Journal of the Neurological Sciences 428 (2021) 117575

Contents lists available at ScienceDirect

Journal of the Neurological Sciences

journal homepage: www.elsevier.com/locate/jns

Paired cognitive flexibility task with symptom factors improves detection of sports-related concussion in high school and collegiate athletes

Amanda L. McGowan [a,*], Abigail C. Bretzin [b], Morgan Anderson [c], Matthew B. Pontifex [c], Tracey Covassin [c]

[a] Addiction, Health, and Adolescence Lab, Annenberg School for Communication, University of Pennsylvania, Philadelphia, PA, United States of America
[b] Penn Injury Science Center, Department of Biostatistics, Epidemiology and Informatics, University of Pennsylvania, Philadelphia, PA, United States of America
[c] Department of Kinesiology, Michigan State University, East Lansing, MI, United States of America

ARTICLE INFO

Keywords:
Brain concussion
Cognition
Neurocognitive testing
Reaction time
Sideline measures

ABSTRACT

Determining the sensitivity and specificity of short neurocognitive assessments to objectively detect concussion will help clinicians more confidently integrate such tools in clinical management decisions. This study quantified the sensitivity and specificity of a computerized cognitive flexibility task isolating shifts of visuospatial attention in combination with clinical symptoms acutely (< 72 h) following concussion. A total of 100 athletes (53 concussed; 47 non-injured control; 42% female) completed computerized neurocognitive testing and clinical symptom reports (Sport Concussion Assessment Tool 3rd edition: SCAT3). Separate discriminant function analyses were performed for individual, combination, and stepwise inclusion of neurocognitive and clinical symptomology assessments. Findings revealed the combination of neurocognitive outcomes (i.e., mean reaction time, response accuracy, and response accuracy cost) with clinical symptom factor scores exhibited the greatest sensitivity (95.7%) and specificity (88.7%) as well as the highest positive predictive value (95.9%) and negative predictive value (88%) relative to other approaches. Further, a stepwise approach predicting concussion status using the discriminant functions improved detection of concussion (98.2% sensitivity, 95.7% specificity, 96.4% positive predictive value, and 97.8% negative predictive value) when clinical symptom factors failed to indicate the presence of a concussion. Incorporating a cognitive flexibility task involving shifts of visuospatial attention combined with clinical symptom factor scores may improve clinical decision-making as this approach exceeds the sensitivity and specificity of widely popular neurocognitive test batteries and takes less than 10 min to administer.

1. Introduction

Sports-related concussion continues to be a growing healthcare concern, with an overall rate of 4.2 and 4.5 injuries per 10,000 athlete exposures in high school and college athletes, respectively [1,2]. Health professionals are under increased scrutiny to accurately detect and predict length of recovery following concussive injuries. Thus, experts recommend using computerized neurocognitive testing as part of a multifaceted approach given the high degree of sensitivity (81.9%) and specificity (89.4%) in differentiating between concussed and noninjured athletes [3–9]. However, an emerging body of research has indicated that these neurocognitive test batteries may fail to capture concussion-related impairments in aspects of cognition, such as cognitive flexibility, which show persistent impairments well beyond the return-to-play period [10–12]. Another limitation is that widely popular neurocognitive test batteries used to assess concussion take nearly 30 min to administer, making them difficult to administer on the sideline. Thus, it is plausible that athletes are returned to full sport participation when still experiencing cognitive decrements not identified by widely popular neurocognitive test batteries despite no longer exhibiting symptoms. However, an emerging body of literature has demonstrated that incorporating brief 5-min tasks assessing cognitive flexibility differentiate between concussed and noninjured control athletes within 72 h following injury and up to one month later [10–12]. A critical limitation to the clinical utility of these easily administered cognitive flexibility tasks is a lack of evidence demonstrating their sensitivity and specificity in detecting concussion alone and when combined with currently employed clinical symptomology assessments.

* Corresponding author at: 3620 Walnut St., Annenberg School for Communication, University of Pennsylvania, Philadelphia, PA 19104, United States of America.
E-mail address: amanda.mcgowan@asc.upenn.edu (A.L. McGowan).

https://doi.org/10.1016/j.jns.2021.117575
Received 19 January 2021; Received in revised form 24 June 2021; Accepted 8 July 2021
Available online 10 July 2021

Cognitive flexibility broadly encompasses the capacity to shift attention or change behavioral goals [13]. This capacity is a component of cognitive control and is integral for maintaining control over one's actions in the face of dynamic, ever-changing environmental demands [14]. Cognitive flexibility can be dissociated into two distinct forms: perceptual-based and contextual rule-based [13]. Perceptual-based cognitive flexibility involves shifts of visuospatial attention, which are functionally distinct from shifts in contextual rule-based cognitive flexibility, which involves changing stimulus-response mappings [13]. Importantly, athletes must meet the demands of competitive sports environments by shifting their visuospatial attention to contextual cues to execute appropriate behavioral responses in the face of a rapidly changing environment, thereby relying upon perceptual-based cognitive flexibility. In this context, then, concussion-related impairments in shifting visuospatial attention may impact athletes' sports performance. Presently used neurocognitive assessments do not incorporate perceptual-based cognitive flexibility paradigms even though impairments have been observed in the acute (i.e., within 72 h) and protracted (i.e., one month) phases of recovery following concussive injury using such assessments [12]. Furthermore, present test batteries assess cognitive flexibility as a unitary construct, conflating the two functionally distinct components of cognitive flexibility even though these subcomponents are subserved by distinct neural networks. Changing stimulus-response mappings (contextual-based) relies upon activation of the dorsolateral prefrontal cortex and shifting attentional focus (perceptual-based) relies upon activation of the superior parietal cortex [13]. Although there is some evidence to suggest that the dorsolateral prefrontal cortex is sensitive to concussion [15], a preponderance of evidence has demonstrated an association between concussion and visuospatial deficits [16–21]. Indeed, impairments in shifting visuospatial attention alongside hypoactivation of the superior parietal cortex have been observed up to a month following concussion [18]. Such findings provide compelling evidence to suggest that cognitive flexibility tasks isolating visuospatial attention may enhance concussion detection and management, thus warranting investigation of the sensitivity and specificity of such cognitive flexibility tasks following concussive injury. Understanding the sensitivity and specificity of a perceptual-based cognitive flexibility task in detecting concussion will advance the clinical utility of such assessments so that neurocognitive test batteries may be better equipped to detect neurocognitive profiles that predict a protracted recovery.

An open question is understanding the sensitivity and specificity of cognitive flexibility paradigms isolating shifts of visuospatial attention to detect sports-related concussion decrements in cognition. Although these tasks have differentiated between concussed and noninjured control athletes [10–12], the sensitivity and specificity to which they are able to identify concussion within the acute stage of injury is unclear. For instance, McGowan et al. [12] demonstrated that an odd-man-out task-switching paradigm observed concussion-related impairments in the perceptual-based cognitive flexibility in the acute and protracted (about a month following injury) periods of recovery whereas only acute impairments were observed in the contextual rule-based task condition. Although such findings provide preliminary evidence suggesting that a perceptual-based cognitive flexibility task can detect acute and persistent alterations in visuospatial attention, the sensitivity and specificity of this task remain unknown. Since widely popular neurocognitive test batteries may be limited in their utility beyond the acute recovery period, incorporating perceptual-based cognitive flexibility tasks into a multifaceted approach to detect concussion may be one way to track cognitive recovery well beyond the return-to-play period.

Other neurocognitive tests that evaluate the immediate mental status following a concussive injury, such as alterations in attention or working memory, are widely used to detect, manage, and assess concussion. Several methods exist for evaluating the cognitive function of a concussed athlete. Although these test batteries differentiate between concussed and noninjured control athletes immediately following injury, there is a growing body of evidence showing that athletes return to baseline performance within 10 days following injury [22], dampening enthusiasm for the long-term clinical utility of such assessments after athletes return to play. However, tasks isolating precise cognitive domains (e.g., cognitive flexibility) not assessed by popular post-concussion test batteries (or inaccurately treated as a unitary construct) have shown persistent impairments up to one month following injury [10–12,23], even after all other signs and symptoms have resolved. Thus, experts tout using a multifaceted approach to guide the identification and management of concussion [9,24,25]. Another advantage to using a cognitive flexibility task isolating visuospatial attention over widely popular neurocognitive test batteries is the length of time and resources required. The cognitive flexibility task takes just 5 min to administer and could easily be completed on a mobile device (using touch-screen responses) whereas Immediate Post- Concussion Assessment and Cognitive Testing (ImPACT) takes approximately 30 min and requires the use of a tablet or laptop with a mouse. Combining the cognitive flexibility task with clinical symptomology as part of a multi-faceted approach, such as the Sport Concussion Assessment Tool (SCAT), would take a total of less than 10 min (6 min neurocognitive +1 min symptoms), which is much shorter than currently employed sideline neurocognitive and clinical symptomology batteries. The paired cognitive flexibility task with SCAT could easily be employed on a mobile device application using touch screen responses for both the neurocognitive task measure and clinical symptom report.

