identifying no changes in IIV or overall cognitive performance post concussion. A cluster analysis identified that athletes with higher baseline dispersion tended to increase in IIV post concussion; however, this conclusion derived from solely a statistical trend.

Overall, the existing IIV research remains preliminary, with conflicting conclusions and diverse methodology. Notably, the limited control for mean confounds across studies ignores the high correlations that frequently occur between ISDs and individual means (Jensen, 1992). In turn, it remains unclear whether the heightened IIV among past concussed participants (Bleiberg et al., 1997; Burton et al., 2002; MacFlynn et al., 1984; Makdissi et al., 2001; Stuss et al., 1989) represents unique and informative phenomena or merely reflects underlying mean RT differences. These disparate results parallel the diverse measurements of executive functions across studies and their incongruent effect sizes across meta-analyses (Karr et al., 2013).

The current study

The long-term outcomes of executive functions and IIV following concussion appear unclear due to inconsistent and limited research findings, respectively. Responding to these gaps in scientific understanding, the current study aimed to assess the diagnostic utility of both executive functions and IIV (i.e., inconsistency and dispersion) at predicting concussion history. In turn, we hypothesized that both executive functions and IIV would uniquely predict concussion group membership among an athletic sample believed to be fully recovered (i.e., past seven days post injury; Belanger & Vanderploeg, 2005).

METHOD

Participants

Recruitment targeted university-aged athletes with or without a history of concussion from a psychology research participant pool. Due to policies on Canadian interuniversity athletics, each sport at the research institution had equal gender representation, with the researchers aiming for a gender-balanced sample. A total of 138 university students participated in this study (M_{age} = 19.9 ± 1.91 years, 60.8% female), including 86 without concussion (M_{age} = 19.9 ± 1.62 years, 62.8% female), 27 with one past self-reported concussion (M_{age} = 19.85 ± 2.07 years, 63.0% female), and 25 with two or more past self-reported concussions (M_{age} = 20.0 ± 2.63 years, 56.0% female). Participants were asked whether they had ever experienced a concussion. If they responded affirmatively, they were asked whether or not the concussion was sports related, the approximate date of each concussion, and whether or not the concussion involved LOC. Among participants disclosing a past concussion, 96.2% reported at least one sports-related concussion. The concussion variable was collapsed into three sequential categories, representing 0, 1, and 2 + self-reported concussion(s) to avoid overestimates of past concussion frequencies. Deficits in executive functions appear most common in comparisons of multiple concussion groups over single concussion groups (Belanger et al., 2010), rationalizing the trichotomous coding over a dichotomous concussed versus nonconcussed group comparison.

As recruitment targeted self-identified athletes, sports affiliations remained particularly heterogeneous, with several athletes reporting multiple sports affiliations. Across the 138 participants, 59.4% reported affiliations with aerobic sports (e.g., swimming, rowing, cross country), 55.8% with court/field sports (e.g., volleyball, tennis), and 65.2% with head-contact sports (e.g., hockey, rugby, boxing, soccer). These affiliations included either recreational or intercollegiate competitive levels. The percentages sum to greater than one hundred due to athletes reporting affiliations across multiple categories. Among athletes with concussion, 50% reported at least one concussion involving LOC. The average time since injury was particularly heterogeneous at 38.47 ± 41.59 (range: 0.69 to 166.19) months. Exclusion criteria included uncorrected vision problems, history of a neurological disorder or brain injury other than concussion, and a concussion less than seven days prior to testing (Belanger & Vanderploeg, 2005).

To improve the homogeneity of concussion cases, a second series of effect size comparisons selected a subsample of concussion participants reporting a single LOC concussion (N = 15; M_{age} = 19.9 ± 2.44 years, 53.3% female) or two or more LOC concussions (N = 11; M_{age} = 21.0 ± 3.20 years, 45.5% female), classified as Grade III concussion based on the American Academy of Neurology criteria (Kelly et al., 1997). Combined, these groups presented a mean time since injury of 34.77 ± 37.13 (range: 0.82 to 152.91) months, and

100% reported at least one concussion as sports related. In addition, a subsample of control participants was randomly selected from the noninjured participant group (N = 15; M_{age} = 19.9 ± 2.13 years, 66.7% female). This project received full approval by an institutional ethics review board.

Materials and procedure

Participants scheduled appointments for testing sessions through an online participant recruitment system. Once participants provided signed consent, they completed a short history questionnaire and five computerized tasks (only three tasks were assessed in the current analyses). All tasks lasted approximately 45 min. The short questionnaire covered personal information, sports affiliations, and concussion history.

