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Preliminary Evidence for Differential Trajectories of Recovery for Cognitive Flexibility Following Sports-Related Concussion

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Objective: A critical barrier to the understanding of disruptions to cognitive flexibility following sports-related concussion is the use of assessments that conflate shifts of visuospatial attention and contextual rules. Because these dissociable forms of cognitive flexibility are subserved by distinct neural networks, the utility of a cognitive flexibility assessment following concussion may be reduced, depending upon the extent to which the task requires shifting visuospatial attention relative to shifting contextual rules. Accordingly, the current investigation examined the extent to which these aspects of cognitive flexibility exhibit differential trajectories of recovery following a sports-related concussion. ***Method:*** Twenty-two athletes with sports-related concussions were assessed on a cognitive flexibility task with 2 switch conditions (i.e., perceptual-based and contextual rule−based) within 72 hr of injury, after return to play, and within 1 month following return to play. Thirty-three healthy control athletes were tested at the same intervals. ***Results:*** Findings revealed that concussed athletes demonstrated protracted disruptions in task performance on a visuospatial attention−based cognitive flexibility task relative to healthy controls, whereas disruptions in task performance on a contextual rule−based cognitive flexibility task resolved after the acute phase of injury. These findings suggest that dissociable forms of cognitive flexibility exhibit differential trajectories of recovery. ***Conclusions:*** Therefore, evaluations detecting sports-related concussion disruptions in cognitive flexibility may be reduced depending on the extent to which they rely on contextual rule−based decisions. Test batteries focusing on visuospatial attention−based demands may be useful additions to aid in the objective assessment and follow-up management of athletes following the acute phase of injury.

General Scientific Summary
Disruptions to cognitive flexibility are common following sports-related concussion, yet present test batteries conflate dissociable forms of cognitive flexibility, thereby limiting the ability to detect distinct recovery patterns. This study provides evidence that disruptions to visuospatial attention exhibit protracted recovery up to one month following the return to full sport participation, whereas disruptions to rule-response mappings recover by the return to play period. Given the growing interest in enhancing the clinical management of concussed athletes, such findings may be particularly important for guiding interpretations of performance on neuropsychological batteries.

Keywords: sports-related concussion, task switch, executive function, cognitive control, neuropsychological tests

Every year, between 1.6 million and 3.8 million athletes in the United States suffer a concussive injury resulting from sports participation (Langlois, Rutland-Brown, & Wald, 2006). During the acute phase of injury (i.e., <7 days), deficits in information-processing speed (Collins et al., 1999; Covassin, Moran, & Wilhelm, 2013; McCrea et al., 2003), memory (Collins et al., 1999; Covassin et al., 2013; Stephens, Rutherford, Potter, & Fernie, 2010; Terry et al., 2012), and attention (Stephens et al., 2010; Terry et al., 2012) have been consistently observed, with performance returning to near baseline levels within 5−7 days (Belanger & Vanderploeg, 2005; Delaney, Lacroix, Leclerc, & Johnston, 2002; McCrea et al., 2003). However, a growing body of evidence has begun to suggest that some aspects of cognition may exhibit protracted impairments well beyond this period (Broglio, Pontifex, O'Connor, & Hillman, 2009; Ellemberg, Leclerc, Couture, & Daigle, 2007; Howell, Osternig, van Donkelaar, Mayr, & Chou, 2013; Pontifex et al., 2012). Indeed, persistent deficits in cognitive

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flexibility resulting from sports-related concussions have been exhibited 2 months following injury (Howell et al., 2013; Mayr et al., 2014). Such findings provide compelling evidence to suggest that assessing cognitive flexibility may enhance the clinical management of concussed athletes; however, a critical barrier to implementing such assessments is that there has been little evidence whether such decrements in cognitive flexibility occur globally or whether the effects of a concussive injury differentially manifest depending upon the type of cognitive flexibility assessed.

The term *cognitive flexibility* broadly refers to the capacity to change behavioral goals, to shift attentional focus, or to vary stimulus−response mappings. This capacity is vital for maintaining control over one's actions despite an ever-changing and multifaceted environment (Miller & Cohen, 2001). Problematically, most cognitive flexibility assessments treat the ability to switch tasks as a unitary construct, despite evidence suggesting that shifts in visuospatial attention are functionally distinct from shifts in contextual rules (Ravizza & Carter, 2008). One such task that is optimized for differentiating perceptual-based cognitive flexibility from contextual rule−based cognitive flexibility is the "odd man out" paradigm (Ravizza & Carter, 2008). During the perceptual-based cognitive flexibility condition, participants are shown stimuli containing multiple feature sets (i.e., both shapes and letters) and must reorient visuospatial attention away from one set of features (i.e., letters) toward another feature set (i.e., shapes) to respond to the physical location of the odd stimulus. In contrast, the contextual rule−based cognitive flexibility condition presents only a singular feature set at a given time, with participants' being instructed to respond using the response button mapped to the odd stimulus. Because each response button has a stimulus−response mapping for both letters and shapes, a switch between letter and shape stimuli requires the retrieval and implementation of the alternative stimulus−response mappings. Compellingly, perceptual- and rule-based cognitive flexibility also activate different neural networks, with the perceptual condition strongly associated with the superior parietal cortex whereas the rule condition is more strongly associated with the dorsolateral prefrontal cortex (DLPFC; Ravizza & Carter, 2008).