Beyond using neurocognitive assessment, the multifaceted approach also involves using symptom reporting due to its direct relationship to activities of daily living. Interpreting post-concussion symptom reporting may be difficult for health care professionals given that post-concussion symptoms vary between athletes [26,27]. Therefore, researchers have utilized factor analytic approaches to identify patterns in symptom reporting [28–33]. Utilizing symptom factors may aid health care professionals in conceptualizing symptomology and identifying clinical profiles [34] and targeted treatment approaches [35]. In addition, symptom factors may be used to identify athletes at risk for prolonged recovery [34,36]. The SCAT contains a widely endorsed symptom inventory, with 82% of athletic trainers reportedly using this assessment in their clinical practice [37]. In addition, the SCAT is most clinically useful within the acute phase of concussion [38] and is readily available for athletic trainers. A recent investigation revealed a 3-factor solution in acutely concussed athletes for the SCAT: migraine-fatigue, affective, and cognitive-ocular [35]. Although widely popular neurocognitive test batteries typically incorporate some form of clinical symptom assessment tool, which has been shown to enhance sensitivity and specificity of detecting a concussion, the combination of neurocognitive tests with the SCAT three-factor symptom scores has yet to be tested and would provide insight into a much shorter sideline assessment that would only require a mobile device, which many sports medicine professionals have readily available. Moreover, pairing the cognitive flexibility task with symptom factor approach has the potential to identify clinical profiles at risk for prolonged recovery as both assessments have demonstrated sports-related concussion impairments beyond the acute period [12,34,36].

The aim of the current study was to determine the sensitivity and specificity of a cognitive flexibility task isolating visuospatial attention previously shown to exhibit protracted recovery following injury in the acute phase (i.e., within 72 h) of injury [12]. We extend the current understanding of using a multifaceted approach to detect concussion in multiple ways. First, we assess the sensitivity and specificity of a cognitive flexibility task to identify concussion using neurocognitive variables (e.g., reaction time, response accuracy) alone. Second, we examine the extent to which sensitivity and specificity is improved by combining neurocognitive variables with commonly used clinical symptoms from the SCAT. Third, we test the sensitivity and specificity of the task by combining neurocognitive variables with a novel SCAT symptom 3-factor structure [35].

2. Method

2.1. Participants

The concussion group consisted of 53 athletes ($M = 18.2 \pm 2.4$ years, 23 females, 11.3% nonwhite; 67.9% collegiate) with a sports-related concussion identified by a specialized health professional (certified athletic trainer/team physician). Concussion was defined as altered mental status resulting in short-term impairments caused by a blow to the head or body, leading to the presentation of one or more clinical symptoms [24]. A group of 47 athletes served as noninjured controls ($M = 17.7 \pm 2.3$ years, 19 females, 14.9% nonwhite; 55.3% collegiate). Participants were recruited from 2 high schools and 3 colleges in the mid-Michigan area. The sample reported on in the present manuscript is independent from the sample reported on in McGowan et al. [12] Athletic trainers or team physicians referred concussed athletes to the research team within 72 h of sustaining a sport-related concussion. All participants were free of neurological disease (i.e., ADHD) or physical disabilities, indicated normal or corrected-to-normal vision, did not report a loss of consciousness associated with their concussion injury or a history of more severe traumatic brain injury, or hospital admission due to either head injury or collateral injuries for >24 h. One participant in the concussed group self-reported a history of a learning disability; however, results reported in the manuscript were unchanged following removal so this individual was retained in final analyses.

2.2. Procedure

In accordance with the Michigan State University Human Research Protection Program Institutional Review Board, individuals older than 18 years provided informed consent, guardians provided informed consent for participants younger than age 18, and assent was provided by participants younger than age 18. All testing took place in a quiet setting (e.g., empty classroom, laboratory, or medical office) in which the athlete was seated in front of a touchscreen laptop and completed the task individually with only the experimenter present. Athletes with sports-related concussion participated in testing within 72 h of their injury (average time between injury and testing $M = 45.12 \pm 24$) because this time period remains consistent with a robust body of literature demonstrating the signs and symptoms of a concussion occurring within the first 24–72 h following injury as well as being a reasonable time frame for athletic trainers or team physicians to contact the research team to assess the athlete for study eligibility. Athletes were asked to complete a health and demographics screening questionnaire including the Sport Concussion Assessment Tool 3rd edition (SCAT) [38] and then were asked to complete the neurocognitive task on a laptop. Athletes were provided task instruction (emphasizing accuracy) and practice trials prior to the start of experimental trials.

2.3. Neurocognitive task

2.3.1. Perceptual cognitive flexibility task

Athletes completed a switch task using an odd-man-out paradigm [12,13] to determine impairments in shifting visuospatial attention (perceptual-based cognitive flexibility) following sports-related concussion. All stimuli were presented focally on a black background for 2500 ms (or until a response occurred) with an inter-stimulus interval of 1000 ms. The average duration of the task was 346.9 s (5.8 min). Participants viewed instructions depicting the letter and shape trials with examples of correct responses on the laptop alongside verbal instructions from a trained experimenter. Additionally, the button-response mapping cues were visible on the screen during the task to maintain consistency with existing clinically-relevant neurocognitive test batteries and to reduce working-memory load. The button-response cues became increasingly translucent throughout the practice trials to encourage participants to encode the stimulus-response associations. During the experimental trials, the button-response mapping cues were 60% transparent (40% opaque) so that if participants lost the stimulus-response pairings within working memory, they could retrieve them, but the button-response mapping cues did not draw attention away from the primary symbol arrays.

Experimenters explained the task instructions to participants using 3 trials manually advanced by the experimenter in which athletes' responses were not recorded. This approach ensured athletes understood task instructions prior to completing 27 practice trials that gradually increased in speed, so athletes became familiar with the task and the stimulus-response mappings. Following the 30 practice trials in total, athletes completed one block of 95 experimental trials. This number of trials ensures that reliable reaction time could be obtained using at minimum 47 trials assuming 50% accuracy, which surpasses the recommended 30 trials to obtain reliable reaction time [39]. The task consisted of equiprobable nonswitch trials (in which perceptual cue remained the same as the preceding trial) and switch trials (in which the perceptual cue differed from the preceding trial). In the present task, nonswitch trials were when the target perceptual cues were letters followed by letters or shapes followed by shapes, whereas switch trials were when the target perceptual cues changed from letters to shapes or from shapes to letters (see Fig. 1). The task engages perceptual-based cognitive flexibility as it involves the ability to flexibly reorient visuospatial attention, which is distinct from other types of cognitive flexibility involved in flexibly adapting to changes in goal-related information (e.g., switching button-response mappings or contextual-based) [13]. A more detailed description of the task is provided in McGowan et al. [12] This task results in a number of variables of interest, including mean reaction time (ms), response accuracy (% correct), and switch cost of both reaction time and response accuracy. Switch cost is calculated by subtracting the nonswitch (easy trials) outcome from the switch (difficult trials) outcome (e.g., Switch mean reaction time – Nonswitch trial mean reaction time). The magnitude of switch cost is greater when performance on switch trials (difficult) is worse than performance on nonswitch (easy) trials. Although further research is necessary to determine the psychometric properties of these perceptual-based cognitive flexibility assessments, it is important to point out from a construct validity perspective that the current paradigm not only conceptually aligns with the definition of cognitive flexibility but also has demonstrated reliance upon neural networks that can be dissociated from those underlying contextual rule-based cognitive flexibility [13]. Indeed, existing task-switching assessments treat cognitive flexibility as a unitary construct, failing the first and most critical criteria for determining construct validity.