Cognitive tasks

Outcome measures consisted of computerized tasks previously validated as indicators of theoretical executive functions. The tasks were programmed and administered using MatLab R2012b v.8 software package and Psych Toolbox. The selected measures represented specific constructs posited as higher order cognitive factors by past researchers, including the n-back task for the updating of working memory (Kirchner, 1958), a global–local task for shifting (Navon, 1977), and a go/no-go task for inhibition (Donders, 1868/1969). All participants completed these tasks in the same order: go/no-go, n-back, and global–local. The n-back involved keeping track of a sequence of letters appearing on a computer screen, with participants responding by pressing a key when the letter displayed in the sequence matched the letter displayed two back in the same sequence. Each letter stimulus was displayed for 750 ms, separated from the following stimulus by a 750 ms display of a + symbol (e.g., N, +, B, +, N). The outcomes for this measure included accuracy and RT for each trial eliciting a response.

The go/no-go involved two response blocks. For Block I, participants responded as quickly as possible to all presented stimuli, eliciting a prepotent response. Each new stimulus was displayed for 750 ms. Successive stimuli were separated by a blank screen with duration uniformly and randomly distributed between 600 ms and 800 ms in order to prevent rhythmic responding. Block II involved participants responding to all stimuli except one target (i.e., the letter "J" appearing for 20% of the trials). The timing for Block II was identical to that of Block I. The outcomes for this measure included Block II accuracy and trial RTs for both blocks. Block I RT produces a measure of simple RT, whereas Block II RT presents longer latencies due to the potential for inhibited responses, adding an executive component to the task demands.

The global–local involved three response blocks, with each stimulus displayed until the participant elicited a response. During Block I, participants saw shapes and responded with the number of sides of the shape (e.g., circle = 1, square = 4). Similarly, during Block II, participants saw colored shapes and responded based on color. Lastly for Block III, participants saw colored shapes composed of smaller shapes of the same color (e.g., a circle made of small triangles), responding with the number of sides of either the smaller or the larger shapes based on the color of the full design. The outcomes for this measure included accuracy and RT for all blocks, with the RT for Block III presenting longer latencies due to the additive executive component of switching required across trials.

Statistical analyses

To achieve the study aims, performance on the cognitive battery was assessed via ordinal logistic regression and effect size comparisons. Due to limited power for hypothesis testing, only the effect size comparisons were conducted for the LOC subsample analysis.

IIV analyses

The ISD has become a common metric for IIV research, representing the within-person variance in trial-to-trial performance. As no best practice method for ISD calculation exists, three ISD estimates were calculated for each outcome: the raw ISD, the detrended ISD, and the residualized ISD. Prior to ISD calculation, all trial RT scores were converted to T-scores to produce only positive and interpretable variability estimates. Raw ISD was calculated as the standard deviation of the unadjusted RT scores across trials, whereas two alternative statistical techniques extracted the detrended and residualized ISDs from the dataset, through either a multilevel modeling detrending approach or an ordinary least squares residualization technique. The multilevel modeling approach regressed within-person predictors on the outcome at each trial, producing Level 1 residuals detrended for linear, quadratic, and cubic parameters. As Level 2 predictors do not directly impact Level 1 residuals in multilevel modeling, this approach does not partial the systematic variance of between-person predictors, removing solely within-person variance (i.e., practice effects) from the residual RT values.

The ordinary least squares approach produced the residualized ISD, using both within-person (i.e., trial order and its higher order polynomials) and between-person predictors (i.e., concussion status, individual mean performance, task accuracy) along with their cross-level interactions in linear regression models. This method saves residual trial scores as a newly constructed variable representing an unsystematic portion of variance not accounted for by mean, practice, or group variables (Hultsch et al., 2008).

With the trichotomized concussion status variable serving as the outcome, a series of ordinal logistic regression analyses evaluated the unique predictive quality of IIV indicators over performance-level variables (i.e., accuracy, mean RT), with all such analyses conducted using MPlus v.6.12 (Muthén & Muthén, 2011). For each executive-related measure, separate hierarchical regression procedures entered additional variables into the model. For each outcome, Model 1 contained only control variables, including accuracy for the n-back, mean Block I RT for the go/no-go, and Block I/II mean RT and accuracy for the global–local. Model 2 added meaningful performance indicators, including mean RT for the n-back, Block II accuracy and mean RT for the go/no-go, and Block III accuracy and mean RT for the global–local. Lastly, for Model 3, each ISD value (i.e., raw, detrended, and residualized) was included in a separate and identical model, evaluating differences in the unique effects of each predictor. The ISDs derived from n-back RT, go/no-go Block II RT, and global–local Block III RT. Evaluation of each model focused on the unique significance of each predictor, with significance set at $p < .05$. In addition, ΔR^2 values were assessed to examine the amount of explained variance associated with each added predictor or variable set.