Given the dissociable forms of cognitive flexibility—perceptual-based and contextual rule−based—elucidating the relationship between these component constructs and deficits in cognitive flexibility associated with concussive injury is vital for understanding the protracted effects of sports-related concussion. Although there has been some evidence to suggest that the DLPFC is sensitive to the effects of a concussive injury (Dettwiler et al., 2014), a preponderance of evidence has demonstrated an association between concussion and visuospatial deficits (Barth et al., 1983; Cremona-Meteyard & Geffen, 1994; Marsh & Smith, 1995; Mayer et al., 2009; van Donkelaar et al., 2005). Specifically, individuals who have incurred a concussion have demonstrated impairments in visuospatial attention during the acute phase (van Donkelaar et al., 2005) that are protracted at least 30 days following injury (Halterman et al., 2006), as evidenced by poorer performance on orienting and executive attention components of the attentional network task. Further, Mayer and colleagues (2009) observed that concussed individuals exhibit impairments in disengaging and reorienting attention alongside hypoactivation of the superior parietal cortex within 3 weeks of a mild traumatic brain injury. Given such findings, it may be that sports-related concussion impairments in cognitive flexibility are evident only depending upon the degree to which the cognitive flexibility task relies upon visuospatial attention. The purpose of the present study was to test this supposition by investigating the extent to which sports-related concussion decrements in performance differentially manifested across perceptual and contextual rule−based cognitive flexibility during the acute phase (i.e., within 72 hr following injury) and during the period following return to full sport participation (i.e., after return to play and 1 month following return to play).

Method

Participants

The concussion group consisted of 22 varsity and collegiate club athletes (five female, mean age = 17.6 ± 2.6 years), with a sports-related concussion identified by a specialized health professional (certified athletic trainer−physician). A group of 33 athletes (11 female, mean age = 17.2 ± 2.4 years) with a similar history of athletic participation (i.e., varsity or collegiate club athletes) served as healthy controls (see Figure 1 for a CONSORT flow diagram of enrollment). These groups were obtained by recruiting a total of 127 athletes (69 concussed, 58 healthy control) from the mid-Michigan area. Concussed athletes were asked to participate

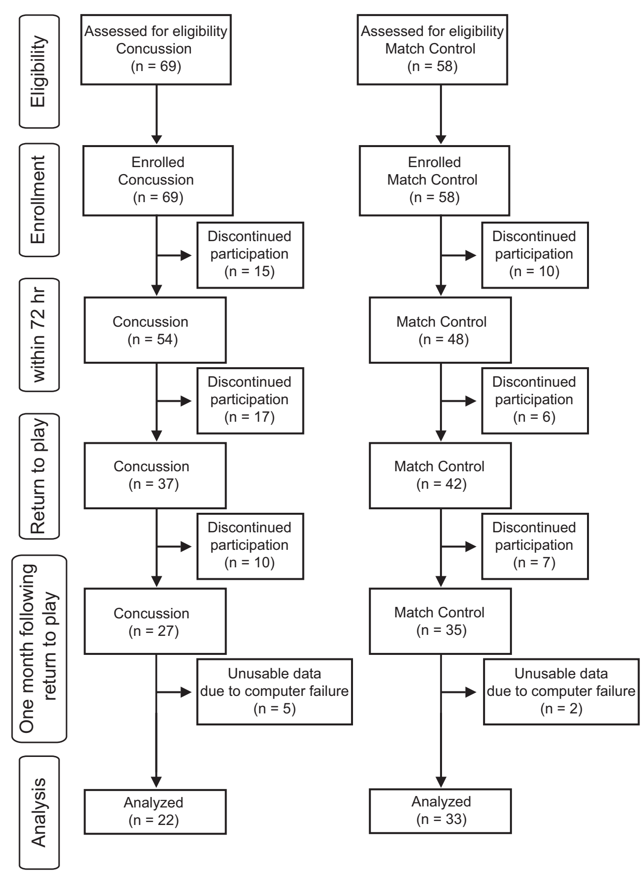

Figure 1. CONSORT flow diagram of the retention of participants in each group through each testing period.

in testing within 72 hr of their sports-related concussion, following return to full athletic participation, and then 1 month following return to play. Following initial enrollment, each concussed participant was matched with a healthy control participant by sex; age; and when possible, sport; and healthy controls were asked to participate in congruent periods of testing. For instance, if the time between the initial assessment (within 72 hr of injury) and the return to play assessment sessions for a participant in the concussion group was 15 days, the respective healthy control athlete was tested at the same interval between the initial assessment and return to play assessment. This experimental protocol required that all participants be tested within ±1 day of the return to play period and within ±5 days of the 1 month following return to play period. Unfortunately, the strict adherence to the experimental protocol resulted in a high attrition rate, with 25 participants (15 concussed, 10 healthy control) failing to complete initial testing within the specified period, 23 participants (17 concussed, six healthy control) failing to complete testing within the return to play period, and 17 participants (10 concussed, seven healthy control) failing to complete testing within the 1 month post−return to play period. Data were from seven participants (five concussed, two healthy control) were unusable as a result of computer failures. All participants were free of neurological disease or physical disabilities, indicated normal or corrected-to-normal vision, and provided informed consent in accordance with the Institutional Review Board at Michigan State University before testing. None of the concussed athletes exhibited a loss of consciousness for 20 min or more related to the concussion injury, evidence of abnormality visible on computerized tomography of the head related to the traumatic event (neuroimaging not required for enrollment), or hospital admission due to either head injury or collateral injuries for more than 24 hr. No participants in the present study reported a loss of consciousness associated with their concussive injury or a history of more severe traumatic brain injury.