2.4. Sport Concussion Assessment Tool (SCAT) symptom scale

The symptom scale from the third edition of the SCAT is a subjective assessment of 22 symptoms on a scale of severity from 0 (none) to 6 (severe), providing an index of severity (maximum possible total symptom severity = 132) [24]. The entire SCAT takes about 10 min to complete; however, the symptom report section, which was the only section of the SCAT used in the present study, takes approximately 1 min to complete. The current study used total symptom and total symptom severity as outcome measures for the SCAT. Recent evidence [35] suggests that three symptom factors emerge as significant during the acute post-concussion period: migraine-fatigue, affective, and cognitive-ocular. The SCAT items that load onto each of these factor scores are migraine-fatigue (headache, pressure in head, sensitivity to light, sensitivity to noise, and don't feel right; maximum total symptoms = 5; maximum total symptom severity = 30), affective (more emotional, irritability, sadness, and nervous or anxious; maximum total symptoms = 4; maximum total symptom severity = 24), and cognitive-ocular (blurred vision, balance problems, difficulty remembering, and confusion; maximum total symptoms = 4; maximum total symptom severity = 24). The current study used total symptoms and total symptom severity

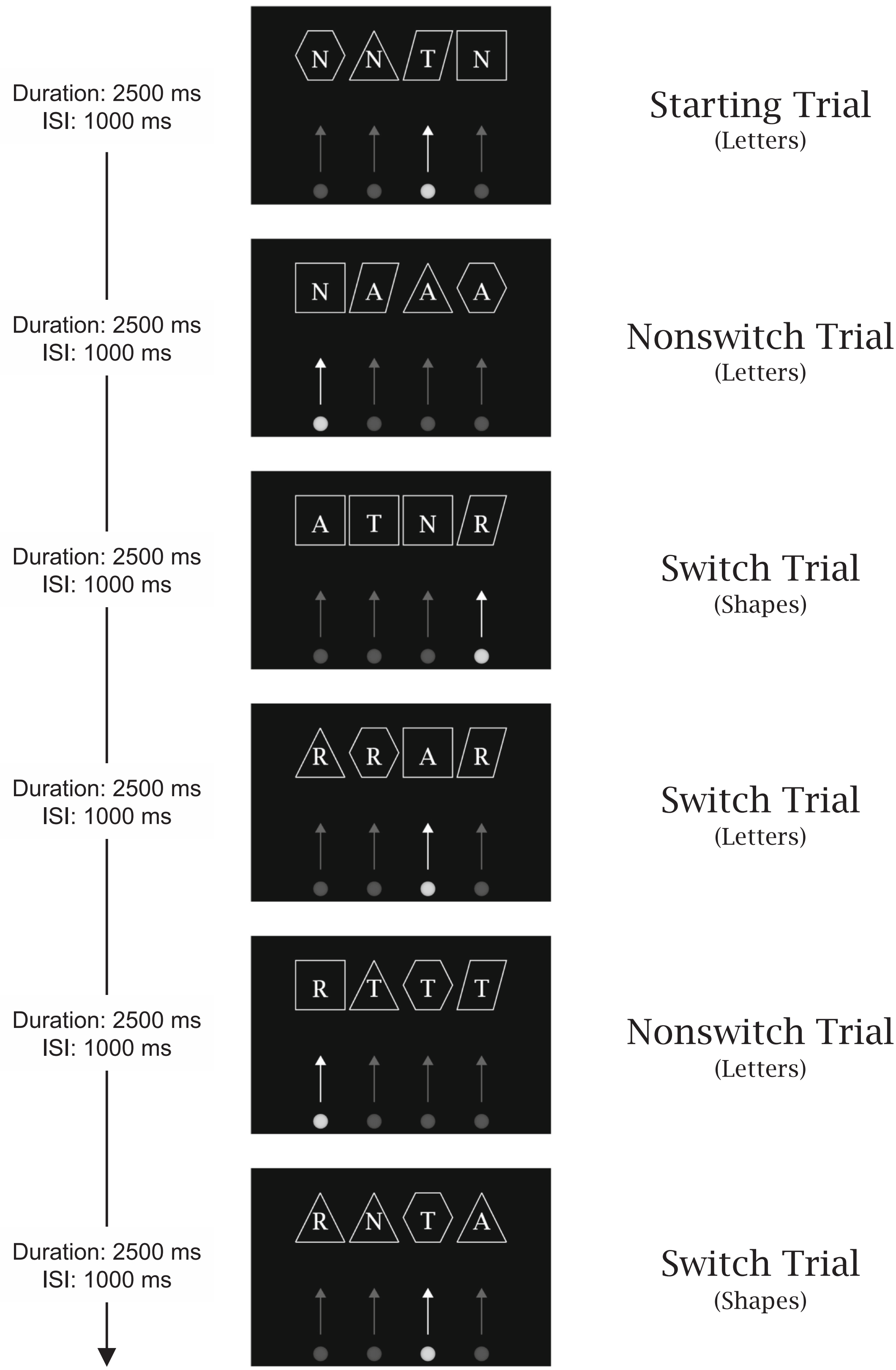

Fig. 1. Illustration of the perceptual-based cognitive flexibility task. For reference, the correct response to each stimulus is highlighted. ISI = interstimulus interval.

within each factor consistent with prior work identifying symptom factors as clinically useful in discriminating concussed athletes from noninjured control athletes and providing more accuracy than the total symptom scores [40].

2.5. Statistical analysis

Demographic characteristics were analyzed using Pearson's chi-square tests (sex, nonwhite, contact sport) and nonparametric Mann-Whitney *U* tests (age and number of previous concussions) since these variables violated assumptions of normal distribution, $W's \geq 0.58$, $p's \leq 0.002$. Overall differences between concussion and noninjured control groups on reaction time and response accuracy were analyzed using a 2 (Group: concussion, noninjured control) × 2 (Congruency: nonswitch, switch) univariate repeated measures ANOVA. SCAT outcomes (i.e., SCAT total symptoms, SCAT total symptom severity) were examined using nonparametric Mann-Whitney *U* tests because variables showed evidence of skewed distribution on the Shapiro-Wilk normality test (W's ≤ 0.95, $p's \leq 0.02$). Holm-Bonferroni corrections were applied to control for multiple comparisons. Analyses of group differences were performed using the stats [41] and ez [42] packages in R Version 3.6.2 [41]. Given a sample size of 100 participants and a beta of 0.20 (i.e., 80% power), the present research design theoretically had sufficient sensitivity to detect *t*-test differences between concussion and noninjured control groups exceeding $d = 0.57$ (with a two-sided alpha) as computed using G*Power 3.1.2 [43]. Although mean reaction time, switch response accuracy, and response accuracy failed to meet the assumption of multivariate normality within each group using Q-Q plots and Shapiro-Wilk tests [44], all findings remained unchanged following transformation of the data (square root, log, inverse rank). Thus, the results presented below reflect use of the raw data. Discriminant function analyses were then performed in SPSS (version 26) with the neurocognitive outcomes that detected group differences (mean reaction time, response accuracy, response accuracy cost), with the SCAT total scores (SCAT total symptom score, SCAT total symptom severity), and with the SCAT factor scores (migraine total, migraine total symptom severity, affective total, affective total symptom severity, cognitive-ocular total, cognitive-ocular total symptom severity) separately, combined, and using a stepwise approach. Classification matrix, sensitivity, and specificity were then assessed for each of the 4 discriminant function analyses (neurocognitive, SCAT total, SCAT factor, neurocognitive + SCAT total, neurocognitive + SCAT factor). Discriminant function equations are provided to allow clinicians to use the combined neurocognitive and symptom factor approach to detect concussion in their own practice.

To complement discriminant analyses, we calculated likelihood ratios, which have the advantage of equally weighting sensitivity and specificity and therefore are less dependent on the proportion of athletes with and without concussion in the sample, thus facilitating comparison across studies. The positive likelihood ratio is calculated as [sensitivity/(100 − specificity)] and the negative likelihood ratio is calculated as [(100 − sensitivity)/specificity]. The positive likelihood ratio is interpreted as the odds of detecting the presence of a concussion relative to the odds of not detecting the presence of a concussion. The negative likelihood ratio can be interpreted as the change in odds of detecting a concussion in athletes without a concussion. The change is in the form of a ratio, with values <1 decreasing the probability of a positive result and values >1 increasing the probability of the injury (lower values are preferred for a negative test result). For example, a negative likelihood ratio of 0.1 would indicate a 10-fold decrease in the odds of detecting a concussion in athletes without a concussion. To ease interpretation of the negative likelihood ratio, these values are interpreted as an approximate change in probability (%) using set clinical thresholds [45].

3. Results

Demographic information for all participants is displayed in Table 1. Mann-Whitney *U* tests did not reveal any significant differences between the concussion and noninjured control groups for age or number of previous concussions ($U's \geq 1013$, $Z's \leq 1.8$, $p's \geq 0.08$, $r's \leq 0.18$). Moreover, groups did not differ on the proportion of athletes identifying as female or nonwhite ($X^2(1)'s \geq 0.06$, $p's \geq 0.8$). However, a greater proportion of participants in the concussion group reported playing contact sports during the season in which data collection occurred ($X^2(1)'s = 30.3$, $p < 0.001$). Contact sports athletes reported included basketball ($n = 8$), broomball ($n = 1$), football ($n = 21$), lacrosse ($n = 5$), cheerleading ($n = 5$), soccer ($n = 9$), and wrestling ($n = 3$). Sports were classified as contact and noncontact consistent with the American Academy of Pediatrics Council on Sports Medicine and Fitness [46,47].