An additional analysis focused on dispersion across the three executive tasks, involving performance measures for each outcome (i.e., n-back, accuracy; go/no-go, Block II RT – Block I RT; global–local, Block III RT – mean Block I/II RT). The n-back accuracy was recoded so that a higher score indicated worse performance. As with the trial RT data, all scores were standardized and converted to T-scores prior to the calculation of an average performance and ISD for the executive function task battery. Two sequential ordinal logistic regression models evaluated the prediction of mean performance and dispersion on the number of past concussions, with the first model including only the average T-score for the battery and the second model adding the across-task ISD as an additional predictor.

Effect size comparisons

As small sample size introduces bias against null results during logistic regression (Nemes, Jonasson, Genell, & Steineck, 2009), the LOC subsample lacked sufficient power for independent logistic regression analyses. In turn, the assessment of this subsample remained purely measurement based rather than inferential, focusing on effect size comparisons rather than hypothesis testing. Effect sizes, d (Cohen, 1988), and 95% confidence intervals (CIs) were calculated for both the full sample and the LOC subsample, identifying any differences based on operational definitions of concussion. All effect sizes and 95% CIs were calculated using Effect Size Generator v.2.3 (Devilly, 2004).

Data preparation

For trial-to-trial data on each measure, RT scores under 150 ms were excluded, based on previously established lower-bound cutoffs recruited for IIV analyses involving young adults (Hultsch, MacDonald, Hunter, Levy-Bencheton, & Strauss, 2000). Thereafter, outliers were removed from within-participant performances based on a ±3 standard deviation cutoff criterion deriving from individual participants' mean scores. Combined with participant nonresponses for some target trials, this process resulted in varying degrees of missing trial values across outcome variables (i.e., 32.3% n-back, 17.6% global–local, 4.4% go/no-go), but the removal of these extreme data points ultimately provides a more conservative estimate of variability.

RESULTS

Table 2 summarizes the descriptive statistics of mean performances and ISDs for each executive-related outcome based on the number of past concussions for both the full sample and the LOC subsample. As well, Table 3 provides the correlations between IIV and mean RT outcomes for each cognitive task and time since injury. As displayed in the correlation matrix, relationships between variables differed across the full and LOC samples. Intratask correlations were consistent across each sample, and most notably the ISDs significantly

TABLE 2
Descriptive statistics for task outcomes based on number of past concussions

Sample	*Number of past concussions*	*Measure*	*N-back*		*Global–local*		*Go/no-go*	
			M	*SD*	*M*	*SD*	*M*	*SD*
Full sample	0	Accuracy	0.693	0.243	0.868	0.182	0.975	0.089
		MRT	0.458	0.071	1.55	0.390	0.339	0.055
		ISD (res.)	10.33	2.99	8.04	3.67	9.08	2.78
		ISD (det.)	10.10	3.22	8.07	3.71	9.06	2.74
		ISD (raw)	8.59	2.74	7.32	3.32	7.35	2.20
	1	Accuracy	0.678	0.235	0.902	0.105	0.968	0.045
		MRT	0.457	0.063	1.75	0.544	0.369	0.071
		ISD (res.)	10.85	3.01	10.87	7.35	11.01	3.34
		ISD (det.)	10.53	2.93	10.77	7.19	10.97	3.43
		ISD (raw)	9.02	2.48	9.78	6.44	8.84	2.69
	2+	Accuracy	0.682	0.247	0.892	0.122	0.982	0.032
		MRT	0.467	0.095	1.80	0.344	0.345	0.032
		ISD (res.)	9.59	2.78	9.59	3.34	9.77	2.80
		ISD (det.)	10.02	2.98	9.49	3.39	9.77	2.56
		ISD (raw)	8.45	2.51	8.81	2.85	7.86	2.12
LOC subsample	0	Accuracy	0.688	0.285	0.769	0.302	0.986	0.008
		MRT	0.437	0.060	1.54	0.457	0.360	0.051
		ISD (res.)	9.73	3.31	7.26	3.13	9.56	2.73
		ISD (det.)	9.18	3.59	7.32	3.05	9.48	2.56
		ISD (raw)	7.86	3.14	6.87	2.68	7.80	2.05
	1	Accuracy	0.673	0.180	0.888	0.117	0.960	0.064
		MRT	0.458	0.070	1.66	0.328	0.373	0.090
		ISD (res.)	9.64	3.13	10.71	5.86	10.96	3.64
		ISD (det.)	9.37	2.80	10.34	5.80	10.96	3.80
		ISD (raw)	7.94	2.47	9.79	5.08	8.78	3.00
	2+	Accuracy	0.669	0.319	0.921	0.030	0.986	0.009
		MRT	0.446	0.091	1.92	0.329	0.352	0.044
		ISD (res.)	8.63	3.19	9.73	3.11	9.66	2.77
		ISD (det.)	9.32	3.26	9.70	3.23	10.02	2.75
		ISD (raw)	7.61	2.80	8.99	2.71	7.87	2.05

Notes. LOC = loss of consciousness; ISD = intraindividual standard deviation; det. = detrended; MRT = mean response time; res. = residualized. All accuracy scores are displayed as percentages from 0 to 1, and all MRT scores are displayed in seconds.