Procedure

A repeated-measures design was used in which each participant was tested at three time points following a sports-related concussion: within 72 hr of injury (2.1 ± .76 days following injury), at return to play (16.7 ± 9.1 days following injury), and 1 month following return to play (55.8 ± 15.9 days following injury). For the concussed group, this return to play period was within the 14-day recovery consistent with previous reports (Field, Collins, Lovell, & Maroon, 2003; McCrea et al., 2003; Wasserman, Kerr, Zuckerman, & Covassin, 2016). Healthy control participants were matched with concussed athletes regarding the time lag between testing periods and brought in for initial testing, testing aligning with the concussed athlete's return to play (19.5 ± 15.2 days following initial testing), and testing aligning within 1 month following the concussed athlete's return to play (59.9 ± 24.5 days following initial testing). Prior to the initial testing (within 72 hr of injury), a trained experimenter administered the Conley Evaluation (DeRenzo, Conley, & Love, 1998) to assess the capacity of individuals older than 18 years to provide informed consent; guardians provided informed consent for participants younger than 18, and assent was provided by participants younger than 18. Participants were asked to complete a health and demographics screening questionnaire and were then asked to complete the cognitive flexibility task on a laptop.

Cognitive Flexibility Task

An odd-man-out paradigm (Ravizza & Carter, 2008) was used to determine how a sports-related concussion might differentially relate to perceptual- and rule-based cognitive flexibility. In each of the conditions of the task, all stimuli were presented focally for 2,500 ms (or until a response occurred), with an interstimulus interval of 1,000 ms. For each condition, one block of 95 trials was presented focally on a laptop monitor, with the order of the task conditions counterbalanced across participants. Participants were provided task instructions and practice trials prior to the start of each condition. Nonswitch trials (in which the perceptual cue or response mapping remained the same as the preceding trial) and switch trials (in which the perceptual cue or response mapping differed from the preceding trial) were presented with equal probability.

In both perceptual-based and contextual rule−based tasks, participants were presented with instructions depicting the letter and shape trials with examples of correct responses alongside verbal instructions from a trained experimenter. Following provision of the instructions, participants completed 27 practice trials to familiarize themselves with the task and the stimulus−response mappings. Trained experimenters closely monitored the participants throughout the task to ensure participants were performing the task in a manner that demonstrated comprehension. If experimenters believed that participants did not fully understand the task, the task was stopped and restarted with the same explanation. Additionally, the button-response mapping cues were visible on the participant's screen during the task through both conditions to maintain consistency with existing clinically relevant neurocognitive assessment batteries. Further, this approach served to reduce the working-memory load associated with the contextual-rule condition for greater consistency with the perceptual condition. The button-response mapping cues appeared on the screen and became increasingly translucent throughout the practice trials to encourage participants to encode the stimulus–response associations. During the testing 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 without the button-response mapping cues' drawing attention away from the primary symbol arrays.

Perceptual-based switch condition. The perceptual-based switch condition involved the ability to flexibly reorient visuospatial attention (Ravizza & Carter, 2008). Participants were shown symbol arrays composed of letters (i.e., *A, N, R, T*) presented within shapes (i.e., hexagon, parallelogram, square, triangle; see Figure 2). Letter trials consisted of four letters (three alike, one different), with a different shape surrounding each letter, whereas shape trials consisted of four shapes (three alike, one different), with a different letter inside each shape. Thus, a switch between the letter trials and the shape trials required the reorientation of attention to the correct feature set (i.e., either the shapes or the letters; Ravizza & Carter, 2008). Participants were instructed through both verbal and visual prompts to respond using the key button that was spatially congruent with the odd stimulus. Participants were additionally instructed that if the shapes were all