Table 1
Demographic characteristics as a function of group (± SD).

Measure	Concussion	Noninjured control	p
N	53 (23 females)	47 (19 females)	0.76
Age (years)	18.2 ± 2.4 [range: 14–22]	17.7 ± 2.3 [range: 14–22]	0.25
Nonwhite	11.3%	14.9%	0.8
Previous Concussions (n)	15	4	0.08
Time Since Last Concussion (years)	2.3 ± 1.1	2.3 ± 1	1
Contact Sport	79.2%	23.4%	< 0.001*

Note: p-values reflect group differences as compared using Mann-Whitney U tests (age, previous concussions, time since last concussion) and chi-square (sex, nonwhite, contact sport). * denotes $p < 0.05$.

3.1. Cognitive task performance

Analysis of neurocognitive outcomes revealed a Group × Congruency interaction for response accuracy (F (1,97) = 5.3, $p = 0.024$, $f^2 < 0.01$ [95% CI: 0 to 0.02]). Post-hoc decomposition of this interaction revealed that concussion athletes were less accurate (73.6 ± 21%) than noninjured controls (83.4 ± 14.2%) only on switch trials ($t(97) = 2.7$, $p = 0.009$, $d_s = 0.54$ [95% CI: 0.13 to 0.94]). Analysis of response accuracy cost revealed a main effect of Group ($F(1, 97) = 5.3$, $p = 0.024$, $f^2 = 0.05$ [95% CI: 0 to 0.15] such that concussion athletes exhibited a greater switch cost (−4.8 ± 8.2) than noninjured controls (−1.6 ± 5.4), $t(90.4) = 2.4$, $p = 0.02$, $d_s = 0.48$ [95% CI: 0.07 to 0.88]. However, there were no main effects for reaction time cost, $F(1, 97) = 0.4$, $p = 0.52$, $f^2 < 0.01$ [95% CI: 0 to 0.03].

3.2. Clinical outcomes

3.2.1. SCAT total scores

Analysis of SCAT clinical outcomes revealed greater total symptoms and total symptom severity reported by concussion relative to noninjured control athletes ($U's \geq 155$, $Z's \geq 7.4$, $p's < 0.001$, $r's \geq 0.72$, see Table 2).

3.2.2. SCAT factor scores

Analysis of SCAT factor scores revealed both greater total symptoms and symptom severity for migraine, affective, and cognitive-ocular symptom severity scores by concussion relative to noninjured control athletes ($U's \geq 123$, $Z's \geq 3.7$, $p's \leq 0.001$, $r's \geq 0.37$, see Table 2).

3.3. Discriminant analyses

All discriminant function analyses were significant ($p's \leq 0.037$). The neurocognitive + SCAT factor function outperformed all functions and neurocognitive alone performed the worst (see Table 3). The stepwise approach further improved the discriminant performance of the combined neurocognitive and symptom factor approach (see Table 3). However, implementing the neurocognitive + SCAT total in a stepwise fashion deteriorated discriminant ability. We provide eqs. 1–5 for each of the discriminant function analyses. Eqs. 2–5 were used in the stepwise approaches.

3.3.1. Neurocognitive

The equation representing the discriminant function using neurocognitive variables alone is:

$$\hat{y} = .504 + -.002RT + -.084ACC + .120ACC_{cost} \quad (1)$$

Table 2
Means and standard deviations of variables as a function of group.

Measure	Concussion (n = 53)	Noninjured control (n = 47)	p
Neurocognitive			
Reaction time (ms)	1342.9 ± 205.2	1262.2 ± 156.6	0.032*
Reaction time cost (ms)	196.6 ± 124.3	212.7 ± 121.5	0.52
Response accuracy (% correct)	76 ± 20.3	84.2 ± 14.5	0.026*
Response accuracy cost (% correct)	- 4.8 ± 8.2	−1.6 ± 5.4	0.02*
SCAT Total			
Total symptoms	12.2 ± 5.6	1.8 ± 2.7	< 0.001*
Total symptom severity	27.7 ± 19.6	2.9 ± 4.7	< 0.001*
SCAT Factor			
Migraine total	3.7 ± 1.4	0.4 ± 1	< 0.001*
Migraine symptom severity	8.6 ± 5.7	0.5 ± 1.3	< 0.001*
Affective total	1.4 ± 1.4	0.4 ± 1.2	< 0.001*
Affective symptom severity	3.2 ± 4.1	0.7 ± 1.8	< 0.001*
Cognitive-ocular total	1.8 ± 1.5	0.3 ± 0.7	< 0.001*
Cognitive-ocular symptom severity	3.4 ± 3.9	0.3 ± 0.6	< 0.001*

Note: Mean performance was collapsed across switch and nonswitch trials for the cognitive flexibility task. Cost represents the additional cost associated with greater interference of the switch trials relative to the nonswitch trials (switch trials – nonswitch trials). * denotes $p < 0.05$ for omnibus group differences.

3.3.2. SCAT total

The equation representing the discriminant function using the symptom total scores alone is:

$$\hat{y} = -1.74 + -.036SCAT_{TotalSS} + .318SCAT_{Total} \quad (2)$$

3.3.3. SCAT factor

The equation representing the discriminant function using the symptom factor scores alone is:

$$\hat{y} = -1.844 + .006CognitiveOcular_{TotalSS} + .220CognitiveOcular_{Total} + -.028Affective_{TotalSS} + -.017Affective_{Total} + -.047Migraine_{TotalSS} + .910Migraine_{Total} \quad (3)$$

3.3.4. Neurocognitive + SCAT total

The equation representing the discriminant function using the neurocognitive variables combined with symptom total scores is:

$$\hat{y} = -1.607 + .001RT + -.012ACC + .003ACC_{cost} + -.038SCAT_{TotalSS} + .317SCAT_{Total} \quad (4)$$

3.3.5. Neurocognitive + SCAT factor

The equation representing the discriminant function using the neurocognitive variables combined with symptom factor scores is:

$$\hat{y} = -1.714 + .001RT + -.004ACC + -.005ACC_{cost} + .038CognitiveOcular_{TotalSS} + .119CognitiveOcular_{Total} + -.049Affective_{TotalSS} + .018Affective_{Total} + -.051Migraine_{TotalSS} + .920Migraine_{Total} \quad (5)$$

where RT is the mean reaction time, ACC is the response accuracy, ACC_{cost} is the response accuracy cost, $SCAT_{TotalSS}$ is the total symptom severity on the SCAT, $SCAT_{Total}$ is the total number of symptoms on the SCAT, $CognitiveOcular_{TotalSS}$ is the total symptom severity for the cognitive ocular factor score, $CognitiveOcular_{Total}$ is the total number of symptoms for the cognitive ocular factor score, $Affective_{TotalSS}$ is the total symptom severity for the affective factor score, $Affective_{Total}$ is the total

Table 3
Significance of the discriminant function predicting concussion and discriminating power of each function.

Function	Wilks Lambda	X^2	P	Eigenvalue	Canonical correlation	Sensitivity (%)	Specificity (%)	Overall classification rate (%)	Positive predictive value	Negative predictive value	Positive likelihood ratio	Negative likelihood ratio
Neurocognitive	0.92	8.47	0.037*	0.09	0.29	70.2	54.7	62	67.4	57.9	1.6	0.54
SCAT total	0.40	87.94	< 0.001*	1.48	0.77	91.5	83	87	91.7	82.7	5.4	0.10
SCAT factor	0.31	110.04	< 0.001*	2.22	0.83	93.5	83	87.9	93.6	82.7	5.5	0.08
Combined (neurocognitive + SCAT total)	0.40	88.61	< 0.001*	1.53	0.78	93.6	81.1	87	93.5	81.5	5.0	0.08
Combined (neurocognitive + SCAT factor)	0.30	110.85	< 0.001*	2.32	0.84	95.7	88.7	91.9	95.9	88	8.5	0.05
Stepwise Approach using SCAT total and only Combined (neurocognitive + SCAT total) if SCAT total indicates 'not concussed'	–	–	–	–	–	81.1	85.1	83.3	81.1	85.1	5.4	0.22
Stepwise Approach using SCAT factor and only Combined (neurocognitive + SCAT factor) if SCAT factor indicates 'not concussed'	–	–	–	–	–	98.2	95.7	97.1	96.4	97.8	23.1	0.02

Note. Stepwise approaches were calculated by using the respective discriminant function equations. In step 1, the clinical symptom equation (SCAT total or SCAT factor) was used to predict concussion status from athlete scores. In step 2, the combined (neurocognitive + clinical symptoms) approach was used to predict concussion status only for athletes for whom symptom factors (step 1) failed to indicate the presence of a concussion. Negative likelihood ratios can be interpreted along the scale that the power to rule out <0.1 is greater than 45% decrease (large), 0.1–0.2 is approximately 30% (moderate), and 0.2–0.5 is approximately 15% (small) decrease in odds of misidentifying a concussion in someone without a concussion [45]. * denotes $p < 0.05$.

number of symptoms for the affective factor score, $Migraine_{TotalSS}$ is the total symptom severity for the migraine-fatigue factor score, and $Migraine_{Total}$ is the total number of symptoms for the migraine-fatigue factor score. When using discriminant function equations, a threshold of 0.5 is used even though the predicted group membership is 0 (noninjured) or 1 (concussed). If predicted performance ($\hat{y}$) is less than the threshold (< 0.5), the athlete is assigned to "noninjured group" and if ($\hat{y}$) is greater than the threshold (> 0.5), the athlete is assigned to the "concussion group".