TABLE 3
Correlations between IIV and mean performances

Task	*Measure*	*N-back*			*Go/no-go*			*Global–local*			
		Acc.	*MRT*	*ISD*	*Acc.*	*MRT*	*ISD*	*Acc.*	*MRT*	*ISD*	*TSI (mos.)*^{a}
N-back	Acc.	1	*–.481***	*–.366***	–.053	–.151	*–.361***	.069	*–.226***	*–.300***	–.024
	MRT	*–.457***	1	*.464***	–.114	*.205**	*.201**	.103	*.240***	*.222**	–.011
	ISD	–.109	*.438***	1	–.034	.071	*.193**	.016	*.246***	*.290***	.133
Go/no-go	Acc.	–.052	–.130	–.140	1	*–.668***	.095	–.044	*–.175**	–.116	.076
	MRT	–.201	.229	.088	*–.660***	1	*.320***	–.019	*.244***	*.230***	–.157
	ISD	*–.411***	*.367**	.095	–.115	.309	1	–.036	*.292***	*.307***	–.111
Global–local	Acc.	.196	.234	.142	–.076	–.013	.129	1	*.243***	–.015	–.044
	MRT	–.036	.264	.167	–.107	.023	.123	*.450***	1	*.858***	–.047
	ISD	–.214	.275	.310	–.223	.201	.207	.221	*.733***	1	.169
	TSI (mos.)^{a}	–.149	.298	.207	–.003	–.047	.119	–.183	.063	.394	1

Notes. Italic values reached significance. The full sample is displayed above the diagonal and the loss of consciousness subsample below the diagonal. IIV = intraindividual variability; Acc. = accuracy; MRT = mean response time; ISD = intraindividual standard deviation; TSI (mos.) = time since injury in months. All ISD values used in correlation analyses derived from the detrending methodology.

[a] TSI correlations involved only participants reporting a past concussion.

*Significance at $p > .05$. **Significance at $p > .01$.

correlated with mean RTs for each measure. This correlation appeared highest within the global–local, correlating at .858 among the full sample. Notably, time since injury did not correlate with any cognitive measures for concussion participants, indicating that the sample had passed the acute recovery phase.

IIV outcomes

Aside from lower variability estimates associated with raw ISD, the detrending and residualization methodologies for ISD calculations produced analogous values across outcomes. This similarity likely implies that the majority of variance derived from within-person sources. In turn, the additive control for between-person confounds associated with the residualization approach presented no inferential advantage within this dataset.

Pertaining to the logistic regression models, Tables 4–6 report the estimates for each model across all executive outcomes. Neither mean performances nor IIV indicators significantly predicted the number of past concussions for either the n-back or the go/no-go tasks. These analyses indicated only one uniquely significant predictor of the polytomous concussion outcome: mean RT for Block III of the global–local task. For every one unit increase in RT for this task, the model presented a 1.52 increase in the logit of moving from fewer concussions to a higher ordinal category, given that all other variables are held constant. This estimate increased with the addition of any form of ISD into the model (i.e., raw, detrended, or residualized), indicating that ISD accounted for some unique variance in the categorical outcome, but not enough to reach significance. Concerning explained variance, the addition of mean Block III RT for the global–local accounted for a modest portion of variance (i.e., ΔR^2 = .163), whereas the addition of ISDs into the model produced much smaller changes in explained variance (ΔR^2 = .043 to .083, depending on ISD calculation). Dispersion analyses identified neither average test performance nor test battery variability as significantly predictive of number of past concussions.

TABLE 4
Ordinal logistic regression results: N-back

		Full sample				
Model	*Predictor*	*β*	*SE*	*p*	R^2	ΔR^2
Model 1	Accuracy	–0.179	0.708	.800	.001	
Model 2	Accuracy	–0.235	0.825	.776	.001	.000
	Mean RT	–0.339	2.87	.906		
Model 3 (res.)	Accuracy	–0.365	0.850	.668	.004	.003
	Mean RT	0.149	3.10	.960		
	ISD (res.)	–0.036	0.067	.584		
Model 3 (det.)	Accuracy	–0.271	0.838	.746	.001	.000
	Mean RT	–0.602	3.07	.845		
	ISD (det.)	0.000	0.067	.998		
Model 3 (raw)	Accuracy	–0.243	0.838	.772	.001	.000
	Mean RT	–0.474	3.07	.877		
	ISD (raw)	0.005	0.075	.952		

Note. All Model 3 ΔR^2 values derive from comparisons with Model 2 R^2 values; ISD = intraindividual standard deviation; RT = response time; det. = detrended; res. = residualized.