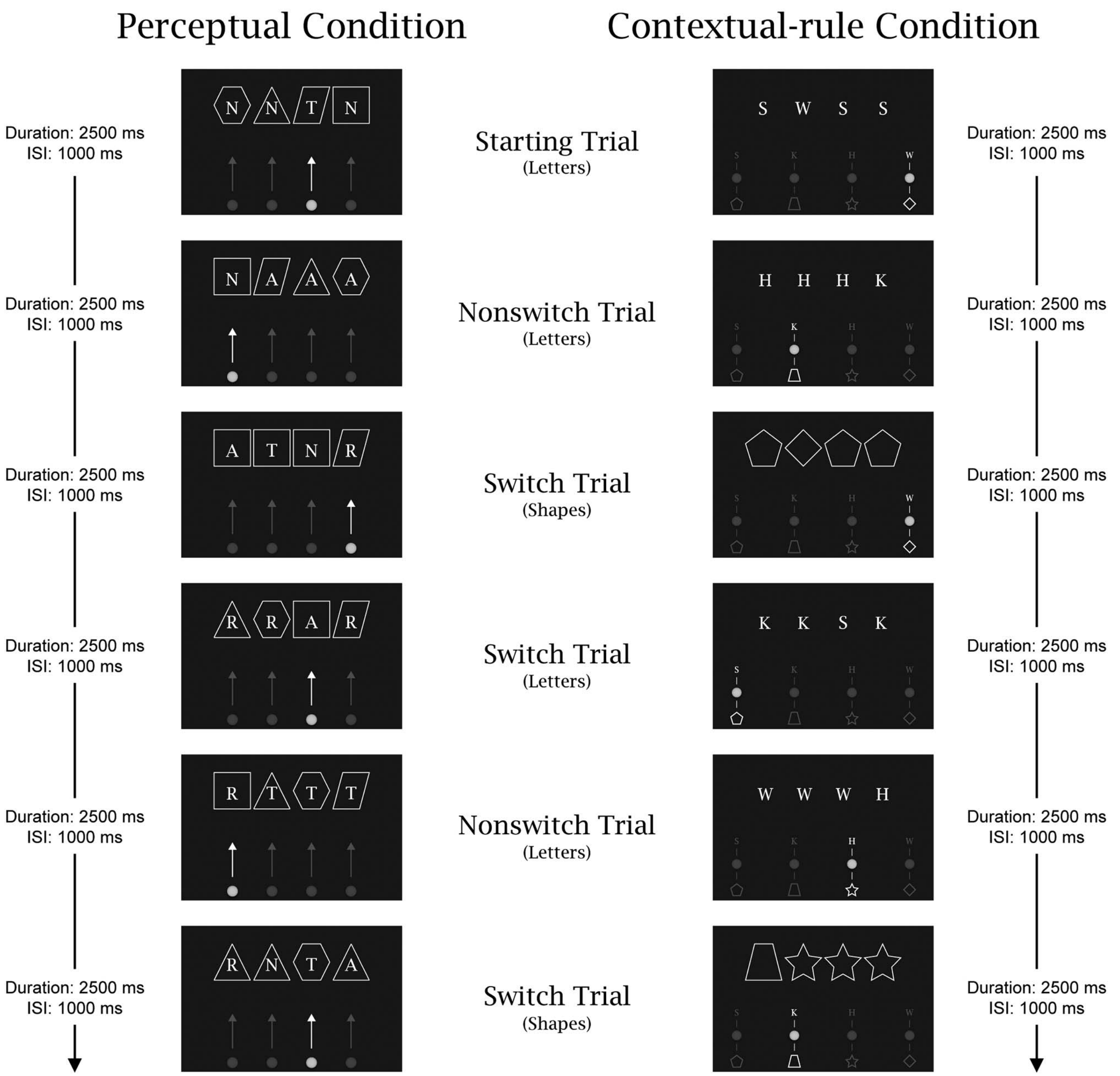

Figure 2. Illustration of the odd-man-out paradigm for both the perceptual condition and the contextual rule−based condition. For reference, the correct response to each stimulus is depicted. ISI = interstimulus interval.

different, then the odd symbol must be within the letter array; conversely if the letters were all different, the odd symbol must be within the shape array. Stimuli were 3 cm tall, with a visual angle of 3.2°.

Contextual rule–based switch condition. The contextual rule–based switch condition involved the ability to flexibly adapt to goal-related information changes (Ravizza & Carter, 2008). Participants were shown symbol arrays composed of either four letters (i.e., *H, K, S, W*) or four shapes (i.e., diamond, pentagon, star, trapezoid), with three similar symbols and one that differed (see Figure 2). Participants were instructed through both verbal and visual prompts to respond to the odd symbol using the button mapped to the corresponding symbol. Each response button was assigned to both a letter and a shape; thus, a switch between the letter trials and the shape trials required the retrieval and implementation of the alternative stimulus−response rules (i.e., changing the feature set that a button was associated with; Ravizza & Carter, 2008). Letter stimuli were 1 cm tall, with a visual angle of 1.1°, and shape stimuli were 3 cm tall, with a visual angle of 3.2°.

Statistical Analysis

Demographic characteristics are provided in Table 1, and mean task performance at each time point is provided in Table

Table 1
Sample Demographic Characteristics (Means, Standard Deviations, and Frequency) as a Function of Group

Variable	Concussion	Healthy control	*p*
n	22	33	
Female (%)	22.7	33.3	.4
Age (years)	17.6 ± 2.6	17.2 ± 2.4	.5
Race (% non-White)	18.2	18.2	.9
Self-reported GPA (4.0 scale)	3.0 ± .6	3.6 ± .4	<.001
Incurred a previous concussion (%)	18.2	15.2	.8
No. of previous concussions	.4 ± 1.1	.3 ± .8	.8
Time since last concussion (years)	.4 ± 1.0	.3 ± .9	.8

Note. Self-reported grade-point average (GPA) was not reported by seven participants from the concussion group and four participants from the healthy control group.