3.4. Likelihood ratios

Positive likelihood ratio of the combined neurocognitive and SCAT symptom factor approach indicated that a concussion is detected 8.5 times as often as not detecting a concussion. Negative likelihood ratio of the combined neurocognitive and SCAT symptom factor indicated a 5-fold decrease in the odds of misidentifying a concussion in athletes without a concussion, which can be interpreted as more than 45% decrease in odds of misidentifying a concussion in an athlete who does not have a concussion.

3.5. Exploratory analyses

Prior work has demonstrated persistent deficits in cognitive flexibility following sports-related concussion [10–12]. Although these analyses are likely underpowered given that $n = 19$ athletes in the present sample reported having sustained a prior concussion, these data provide preliminary support to further investigate the persistent deficits in visuospatial attention observed following repetitive concussive injuries. Because a larger proportion of athletes in the concussion group participated in contact sports during the season in which data collection occurred, we addressed the question of the relationships of potential exposure to subconcussive impacts on task performance using exploratory linear regressions. Analyses revealed no significant associations between task performance and sport group (contact/noncontact) or having sustained a prior concussion (p's ≥ 0.08).

4. Discussion

The aim of the present study was to evaluate the sensitivity and specificity of a perceptual-based cognitive flexibility task in detecting concussion in the acute period (i.e., within 72 h) following injury. Replicating prior work by McGowan et al. [12] in an independent sample, behavioral task performance indices discriminating between concussed and noninjured control athletes included mean reaction time, response accuracy, and response accuracy cost. The findings from the current study suggest that combining neurocognitive outcomes with SCAT symptom factor scores exhibited the highest sensitivity (95.7%), specificity (88.7%), overall classification rate (91.9%), positive predictive value (95.9%), and negative predictive value (88%)—outperforming other individual and combinations of neurocognitive and SCAT symptom approaches. Furthermore, a stepwise approach using cognitive flexibility task performance if SCAT symptom factor scores alone failed to detect a concussion outperformed all other approaches exhibiting 98.2% sensitivity, 95.7% specificity, 97.1% overall classification rate, 96.4% positive predictive value, and 97.8% negative predictive value. Collectively, these findings suggest that pairing cognitive flexibility tasks relying upon shifts of visuospatial attention with symptom reports has the sensitivity and specificity to detect sports-related concussion within 72 h following injury. These findings also suggest that such an approach would take less time (less than 10 min) than current assessment batteries pairing neurocognitive assessment with symptom scales ($\geq$ 30 min).

Importantly, the performance of the combined cognitive flexibility and SCAT factor scores exceeds the widely-used ImPACT (83–95% sensitivity and 75–83% specificity) [8,48,49] and CogSport/Axon (69% sensitivity and 91% specificity) [50] test batteries when testing the discriminant ability of each neurocognitive test combined with their respective symptom inventories. Likelihood ratios indicate that the combined cognitive flexibility task and SCAT symptom factor assessment detects a concussion 8.5 times more often than not detecting a concussion and has a more than 45% decrease in the odds of detecting a concussion in an athlete without a concussion. The combined cognitive flexibility task and symptom factors outperforms currently used concussion assessments. For example, positive and negative likelihood ratios range from 3.32 to 5.59 and 0.06 to 0.23, on ImPACT, respectively; suggesting a 6- to 34- fold increase in the odds of detecting a concussion in athletes without a concussion or ~ 30% decrease in odds of detecting a concussion in athlete without concussion) [8,48]. Previous reports using CogSport reported positive and negative likelihood ratios as 7.7 and 0.34, respectively, when combined with clinical symptoms, suggesting a 34-fold increase in the odds of detecting a concussion in athletes without concussion or about 25% decrease in odds of detecting a concussion in athlete without concussion [50]. The combined cognitive flexibility and symptom factors assessment has up to 5 times higher odds of detecting a concussion and has up to 20% greater decrease in the odds of detecting a concussion in athletes without concussion relative to currently used assessments. Taken together, the present findings indicate that the combined cognitive flexibility and symptom factor assessment outperforms currently used assessments in detecting a concussion, and requires less specialized equipment (e.g., mouse) and shorter administration time.

The current study demonstrates that incorporating computerized assessments of cognitive flexibility is both a sensitive and specific instrument for the assessment of neurocognitive sequelae of concussion, which is superior to present neurocognitive assessments, at least relative to noninjured control athletes. Our results show that neurocognitive outcomes on a cognitive flexibility task provides post-injury cognitive data that can assist a clinician in detecting sports-related concussion. Using the neurocognitive data provided by the cognitive task alone, 62% of cases were correctly classified. Previous researchers classified 82% of concussed participants and 89% of control participants correctly at a similar acute injury interval; however, prior approaches included composites for processing speed, visual memory, and impulse control in addition to the post-concussion symptom checklist and took 30–40 min to administer [8]. A limitation to the aforementioned neurocognitive test battery, however, is that it predominantly relies upon contextual rule-based cognitive flexibility demands without concurrently taxing visuospatial attention, which is appropriately assessed in the current study using a perceptual-based task. Accordingly, these differences in cognitive tasks may explain why current test batteries fail to detect concussion-related impairments in cognitive function beyond the acute period [51]. Further, Sicard et al. [52] noted the importance of analyzing raw scores to identify subtle, but lasting cognitive impairments following concussion on tasks of higher-order cognition. In line with this supposition, the cognitive flexibility task employed in the present study uses raw neurocognitive variables unlike widely popular test batteries that provide composite scores. Thus, it is plausible that incorporating assessments of cognitive flexibility into currently employed neurocognitive testing would be feasible and potentially increase clinical utility of neurocognitive test batteries. Alternatively, if the cognitive flexibility task is not incorporated into widely popular test batteries, using the perceptual-based task in combination with the SCAT could easily be implemented on a mobile device using touchscreen responses, taking less than 10 min to administer (6 min neurocognitive task +1 min symptom report). Although the present study used keyboard responses to maintain consistency with currently employed neurocognitive tasks, future work should determine the feasibility of using touchscreen responses for the potential to implement this task through a mobile device application. Such an approach may be preferable to widely popular neurocognitive tasks, which are administered using a tablet or laptop with a mouse. Testing the feasibility of implementing the combined cognitive flexibility and symptom factors on a mobile device opens the potential to easily incorporating neurocognitive testing into sideline assessments to aid objective clinical decision-making and complement current sideline approaches.

Our findings also indicated improved detection of concussion when pairing neurocognitive outcomes and the SCAT total symptom score. These findings align with current recommendations and practices adopted by clinicians incorporating a multifaceted approach into concussion identification and management [9,24,49,53–55]. In fact, 52.7% of clinicians indicate using a 3-domain assessment battery (cognition, symptom assessment, balance) whereas 86.4% report using at least a 2-domain assessment [37]. Importantly, the most widely utilized symptom inventory by clinicians during concussion identification is the symptom checklist included in the SCAT [37]. Anderson et al. [35] further defined the clinical utility of the SCAT by identifying a 3-factor symptom structure (e.g., migraine-fatigue, affective, and cognitive-ocular) to guide treatment in acutely concussed patients. Our inclusion of the SCAT 3-factor symptom structure with the neurocognitive outcomes in the present study provided the greatest sensitivity (95.7%) and specificity (88.7%) and higher positive predictive value (91.9%) and negative predictive value (89%) over currently used neurocognitive test batteries commonly used by clinicians [37]. These are important findings as the inclusion of perceptual-based tasks with objective outcomes (e.g., reaction time, response accuracy, cost) may extend the clinical decision making of subjective symptom reporting. Indeed, it is important to highlight that a stepwise assessment in which clinicians add neurocognitive testing when clinical symptom factors alone fail to detect concussion outperforms all other approaches, with 98.2% sensitivity, 95.7% specificity, and 97.1% overall classification accuracy. However, a stepwise approach combining neurocognitive variables with clinical symptom total scores worsened performance—further highlighting the utility of a clinical symptom factor approach. Thus, the detection of concussion is improved when adding a cognitive flexibility task requiring shifts of visuospatial attention if clinical symptom factors fail to detect an injury.