Effect size comparisons

A forest plot in Figure 1 schematically illustrates effect sizes and 95% CIs across samples, tasks, and outcomes. All effect sizes were coded with negative values indicating worse performance for participants with a greater number of past concussions. Only the full sample presented effect sizes with 95% CIs that did not overlap the zero demarcation. Although the go/no-go did not predict concussion status, its effect sizes for mean RT (d = –0.47) and ISD (d = –0.62) appeared reliably different from zero and showed worse performance of single concussion participants when compared to noninjured participants. Also based on noninjured to single concussion comparisons, the global–local presented worse performance for the concussion group on ISD with an effect size reliably distinct from zero (d = –0.47); however, the 95% CI for its mean RT effect size (d = –0.42) slightly overlapped the zero demarcation, but trended toward worse performance for single concussion participants. Among the LOC subsample, the 95% CI for the mean global–local RT effect size (d = –0.79) also slightly overlapped zero, but trended toward worse performance for the 2+ concussion group over the single concussion group.

DISCUSSION

Examining three established executive functions (Miyake et al., 2000), shifting performance best differentiated between groups based on self-reported histories of past mTBI status, although group differences presented fairly minute effect sizes. Overall, mean RT performance on the global–local task served as the only significant predictor that uniquely distinguished between noninjured participants and those with past concussions. Neither tasks of inhibition nor those of updating presented group differences based on concussion

TABLE 5
Ordinal logistic regression results: Go/no-go

Model	*Predictor*	*Full subsample*			R^2	ΔR^2
		β	*SE*	*p*		
Model 1	Block I mean RT	2.76	1.97	.161	.016	
Model 2	Block I mean RT	2.53	3.03	.402	.036	.020
	Block II accuracy	4.56	3.61	.206		
	Block II mean RT	4.74	4.70	.313		
Model 3 (res.)	Block I mean RT	3.27	3.09	.291	.053	.017
	Block II accuracy	2.44	3.83	.523		
	Block II mean RT	0.549	5.31	.918		
	Block II ISD (res.)	0.100	0.064	.122		
Model 3 (det.)	Block I mean RT	3.23	3.08	.295	.053	.017
	Block II accuracy	2.40	3.78	.525		
	Block II mean RT	0.839	5.26	.873		
	Block II ISD (det.)	0.098	0.064	.125		
Model 3 (raw)	Block I mean RT	3.22	3.08	.297	.051	.015
	Block II accuracy	2.48	3.82	.516		
	Block II mean RT	0.948	5.26	.857		
	Block II ISD (raw)	0.117	0.080	.146		

Note. All Model 3 ΔR^2 values derive from comparisons with Model 2 R^2 values; ISD = intraindividual standard deviation; RT = response time; det. = detrended; res. = residualized.

status, implying distinct post acute outcomes across executive functions based on history of concussion. In turn, past meta-analyses may have masked the diversity of executive-related outcomes when collapsing effect sizes for higher order cognitive tasks into a single neuropsychological domain. Across tasks, the noninjured to single concussion effect sizes for mean RT ranged in magnitude from zero to medium in size (range: d = 0.01 to –0.47). If averaged, the overall effect size becomes quite small (d = –0.29), conforming to similar estimates reported by past meta-analyses for executive functions (Belanger et al., 2005; Frencham et al., 2005; Rohling et al., 2011). In turn, the current results match meta-analytic conclusions for a unitary executive construct, but also demonstrate the diverse sensitivity of each executive function to past concussion.

Contrary to logistic regression results, effect size evaluations of mean RT and ISD for the go/no-go task indicated worse performance for participants reporting a single concussion than for noninjured participants; however, these measurement-based comparisons did not control for relevant variables (i.e., Block I RT, accuracy). Together, the inhibition and updating tasks did not elicit any group differences, while the frontally mediated attentional process of shifting appeared specifically sensitive at detecting group differences. The sensitivity of the shifting task may derive from its overall difficulty compared to the other two executive tasks. Notably, the global–local showed a much slower mean RT than the other two tasks, demonstrating slower performance likely due to difficulty with shifting. The n-back (i.e., only a 2-back task in the current design) and go/no-go presented fairly quick average RTs (i.e., 0.30 to 0.40 s) when compared to global–local performance (i.e., over 1.5 s). This discrepancy may indicate that the prior two tasks did not sufficiently challenge the young and otherwise cognitively healthy participants. Another possible conclusion considers the impact of fatigue on participant performance. All participants completed the global–local last in the sequence of tasks, with participants potentially experiencing some exhaustion at this point in testing; however, it remains unlikely that a brief session of cognitive testing (i.e., 45 min) would fatigue a predominantly healthy university-aged sample of participants. In turn, both inhibition and updating may be sensitive to concussion, but their respective measures did not strain these abilities enough to elicit any group differences.