2. Data from both the perceptual- and contextual-rule conditions were analyzed using a 2 (group: concussed, healthy controls) × 3 (time: within 72 hr, return to play, 1 month following return to play) × 2 (trial type: nonswitch, switch) repeated-measures univariate analysis of variance (ANOVA) for both mean reaction time (RT) and response accuracy. Additional analyses were performed to determine whether a sports-related concussion differentially impacted the additional cost of switching the perceptual cue or response mapping for each task. Analyses of the switch cost (switch trials vs, nonswitch trials) were conducted for the perceptual- and contextual-rule conditions using a 2 (group: concussed, healthy controls) × 3 (time: within 72 hr, return to play, 1 month following return to play) repeated-measures univariate ANOVA for both switch cost RT and switch cost response accuracy. Across all analytical procedures, the family-wise alpha level was set at .05. Data analyses were performed in SPSS (Version 24), using the Wilks's lambda statistic with Bonferroni-corrected *t* tests for post hoc comparisons. Cohen's *d* with 95% confidence intervals were computed in R (Version 3.4.0; R Core Team (2017)) as a standardized measure of effect size, using appropriate variance corrections for between-subjects comparisons (d_s) and repeated-measures comparisons (d_{rm}; Lakens, 2013). To facilitate interpretation of the observed findings, we performed a sensitivity power analysis given a sample size of 55 participants, a beta of .2 (i.e., 80% power), and a correlation among repeated measures of .75. Based upon these assumptions, the present research design theoretically had sufficient sensitivity to detect repeated-measures ANOVA interactions exceeding $f = .12$, independent-samples *t* test differences exceeding $d_s =$ .69, and paired-samples *t* tests differences exceeding $d_{rm} = .38$ as computed using G*Power 3.1.2 (Faul, Erdfelder, Lang, & Buchner, 2007).

Results

Demographics

Analysis of demographic variables revealed no significant differences between groups for age, the number of previous concussions, or the time since last concussion, *t*s(53) ≤ .6, *p*s ≥ .5, d_ss ≤ .17, 95% confidence interval [CI: −.48, .71]. Similarly, no differences between groups were observed regarding the proportion of the sample identifying as female or non-White or incurring a previous sports-related concussion (χ^2s ≤ .7, *p*s ≥ .4). Concussed individuals (3.0 ± .6) were observed to exhibit lower self-reported grade-point average (GPA) than did healthy controls (3.6 ± .4), $t(42) = 3.9$, $p < .001$, $d_s = 1.24$, 95% CI [.56, 1.92]; however, self-reported GPA was not reported by seven participants from the concussion group and four participants from the healthy control group.

Table 2
Sample Means and Standard Deviations for Each Time Point as a Function of Group

Measure	Concussion (*n* = 22)			Healthy control (*n* = 33)		
	Within 72 hr	RTP	1 month after RTP	Within 72 hr	RTP	1 month after RTP
			Perceptual-based switch task			
Reaction time (ms)	1,378.9 ± 117.8	1,257.8 ± 179.5	1,191.1 ± 185.9	1,253.5 ± 161.2	1,100.2 ± 213.5	1,069.5 ± 196.4
Switch cost reaction time (ms)	2,02.9 ± 157.0	161.4 ± 86.1	90.9 ± 86.0	214.1 ± 104.7	94.3 ± 89.5	85.1 ± 85.1
Response accuracy (%)	73.4 ± 21.7	87.0 ± 12.4	88.7 ± 10.0	85.6 ± 14.2	89.3 ± 13.1	90.0 ± 7.8
			Contextual rule−based switch task			
Reaction time (ms)	1,383.1 ± 274. 3	1,144.7 ± 253.1	1,159.4 ± 244.8	1,160.8 ± 274.8	1,075.4 ± 239.4	1,092.5 ± 268.6
Switch cost reaction time (ms)	89.1 ± 178.5	32.2 ± 125.5	44.3 ± 99.7	56.2 ± 107.6	25.0 ± 154.8	19.0 ± 74.6
Response accuracy (%)	68.7 ± 30.8	72.4 ± 33.8	72.1 ± 33.3	68.6 ± 34.1	76.6 ± 32.9	77.5 ± 30.7

Note. RTP = return to play.

Perceptual-Based Switch Condition

Reaction time. Analysis of perceptual-based RT revealed main effects of group, $F(1, 53) = 9.2$, $p = .004$, $\eta_p^2 = .15$; time, $F(2, 52) = 46.3$, $p < .001$, $\eta_p^2 = .64$; and trial type, $F(1, 53) = 185.6$, $p < .001$, $\eta_p^2 = .78$. These main effects were superseded by a Group × Time × Trial Type interaction, $F(2, 52) = 4.1$, $p = .023$, $\eta_p^2 = .14$. Decomposition of the Group × Time × Trial Type interaction was performed by examining Group × Time within each trial type. Regardless of trial type, a main effect of group was observed, $Fs(1, 53) \geq 8.6$, $ps \leq .005$, $\eta_p^2s \geq .14$, with slower RT for concussed individuals (1,279.9 ms ± 150.3) relative to healthy controls (1,142.5 ms ± 179.6), $ts(53) \geq 2.9$, $ps \leq .005$, $d_s s \geq .81$, 95% CI [.24, 1.38] (see Figure 3).