Of note is that SCAT factor symptoms and symptom severity outperformed (sensitivity 93.5%, specificity 83%) SCAT total symptoms and total symptom severity alone (sensitivity 91.5%, specificity 83%). This finding suggests that a 3-symptom factor structure (migraine-fatigue, affective, cognitive-ocular) is preferable. Such a finding suggests that instruments used to detect a concussion could be shortened to only incorporate symptoms critical for detecting a concussion. A limitation to only relying upon symptom report for concussion identification, however, is that this approach is subjective and susceptible to nondisclosure behaviors. For example, more than 70% of athletes failing to report a concussion due to concerns of missing playing time or letting down their team [56,57]. Thus, despite the clinical utility of the SCAT, which sports medicine professionals rely upon heavily to recognize a concussion, there is an increased need to combine these symptom reports with objective neurocognitive testing. Our stepwise findings further support the notion that neurocognitive testing improves detection of concussion when clinical symptom factors fail to detect the presence of a concussive injury. A limitation to a number of widely-used neurocognitive test batteries, however, is that they lack the requisite sensitivity to detect persistent concussion-related cognitive impairments (i.e., beyond 3–10 day recovery period); instead, these test batteries are better suited for detecting immediate effects of sports-related concussion [3,8]. Thus, the present findings are promising given that other work has demonstrated differences in perceptual-based cognitive flexibility (using the present task) between concussed and noninjured control athletes up to one month following injury and return to play [10–12]. Moreover, combining these objective neurocognitive outcomes with subjective SCAT symptom factor scores demonstrates superior performance in detecting a concussion relative to SCAT symptom scores and neurocognitive tasks alone while overcoming the limitations of self-report scales susceptible to nondisclosure behaviors.

However, the decision to use the combined neurocognitive and SCAT symptom factors appears more nuanced than simply defaulting to this approach. Instead, it seems that using a stepwise assessment in which clinicians add neurocognitive testing when clinical symptom factors alone fail to detect concussion further improves performance of the combined neurocognitive and clinical symptom factor assessment. In practice, this would mean that the SCAT symptom factors should be used as the first step to detect a concussion. In line with the multifaceted approach, the stepwise assessment of the paired neurocognitive task with clinical symptoms aids in objectively detecting a concussion beyond subjective symptom reporting, in which some concussions may be missed. It is estimated that the extent of athletes' non-disclosure of concussions ranges from 16 to 62% [58,59] and symptom underreporting is influenced by numerous socioecological factors, including the desire to remain in the sport [60]. Thus, adding neurocognitive assessments, such as the cognitive flexibility task in the present study, has the potential to aid clinicians in objective decision-making.

In addition, the clinical utility during the acute stages of injury reported within these preliminary findings motivate future research to identify concussed patients at risk for prolonged recovery. For example, worse symptom presence within certain symptom factors at an initial evaluation demonstrate clinical utility in identifying patients with higher symptom burden at follow-up appointments [61]. Further, Eagle et al. [40] suggested that utilizing a symptom factor approach was beneficial in predicting athletes with a prolonged recovery that persisted beyond 30 days. Other studies have identified a relationship between persistent post-concussion symptom factors and impaired neurocognitive performance [62]. Therefore, pairing subjective symptom factor assessments with objective neurocognitive tasks assessing higher-order cognitive operations that demonstrate persistent impairments beyond clinical recovery (i.e., full return to sport) [12,52] may aid in identifying concussed patients at risk for prolonged recovery. As such, our findings emphasize the potential for clinical utility of these paired assessments in acute stages (e.g., within 72 h), and should be studied throughout concussion recovery (e.g., at return to play). In addition, future research may aim to combine these two measures, both measures of cognitive flexibility paired with symptom factors, as a novel approach for determining athletes at risk for prolonged recovery from concussion.

4.1. Limitations

Although the present study provides preliminary evidence that combining neurocognitive variables from task-switching paradigm with SCAT symptom factor structures provides sensitivity and specificity to detect concussion surpassing currently employed test batteries, the findings are not without limitations that should be addressed by future investigations. In the current study, the researchers assumed that participants were honest when completing the self-report concussion symptom scale. To mitigate this issue, athletes were informed results of their symptom reporting would only be used for research and would not be used in determining their eligibility to return to competition nor disclosed to their athletic trainer or team physician. In addition, there is no gold standard to measure symptoms for comparing results, and every concussion is variable, making comparisons across all concussions difficult. A strength of the present study design was that participants were recruited within a stringent time frame (within 72 h) to examine modulations in cognition following injury. Although there is no baseline assessment, athletes completed practice trials for the computerized task prior to experimental trials and performed with an average of 80% suggesting participants put forth effort. Moreover, the present findings should be interpreted in light of the fact that there is no comparison to normative data or relative to participants' performance on other clinically-relevant neurocognitive tests. The present study used a limited age group (high school and college) of athletes. Although a robust body of literature demonstrates the relationship of age to executive functioning, cognitive maturity effects on task performance would be more likely to manifest in the noninjured control group given there were more high school athletes than in the concussed group; however, our findings demonstrate concussion-related decrements in perceptual-based cognitive flexibility despite the concussed group consisting of more collegiate athletes thus decreasing the likelihood maturity influenced the present data. Future investigations should incorporate long-term assessments to confirm or refute whether the present findings demonstrate that the task-switching paradigm in combination with SCAT symptom factor structures indicate athletes at risk of a longer recovery profile. Finally, although this study utilized a multifaceted assessment to detect concussion, inclusive of cognition and symptomology, we did not include an assessment of balance, vestibular, and ocular measures, which are commonly recommended during concussion evaluation. However, the cognitive flexibility task isolates shifts of visuospatial attention, which rely upon activation of the superior parietal cortex, which is involved in sensorimotor integration (e.g., general awareness of the body and location of its parts, proprioception) and has projections to the occipital lobe [63,64]. Although untested, it is plausible that in isolating visuospatial attention, the cognitive flexibility task taps into brain regions missed by balance, vestibular, and ocular assessments. Indeed, lesions in the superior parietal cortex have been associated with normal saccadic and smooth-pursuit eye movements as well as gait despite showing impairments in visuospatial attention and proprioception [63]. Accordingly, future research should investigate the clinical utility of including balance, vestibular, and ocular paired with cognitive flexibility and symptom factors.

5. Conclusions

Our findings provide preliminary evidence that integrating neurocognitive tests involving cognitive flexibility have clinical utility in detecting concussion and potentially higher sensitivity and specificity relative to current clinical test batteries when combined with SCAT symptom factors. Presently, widely-used computerized neurocognitive tests do not incorporate such assessments for identifying concussion and so the acute and long-term impairments in cognition may be missed during clinical management of concussive injuries. The present findings provide preliminary evidence that combining a perceptual-based cognitive flexibility task with SCAT symptom factors may be more sensitive for detecting a concussion than widely-used test batteries, and this approach could feasibly be implemented on a mobile device in less than 10 min. However, these findings should be interpreted in light of the fact that the present study used keyboard responses to maintain consistency with current neurocognitive assessments and future work should determine the feasibility of employing the task using touchscreen responses for mobile device use.

Widely popular neurocognitive test batteries used to detect concussion only differentiate between concussed and matched control athletes when combined across multiple cognitive domains, take 30–40 min to administer, and require the use of a tablet or laptop with a mouse. Although these test batteries are widely-used, they fail to detect lasting cognitive impairments and baseline performance returns within 10 days. Instead, a perceptual-based cognitive flexibility task has shown persistent cognitive impairments in concussed athletes up to one month following return to play [12]. Thus, employing perceptual-based cognitive flexibility tasks has the potential for identifying those athletes at risk of longer recovery. We show that the combination of neurocognitive outcomes (i.e., mean reaction time, response accuracy, response accuracy cost) with SCAT factor scores (migraine, affective, cognitive-ocular) exhibited the greatest sensitivity (95.7%), specificity (88.7%), and overall classification rate (91.9%), outperforming other approaches, which is further improved by a stepwise approach (step 1: symptom factors, step 2: neurocognitive outcomes). Therefore, pairing symptom factor assessments with tasks assessing the shifting of visuospatial attention may aid in identifying a concussion and identifying concussed patients at risk for prolonged recovery. Our findings emphasize pairing neurocognitive and symptom assessments in acute stages (e.g., within 72 h) to aid clinical decision-making. Importantly, pairing the perceptual-based cognitive flexibility task with SCAT symptom factor scores could easily be administered on a mobile device in 10 min or less (6 min neurocognitive + 1 min symptoms); future work should determine the feasibility of employing this approach on a mobile device with sports medicine practitioners.