Despite limitations surrounding task difficulty, the group differences in shifting performance appear consistent with two past research findings assessing attentional processes following concussion. These researchers identified similarly null IIV results alongside impairments in anterior attentional networks (Halterman et al., 2006; Sosnoff et al., 2007). Underlying these networks, the ACC is involved in executive attention (Posner & Rothbart, 2007; Posner et al., 2007) as part of the neural circuit regulating shifting processes (Miyake et al., 2000). As proposed by past researchers, “it

TABLE 6
Ordinal logistic regression results: Global–local

		Full sample				
Model	*Predictor*	*β*	*SE*	*p*	R^2	ΔR^2
Model 1	Block I accuracy	–0.455	1.04	.663	.011	
	Block I mean RT	–0.113	0.332	.734		
	Block II accuracy	–0.059	1.21	.961		
	Block II mean RT	–0.322	0.451	.475		
Model 2	Block I accuracy	–0.711	1.10	.519	.174	.163
	Block I mean RT	–0.279	0.417	.503		
	Block II accuracy	–1.91	1.54	.215		
	Block II mean RT	–1.29	0.781	.098		
	Block III accuracy	1.46	1.86	.431		
	Block III mean RT	1.52	0.520	*.004*		
Model 3 (res.)	Block I accuracy	–1.03	1.14	.369	.243	.069
	Block I mean RT	–0.395	0.444	.373		
	Block II accuracy	–2.07	1.54	.179		
	Block II mean RT	–1.64	0.914	.074		
	Block III accuracy	0.672	1.98	.734		
	Block III mean RT	2.87	1.19	*.016*		
	Block III ISD (res.)	–0.012	0.086	.194		
Model 3 (det.)	Block I accuracy	–0.920	1.13	.416	.257	.083
	Block I mean RT	–0.415	0.458	.365		
	Block II accuracy	–2.02	1.55	.193		
	Block II mean RT	–1.71	0.999	.088		
	Block III accuracy	0.683	1.96	.728		
	Block III mean RT	3.13	1.34	*.019*		
	Block III ISD (det.)	–0.135	0.097	.166		
Model 3 (raw)	Block I accuracy	–0.932	1.15	.417	.217	.043
	Block I mean RT	–0.409	0.462	.376		
	Block II accuracy	–1.99	1.57	.204		
	Block II mean RT	–1.40	0.920	.127		
	Block III accuracy	1.17	1.92	.543		
	Block III mean RT	2.61	1.19	*.029*		
	Block III ISD (raw)	–0.105	0.099	.289		

Notes. All Model 3 ΔR^2 values derive from comparisons with Model 2 R^2 values; ISD = intraindividual standard deviation; LOC = loss of consciousness; det. = detrended; res. = residualized; RT = response time. Italic values reached significance.

appears that the ACC may be particularly susceptible to injury via concussion and the damage created may take more time to resolve relative to the other attentional components localized to different regions of the brain" (Halterman et al., 2006, p. 752). Despite this proposal, event-related potential researchers have reported inconsistent findings regarding ACC functioning following mild TBI (Larson, Clayson, & Farrer, 2012; Pontifex, O'Connor, Broglio, & Hillman, 2009).

Examining error-related negativity (ERN), which is notably related to ACC functioning (Holroyd & Coles, 2002), Larson and colleagues (2012) found no group differences between non-injured and concussed participants for either their ERN or cognitive performance, whereas Pontifex and colleagues (2009) found reduced ERN amplitude linearly associated with an increased number of past concussions. In turn, although the anterior attentional network appears affected by minor head injury (Halterman et al., 2006; Sosnoff et al., 2007), the neural mechanisms underlying this relationship remain unclear. Sequentially, although past researchers have linked IIV with many frontal processes (MacDonald et al., 2006), no past findings have implicated the ACC in heightened variability, implying that the potential executive-related impairments linked to concussion may derive from neurological systems distinct from those eliciting response variability.