For nonswitch trials, a main effect of time was observed, $F(2, 52) = 19.4$, $p < .001$, $\eta_p^2 = .43$, with faster RT at return to play (1,104.6 ms ± 202.5) and 1 month following return to play

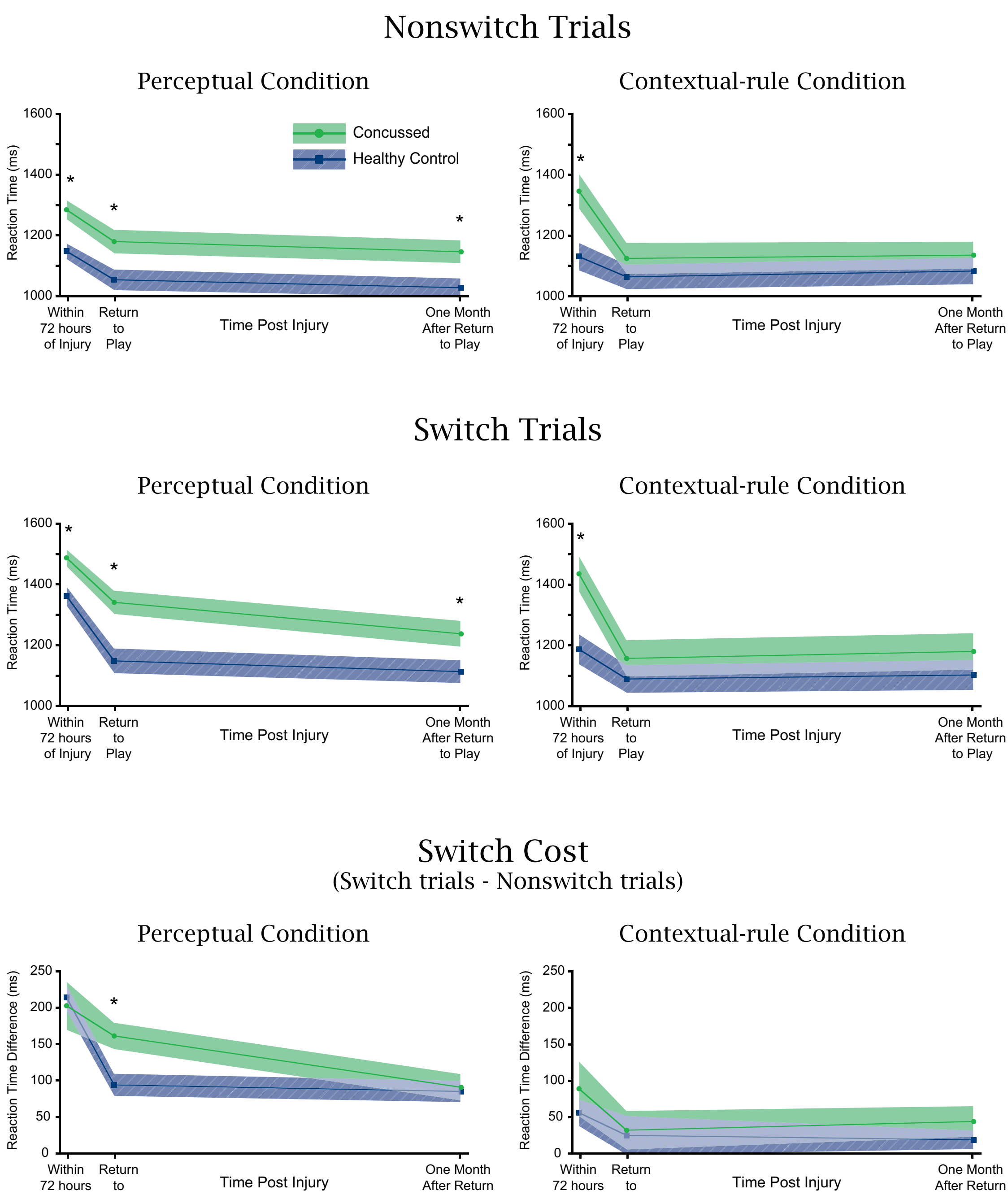

Figure 3. Illustration of reaction time latency (±SE) for each group (Concussed in solid bars, Healthy Control in dashed bars) at each testing period. * $p \leq 0.05$. See the online article for the color version of this figure.

(1,075.4 ms ± 187.9), relative to within 72 hr of injury (1,203.2 ms ± 165.8), ts(54) ≥ 5.0, ps < .001, d_{rm}s ≥ .52, 95% CI [.29, .97].

For switch trials, a main effect of time was observed, $F(2, 52) = 61.0$, $p < .001$, $\eta_p^2 = .7$, with faster RT on each subsequent testing period (within 72 hr of injury: 1,412.8 ms ± 179.0, return to play: 1,225.8 ms ± 236.3, 1 month following return to play: 1,162.8 ms ± 220.5), ts(54) ≥ 3.5, ps ≤ .001, d_{rm}s ≥ .27, 95% CI [.11, 1.12].

Switch cost reaction time. Analysis of perceptual-based switch cost RT revealed a main effect of time, $F(2, 52) = 21.1$, $p < .001$, $\eta_p^2 = .45$, which was superseded by a Group × Time interaction, $F(2, 52) = 4.09$, $p = .023$, $\eta_p^2 = .14$. Decomposition of the Group × Time interaction was performed by examining differences between groups within each testing period. Post hoc comparisons revealed larger switch cost RT for concussed individuals (161.4 ms ± 86.1), relative to healthy controls (94.3 ms ± 89.5), only at return to play, $t(53) = 2.8$, $p = .008$, $d_s = .76$, 95% CI [.20, 1.32] (see Figure 3).

Response accuracy. Analysis of perceptual-based response accuracy revealed main effects of time, $F(2, 52) = 9.2$, $p < .001$, $\eta_p^2 = .26$, and trial type, $F(1, 53) = 23.2$, $p < .001$, $\eta_p^2 = .31$, that were superseded by a Group × Time × Trial Type interaction, $F(2, 52) = 3.5$, $p = .04$, $\eta_p^2 = .12$. Decomposition of the Group × Time × Trial Type interaction was performed by examining Group × Time within each trial type.