Author disclosure statement

No conflicting financial interests exist.

CRediT authorship contribution statement

Amanda L. McGowan: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – original draft, Writing – review & editing, Project Administration. *Abigail C. Bretzin:* Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Project Administration. *Morgan Anderson:* Investigation, Writing – original draft, Writing – review & editing, Project Administration. *Matthew B. Pontifex:* Software, Writing – review & editing, Supervision, Funding Acquisition. *Tracey Covassin:* Writing – review & editing, Supervision, Funding Acquisition, Project Administration.

Declaration of Competing Interest

None.

Acknowledgments

This study was funded in part by a contract to BrainScope Company Inc. from the U.S. Navy (Naval Health Research Center) contract # W911QY-14-C-0098.

References

[1] Z.Y. Kerr, A. Chandran, A.K. Nedimyer, A. Arakkal, L.A. Pierpoint, S.L. Zuckerman, Concussion incidence and trends in 20 high school sports, Pediatrics 144 (5) (2019), https://doi.org/10.1542/peds.2019-2180.
[2] S.L. Zuckerman, Z.Y. Kerr, A. Yengo-Kahn, E. Wasserman, T. Covassin, G. S. Solomon, Epidemiology of sports-related concussion in NCAA athletes from 2009-2010 to 2013-2014: incidence, recurrence, and mechanisms, Am. J. Sports Med. 43 (11) (2015) 2654–2662, https://doi.org/10.1177/0363546515599634.
[3] W.B. Barr, M. McCrea, Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussion, J. Int. Neuropsychol. Soc. 7 (6) (2001) 693–702.
[4] M.W. Collins, S.H. Grindel, M.R. Lovell, et al., Relationship between concussion and neuropsychological performance in college football players, JAMA 282 (10) (1999) 964–970.
[5] D. Erlanger, D. Feldman, K. Kutner, et al., Development and validation of a web-based neuropsychological test protocol for sports-related return-to-play decision-making, Arch. Clin. Neuropsychol. 18 (2003) 293–316.
[6] D. Erlanger, E. Saliba, J. Barth, J. Almquist, W. Webright, J. Freeman, Monitoring resolution of postconcussion symptoms in athletes: preliminary results of a web-based neuropsychological test protocol, J. Athl. Train. 36 (2001) 280–287.
[7] G.L. Iverson, B.L. Brooks, M.W. Collins, M.R. Lovell, Tracking neuropsychological recovery following concussion in sport, Brain Inj. 20 (2006) 245–252.
[8] P. Schatz, J.E. Pardini, M.R. Lovell, M.W. Collins, K. Podell, Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes, Arch. Clin. Neuropsychol. 21 (1) (2006) 91–99, https://doi.org/10.1016/j.acn.2005.08.001.
[9] K.G. Harmon, J.R. Clugston, K. Dec, et al., American Medical Society for Sports Medicine position statement on concussion in sport, Br. J. Sports Med. 53 (4) (2019) 213–225.
[10] D. Howell, L. Osternig, P. van Donkelaar, U. Mayr, L.S. Chou, Effects of concussion on attention and executive function in adolescents, Med. Sci. Sports Exerc. 45 (2013) 1030–1037.
[11] U. Mayr, C. LaRoux, T. Rolheiser, L. Osternig, L.-S. Chou, P. van Donkelaar, Executive dysfunction assessed with a task-switching task following concussion, PLoS One 9 (3) (2014), e91379.
[12] A.L. McGowan, A.C. Bretzin, J.L. Savage, et al., Preliminary evidence for differential trajectories of recovery for cognitive flexibility following sports-related