IIV following concussion

IIV indicators presented no unique differences across groups for any measure, aligning with many past research findings evaluating IIV post concussion. Among most studies identifying increased IIV

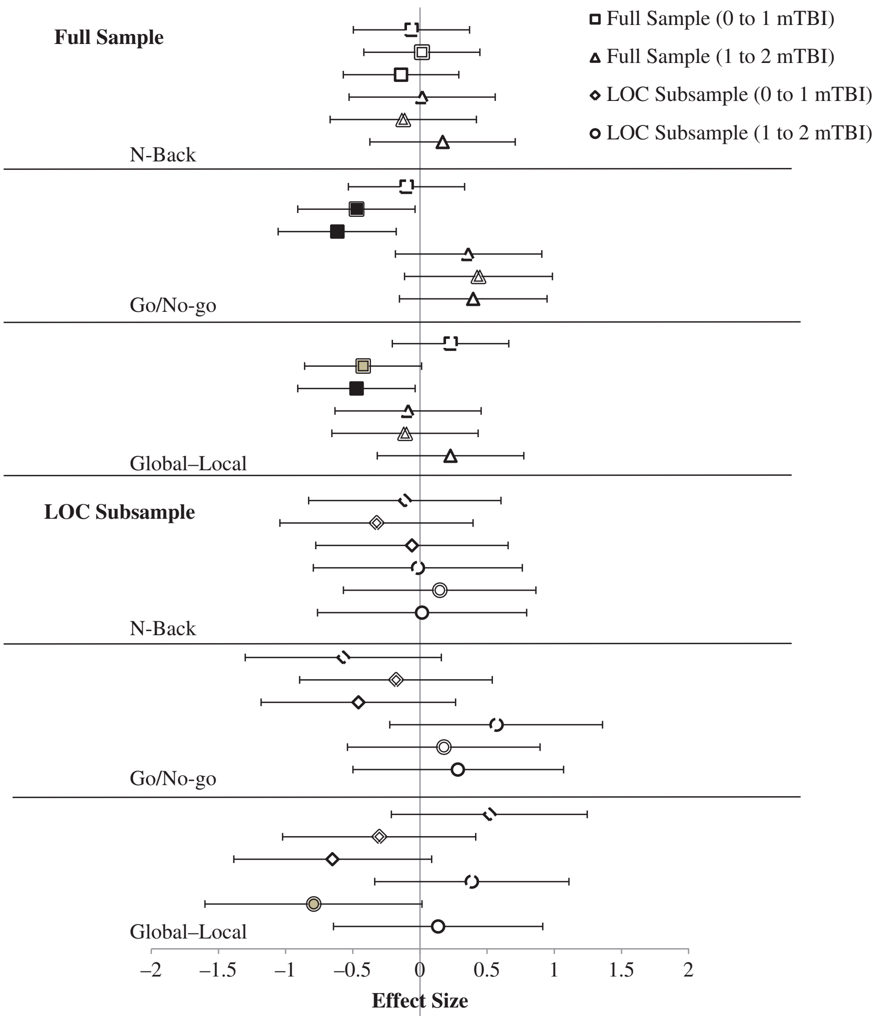

Figure 1. Effect sizes (d) for primary outcome measures with 95% confidence intervals. Negative effect sizes indicate worse performance resulting from an increased number of past concussions. Dashed marker outlines represent accuracy effect sizes, double-line marker outlines represent mean response time effect sizes, and solid marker outlines represent intra-individual standard deviation effect sizes (all ISD effect sizes derived from the multilevel modeling detrending analysis). Black-filled markers indicate effect sizes with 95% confidence intervals that do not overlap the zero demarcation, whereas gray markers indicate effect sizes that very slightly overlap the zero demarcation (<.02 units). LOC = loss of consciousness.

following concussion (Bleiberg et al., 1997; Burton et al., 2002; Makdissi et al., 2001; Stuss et al., 1989), none have analytically controlled for mean confounds, while those that did produced opposite conclusions (Halterman et al., 2006; MacFlynn et al., 1984; Sosnoff et al., 2007). Two studies proposing heightened IIV reported proportionate increases of IIV with slowing RT performances (Bleiberg et al., 1997; Makdissi et al., 2001), indicating that increased IIV likely depended on slowing RT within these samples.

Within the current sample, the single head injury group presented greater IIV during a shifting task than the noninjured participants, as demonstrated by effect size comparisons; however, this group difference provided no unique additional information beyond mean RT performance, which correlated with its ISD at .858 for the full sample. Increased variability often occurs in conjunction with worsened mean performance (Crawford & Garthwaite, 2006). In turn, “it seems that the vigilance lapses [referring to IIV] are unlikely to be a major feature in the long term recovery from minor head injury,” as posited by the first researchers evaluating post concussion variability (MacFlynn et al., 1984, p. 1330). As with trial-to-trial inconsistency, dispersion did not differentiate between concussion and control participants, as largely shown in the acute post concussion phase as well (Rabinowitz & Arnett, 2013), and, sequentially, dispersion levels for concussion patients may not differ from those of individuals without head injury, likely indicating that only more severe TBIs are linked to increased dispersion (Hill & Rohling, 2011).