For nonswitch trials, a main effect of time was observed, $F(2, 52) = 6.8$, $p = .002$, $\eta_p^2 = .21$, with greater response accuracy at return to play (89.8% ± 12.5) and 1 month following return to play (90.3% ± 8.1), relative to within 72 hr of injury (82.3% ± 18.9), ts(54) ≥ 3.1, ps ≤ .003, d_{rm}s ≥ .46, 95% CI [.16, .84] (see Figure 4).

For switch trials, a main effect of time, $F(2, 52) = 11.1$, $p < .001$, $\eta_p^2 = .3$, was superseded by a Group × Time interaction, $F(2, 52) = 4.5$, $p = .016$, $\eta_p^2 = .15$. Post hoc comparisons revealed poorer response accuracy for concussed individuals (70.7% ± 21.7), relative to healthy controls (84.7% ± 14.1), only within 72 hr of injury, $t(53) = 2.9$, $p = .005$, $d_s = .80$, 95% CI [.24, 1.36] (see Figure 4).

Switch cost response accuracy. Analysis of perceptual-based switch cost response accuracy revealed a Group × Time interaction, $F(2, 56) = 4.03$, $p = .023$, $\eta_p^2 = 2.5$. Decomposition of the Group × Time interaction was performed by examining differences between groups within each testing period. Post hoc comparisons revealed greater switch cost response accuracy for concussed individuals within 72 hr of injury (5.4% ± 9.1) relative to return to play (4.0% ± 7.9) and 1 month following return to play (.05% ± 5.0), ts(21) ≥ 2.4, ps ≤ .02, d_{rm}s ≥ .71, 95% CI [.09, 1.33]. For healthy controls, reduced switch cost response accuracy was observed within 72 hr of injury (1.7% ± 5.9) relative to return to play (2.1% ± 6.3) and 1 month following return to play (2.8% ± 5.4), ts(21) ≥ 2.4, ps ≤ .02, d_{rm}s ≥ .71, 95% CI [.03, .71].

Contextual Rule–Based Switch Condition

Reaction time. Analysis of contextual rule−based RT revealed a main effect of time, $F(2, 52) = 17.3$, $p < .001$, $\eta_p^2 = .4$, which was superseded by a Group × Time interaction, $F(2, 52) = 4.37$, $p < .001$, $\eta_p^2 = .19$. Decomposition of the Group × Time interaction was performed by examining groups within each testing period. Post hoc comparisons revealed slower contextual rule−based RT for concussed individuals (1,391.5 ms ± 264.2), relative to healthy controls (1,159.2 ms ± 273.2), only within 72 hr of injury, $t(53) = 3.1$, $p = .003$, $d_s = .86$, 95% CI [.29, 1.42] (see Figure 3). No differences between groups were observed at return to play (concussed: 1,141.3 ms ± 258.0, healthy controls: 1,076.9 ms ± 240.2) and 1 month following return to play (concussed: 1,158.3 ms ± 245.4, healthy controls: 1,093.1 ms ± 268.2), ts(53) ≤ .9, ps ≥ .3, d_ss ≤ .26, 95% CI [−.29, .8]. A main effect of trial type, $F(1, 53) = 12.6$, $p = .001$, $\eta_p^2 = .19$, was also observed, with faster RT for nonswitch trials (1,136.9 ms ± 220.2) relative to switch trials (1,179.1 ms ± 252.3).

Switch cost reaction time. Analysis of contextual rule−based switch cost RT revealed no main effects or interactions, Fs(2, 52) ≤ 2.3, ps ≥ .1, η_p^2s ≤ .08 (see Figure 3).

Response accuracy. Analysis of contextual rule−based response accuracy revealed a main effect of trial type, $F(1, 53) = 4.5$, $p = .039$, $\eta_p^2 = .08$, with superior response accuracy for nonswitch trials (73.6% ± 28.5) relative to switch trials (72.3% ± 30.8), $d_{rm} = .04$, 95% CI [.0 to .08].

Switch cost response accuracy. Analysis of contextual rule−based switch cost response accuracy revealed no main effects or interactions, Fs(2, 55) ≤ 2.2, ps ≥ .12, η_p^2s ≤ .12 (see Figure 4).

Discussion

The present study provides initial evidence indicating that sports-related concussion impairments in cognitive flexibility exhibit differential trajectories of recovery, depending upon whether the task relies upon perceptual- or contextual rule−based cognitive flexibility. Although the contextual rule−based cognitive flexibility condition was associated with poorer overall response accuracy relative to the perceptual condition, concussed individuals presented with impairments in performance (as indicated by slower RT) during only the acute phase (i.e., within 72 hr following injury) in response to the contextual rule−based condition. No differences in performance were evident between the concussed and healthy control groups during the period following return to full sport participation (i.e., after return to play and 1 month following return to play) for either RT or response accuracy in response to the contextual rule−based cognitive flexibility condition. In contrast, in response to the perceptual-based cognitive flexibility condition—which was associated with greater overall response accuracy—concussed individuals presented with poorer performance (as indicated by slower RT) relative to the healthy control group during both the acute phase of injury and throughout the periods assessed following return to full sport participation.