concussion, Neuropsychology 32 (5) (2018) 564–574, https://doi.org/10.1037/neu0000475.
[13] S.M. Ravizza, C.S. Carter, Shifting set about task switching: behavioral and neural evidence for distinct forms of cognitive flexibility, Neuropsychologia 46 (12) (2008) 2924–2935.
[14] E.K. Miller, J.D. Cohen, An integrative theory of prefrontal cortex function, Annu. Rev. Neurosci. 24 (2001) 167–202.
[15] A. Dettwiler, M. Murugavel, M. Putukian, V. Cubon, J. Furtado, D. Osherson, Persistent differences in patterns of brain activation after sports-related concussion: a longitudinal functional magnetic resonance imaging study, J. Neurotrauma 31 (2) (2013) 180–188, https://doi.org/10.1089/neu.2013.2983.
[16] P. van Donkelaar, J. Langan, E. Rodriguez, et al., Attentional deficits in concussion, Brain Inj. 19 (12) (2005) 1031–1039.
[17] C.I. Halterman, J. Langan, A. Drew, et al., Tracking the recovery of visuospatial attention deficits in mild traumatic brain injury, Brain 129 (3) (2006) 747–753.
[18] A.R. Mayer, M.V. Mannell, J. Ling, et al., Auditory orienting and inhibition of return in mild traumatic brain injury: a FMRI study, Hum. Brain Mapp. 30 (12) (2009) 4152–4166, https://doi.org/10.1002/hbm.20836.
[19] J.T. Barth, S.N. Macciocchi, B. Giordani, R. Rimel, J.A. Jane, T.J. Boll, Neuropsychological sequelae of minor head injury, Neurosurgery 13 (5) (1983) 529–533, https://doi.org/10.1227/00006123-198311000-00008.
[20] S.L. Cremona-Meteyard, G.M. Geffen, Persistent visuospatial attention deficits following mild head injury in Australian rules football players, Neuropsychologia 32 (6) (1994) 649–662, https://doi.org/10.1016/0028-3932(94)90026-4.
[21] N.V. Marsh, M.D. Smith, Post-concussion syndrome and the coping hypothesis, Brain Inj. 9 (6) (1995) 553–562, https://doi.org/10.3109/02699059509008214.
[22] M. Makdissi, R.C. Cantu, K.M. Johnston, P. McCrory, W.H. Meeuwisse, The difficult concussion patient: what is the best approach to investigation and management of persistent (>10 days) postconcussive symptoms? Br. J. Sports Med. 47 (5) (2013) 308–313, https://doi.org/10.1136/bjsports-2013-092255.
[23] A.L. McGowan, A.C. Bretzin, J.L. Savage, K.M. Petit, T. Covassin, M.B. Pontifex, Acute and protracted disruptions to inhibitory control following sports-related concussion, Neuropsychologia 131 (2019) 223–232, https://doi.org/10.1016/j.neuropsychologia.2019.05.026.
[24] P. McCrory, W. Meeuwisse, J. Dvorak, et al., Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016, Br. J. Sports Med. 51 (11) (2017) 838–847.
[25] A. Littleton, K. Guskiewicz, Current concepts in sport concussion management: a multifaceted approach, J. Sport Health Sci. 2 (4) (2013) 227–235.
[26] G.L. Iverson, Network analysis and precision rehabilitation for the post-concussion syndrome, Front. Neurol. 10 (2019), https://doi.org/10.3389/fneur.2019.00489.
[27] A.R. Rabinowitz, A.J. Fisher, Person-specific methods for characterizing the course and temporal dynamics of concussion symptomatology: a pilot study, Sci. Rep. 10 (1) (2020) 1248, https://doi.org/10.1038/s41598-019-57220-1.
[28] D. Pardini, J. Stump, M. Lovell, M. Collins, K. Moritz, F. Fu, The post-concussion symptom scale (pcss): a factor analysis, Br. J. Sports Med. 38 (5) (2004) 661–662.
[29] S. Barker-Collo, A. Theadom, N. Starkey, M. Kahan, K. Jones, V. Feigin, Factor structure of the Rivermead Post-Concussion Symptoms Questionnaire over the first year following mild traumatic brain injury, Brain Inj. 32 (4) (2018) 453–458.
[30] N. Herrmann, M.J. Rapoport, R.D. Rajaram, et al., Factor analysis of the Rivermead Post-Concussion Symptoms Questionnaire in mild-to-moderate traumatic brain injury patients, J. Neuropsychiatry Clin. Neurosci. 21 (2) (2009) 181–188.
[31] A.S. Joyce, C.R. Labella, R.L. Carl, J.-S. Lai, F.A. Zelko, The Postconcussion symptom scale: utility of a three-factor structure, Med. Sci. Sports Exerc. 47 (6) (2014) 1119–1123.
[32] A.P. Kontos, R.J. Elbin, P. Schatz, et al., A revised factor structure for the Post-Concussion Symptom Scale: baseline and postconcussion factors, Am. J. Sports Med. 40 (10) (2012) 2375–2384, https://doi.org/10.1177/0363546512455400.
[33] S.G. Piland, R.W. Motl, M.S. Ferrara, C.L. Peterson, Evidence for the factorial and construct validity of a self-report concussion symptoms scale, J. Athl. Train. 38 (2) (2003) 104.
[34] B.C. Lau, M.W. Collins, M.R. Lovell, Cutoff scores in neurocognitive testing and symptom clusters that predict protracted recovery from concussions in high school athletes, Neurosurgery 70 (2) (2012) 371–379.
[35] M. Anderson, K.M. Petit, A.C. Bretzin, R.J. Elbin, K. Stephenson-Brown, T. Covassin, Sport concussion assessment tool symptom inventory: healthy and acute postconcussion symptom factor structures, J. Athl. Train. (2020), https://doi.org/10.4085/1062-6050-393.19. Published online September 4, 2020.
[36] L.D. Nelson, S. Tarima, A.A. LaRoche, et al., Preinjury somatization symptoms contribute to clinical recovery after sport-related concussion, Neurology 86 (20) (2016) 1856–1863.
[37] L.B. Lempke, J.D. Schmidt, R.C. Lynall, Athletic trainers' concussion-assessment and concussion-management practices: an update, J. Athl. Train. 55 (1) (2020) 17–26.
[38] NINDS Common Data Elements, Sport Concussion Assessment Tool - 3rd Edition (SCAT3). https://www.commondataelements.ninds.nih.gov/report-viewer/25025/Sport%20Concussion%20Assessment%20Tool%20-%203rd%20Edition%20(SCAT3).%20Accessed%20March%2031,%202020, 2018.
[39] K. Hamsher, A.L. Benton, The reliability of reaction time determinations, Cortex 13 (3) (1977) 306–310.
[40] S.R. Eagle, M.N. Womble, R.J. Elbin, R. Pan, M.W. Collins, A.P. Kontos, Concussion symptom cutoffs for identification and prognosis of sports-related concussion: role of time since injury, Am. J. Sports Med. 48 (10) (2020) 2544–2551.
[41] R Core Team, R: A Language and Environment for Statistical Computing. https://www.R-project.org/, 2019.
[42] Lawrence MA, Lawrence MMA, Package 'ez.' R Package Version, Published online 2016, 2016 (4-4).
[43] F. Faul, E. Erdfelder, A.G. Lang, A. Buchner, G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences, Behav. Res. Methods 29 (2007) 175–191, https://doi.org/10.3758/BF03193146.
[44] S.S. Shapiro, M.B. Wilk, An analysis of variance test for normality (complete samples), Biometrika 52 (3–4) (1965) 591–611, https://doi.org/10.1093/biomet/52.3-4.591.
[45] S. McGee, Simplifying likelihood ratios, J. Gen. Intern. Med. 17 (8) (2002) 647–650, https://doi.org/10.1046/j.1525-1497.2002.10750.x.
[46] B.P. Katz, M. Kudela, J. Harezlak, et al., Baseline performance of NCAA athletes on a concussion assessment battery: a report from the CARE Consortium, Sports Med. Auckl. NZ 48 (8) (2018) 1971–1985, https://doi.org/10.1007/s40279-018-0875-7.
[47] S.G. Rice, Medical conditions affecting sports participation, Pediatrics 121 (4) (2008) 841–848, https://doi.org/10.1542/peds.2008-0080.
[48] D.A.V. Kampen, M.R. Lovell, J.E. Pardini, M.W. Collins, F.H. Fu, The "value added" of neurocognitive testing after sports-related concussion, Am. J. Sports Med. 34 (10) (2006) 1630–1636.
[49] J.E. Resch, C.N. Brown, J. Schmidt, et al., The sensitivity and specificity of clinical measures of sport concussion: three tests are better than one, BMJ Open Sport Exerc. Med. 2 (1) (2016), e000012, https://doi.org/10.1136/bmjsem-2015-000012.
[50] A.G. Louey, J.A. Cromer, A.J. Schembri, et al., Detecting cognitive impairment after concussion: sensitivity of change from baseline and normative data methods using the CogSport/Axon cognitive test battery, Arch. Clin. Neuropsychol. 29 (5) (2014) 432–441.
[51] M. McCrea, J.P. Kelly, C. Randolph, et al., Standardized assessment of concussion (SAC): on-site mental status evaluation of the athlete, J. Head Trauma Rehabil. 13 (2) (1998) 27–35.
[52] V. Sicard, R.D. Moore, D. Ellemberg, Sensitivity of the Cogstate Test Battery for detecting prolonged cognitive alterations stemming from sport-related concussions, Clin. J. Sport Med. 29 (1) (2019) 62–68.
[53] T.A. Buckley, G. Burdette, K. Kelly, Concussion-management practice patterns of National Collegiate Athletic Association Division II and III athletic trainers: how the other half lives, J. Athl. Train. 50 (8) (2015) 879–888.
[54] K.C. Kelly, E.M. Jordan, A.B. Joyner, G.T. Burdette, T.A. Buckley, National Collegiate Athletic Association Division I athletic trainers' concussion-management practice patterns, J. Athl. Train. 49 (5) (2014) 665–673.
[55] G.-G.P. Garcia, S.P. Broglio, M.S. Lavieri, et al., Quantifying the value of multidimensional assessment models for acute concussion: an analysis of data from the NCAA-DoD care consortium, Sports Med. 48 (7) (2018) 1739–1749, https://doi.org/10.1007/s40279-018-0880-x.
[56] J.S. Delaney, C. Lamfookon, G.A. Bloom, A. Al-Kashmiri, J.A. Correa, Why university athletes choose not to reveal their concussion symptoms during a practice or game, Clin. J. Sport. Med. 25 (2) (2015) 113–125, https://doi.org/10.1097/JSM.0000000000000112.
[57] J. McAllister-Deitrick, E. Beidler, J. Wallace, M. Anderson, Concussion knowledge and reporting behaviors among collegiate athletes, Clin. J. Sport. Med. (2020) 1, https://doi.org/10.1097/JSM.0000000000000833. Publish Ahead of Print.
[58] M. Anderson, K.M. Petit, J. Wallace, T. Covassin, E. Beidler, Factors associated with concussion nondisclosure in collegiate student-athletes, J. Athl. Train. 56 (2) (2021) 157–163, https://doi.org/10.4085/1062-6050-0102-20.
[59] Z.Y. Kerr, J.K. Register-Mihalik, S.W. Marshall, K.R. Evenson, J.P. Mihalik, K. M. Guskiewicz, Disclosure and non-disclosure of concussion and concussion symptoms in athletes: review and application of the socio-ecological framework, Brain Inj. 28 (8) (2014) 1009–1021, https://doi.org/10.3109/02699052.2014.904049.
[60] F.N. Conway, M. Domingues, R. Monaco, et al., Concussion symptom underreporting among incoming National Collegiate Athletic Association Division I College Athletes, Clin. J. Sport Med. 30 (3) (2020) 203–209, https://doi.org/10.1097/JSM.0000000000000557.
[61] P.E. Cohen, A. Sufrinko, R.J. Elbin, M.W. Collins, A.M. Sinnott, A.P. Kontos, Do initial symptom factor scores predict subsequent impairment following concussion? Clin. J. Sport Med. 30 (Suppl 1) (2020) S61. Published online.
[62] E. Guty, K. Riegler, J. Meyer, A.E. Walter, S.M. Slobounov, P. Arnett, Symptom factors and neuropsychological performance in collegiate athletes with chronic concussion symptoms, Arch. Clin. Neuropsychol. 00 (2020) 1–11, https://doi.org/10.1093/arclin/acaa092. Published online.
[63] D.M. Wolpert, S.J. Goodbody, M. Husain, Maintaining internal representations: the role of the human superior parietal lobe, Nat. Neurosci. 1 (6) (1998) 529–533.
[64] J.L. Wilkinson, 12 - cerebral cortex, in: J.L. Wilkinson (Ed.), Neuroanatomy for Medical Students (Second Edition), Butterworth-Heinemann, 1992, pp. 215–234, https://doi.org/10.1016/B978-0-7506-1447-4.50016-5.