Limitations and future directions

Based on study quality rankings, the top research on concussion often involves controlled prospective designs tracking athletes from preseason baselines through post concussion assessments (Comper et al., 2010). In turn, the current study appears limited through its use of retrospective reporting of concussion and open sampling of self-identified athletes. Retrospective reporting resulted in a very distal average time since injury (i.e., 38.47 months), which limits the current conclusions. As acute recovery occurs rapidly in athletes (Belanger & Vanderploeg, 2005), any impairment remaining three years post injury may be undetectable, even with very sensitive cognitive measures. In turn, although IIV presented limited value at differentiating between groups in the current study, it may present greater value among samples more proximal to their concussive events; however, many past researchers evaluating IIV much closer to injury found similarly null results (e.g., Halterman et al., 2006; Rabinowitz & Arnett, 2013; Sosnoff et al., 2007).

In addition to heterogeneous time since injury, the sampling method limits the generalizability of these findings, as the sample consisted of a homogenous group of similarly aged, active athletic participants with at least some exposure to higher education. However, the array of sports affiliations may actually improve the value of the findings. Few concussion studies have reported athletic samples with affiliations outside of American football (Dougan, Horswill, & Geffen, 2013), resulting in predominantly male sampling across the literature (Broglio & Puetz, 2008). In turn, the current sample, with multisport athletes and a female majority, likely represents a unique group in comparison to past studies. The results may generalize better to university-aged athletes unassociated with football, which represents a large portion of athletes experiencing concussion (Hootman, Dick, & Agel, 2007).

Also related to sampling, the high prevalence of LOC within the sample indicates bias in terms of self-selection, as the majority of concussions among athletes do not involve LOC (McCrory et al., 2013). In turn, when relying on self-reports of concussion, participants likely present a high false-negative rate as well, with many potentially experiencing unidentified lower grade concussions in the past. Roughly half of the participants with concussion history reported multiple past concussions. Among past studies evaluating participants with multiple concussions, rates have varied from a 0.3:1 (Wall et al., 2006) to 1.92:1 (Collie, McCrory, & Makdissi, 2006) multiple to single concussion ratio. One study reported a 1:1 ratio (De Beaumont, Brisson, Lassonde, & Jolicoeur, 2007), roughly analogous to the sample observed in the current study (i.e., 0.92:1). Consistent with the heterogeneous sampling across studies, multiple concussion prevalence in the general population remains similarly unclear. Among a sample of high-school American football players, 34.9% of concussed athletes reported experiencing more than one concussion (Langburt, Cohen, Akhthar, O'Neill, & Lee, 2001). However, rates likely differ across sports based on style of play and associated risk of head injury, with more research needed to identify the prevalence of multiple minor head injuries among both athletes and the general population.

Although many past researchers have used self-reports of concussion (e.g., Broglio et al., 2006; Bruce & Echemendia, 2009; Collie et al., 2006; Collins et al., 1999; De Beaumont et al., 2007; Iverson, Brooks, Lovell, & Collins, 2006; Wall et al., 2006), reliance on self-report decreases the diagnostic rigor of concussion, as actual times since injury and injury severity remain fairly subjective. To decrease the variability in injury grade, the LOC subsample drew effect size comparisons for a more homogenous sample, but identified no effect sizes reliably distinct from zero (i.e., only one trend for mean global–local RT), potentially due to insufficient sample size producing wider CIs. Many operational definitions for concussions have been applied by past researchers (Comper et al., 2010), with variable rigor in diagnostic criteria (Pertab et al., 2009). Ultimately though, reliance of self-report results in significant heterogeneity of concussion diagnoses, times since injury, and sports affiliations, which cumulatively limits the purity of group comparisons.

The limitations of self-report have commonly occurred with studies involving samples reporting multiple concussions (Belanger et al., 2010). In the current study, the multiple concussion group appeared particularly inconsistent and often presented better performances than control or single concussion participants. Past meta-analyses have reported the most prominent effects of repeated concussion on executive functions (Belanger et al., 2010; Belanger & Vanderploeg, 2005), while the current study found only a 5 ms RT increase from single to multiple concussion for the global–local task ($d = –0.11$). Similarly, the control group differed from the single concussion group by only 200 ms on average ($d = –0.42$). In turn, the impact of this RT difference on everyday functioning requires further investigation. As well, it appears unclear whether this observed executive deficit serves as evidence for long-term cognitive impairment or merely an artifact of preexisting group differences unidentified by the cross-sectional design.

Moving forward, future researchers must explore the diverse outcomes of executive functions prospectively from preseason baselines to post concussion assessments, ideally using multiple measures to evaluate each higher order ability. Latent in nature, factor-analytic approaches offer the best method for the examination of executive functions, quantifying executive constructs as the common variance across multiple executive-related tasks (Miyake et al., 2000). To date, no researchers have explored executive functions post concussion beyond the level of manifest variables, indicating the need for more robust factor-level approaches to accurately track these elusive cognitive abilities and identify whether executive dysfunctions underlie the persistent cognitive deficits and fatigue experienced by some individuals post concussion.

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