These findings generally replicate and extend previous research observing sports-related concussion impairments in performance on assessments of cognitive flexibility, with poorer performance persisting at least 1 month beyond return to play (Howell et al., 2013; Mayr et al., 2014). Specifically, both Howell and colleagues (2013) and Mayr and colleagues (2014) observed greater switch cost RT for concussed individuals, relative to control individuals, from the acute phase of injury through testing periods 1−2 months following the concussive injury. Because the cognitive flexibility tasks employed by these previous investigations required participants to perform a sequential switch in perceptual-response mappings every second response, these concussion-related decrements

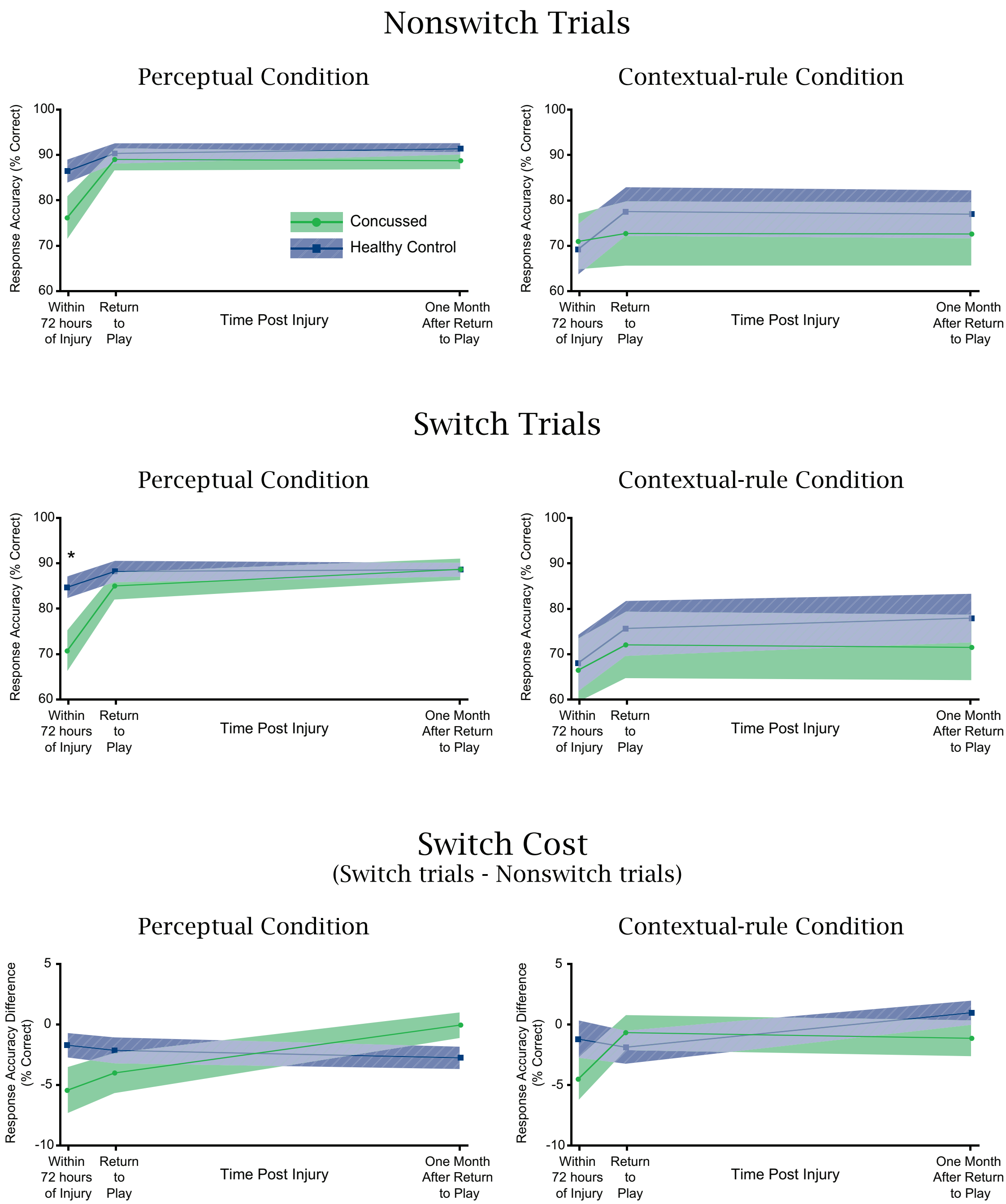

Figure 4. Illustration of response accuracy (±SE) for each group (Concussed in solid bars, Healthy Control in dashed bars) at each testing period. * $p \leq .05$. See the online article for the color version of this figure.

in performance were evident only when this switch occurred and the new task goals were retrieved and implemented.

The focus of the present investigation was to extend this line of work to probe the extent to which such findings were the result of shifts in visuospatial attention or contextual-response mappings. In contrast to the specific effects observed for switch trials by previous investigations, the present investigation observed slower RTs for the concussed, relative to healthy control, group across both switch and nonswitch trials of the perceptual condition of the odd-man-out paradigm. Such general findings suggest that the nature of the cognitive assessment may have greater relevance for detecting sports-related concussion impairments in cognition than the particular aspect of cognition the task is designed to assess. Indeed, the demands placed upon visuospatial attention by the stimuli used in the perceptual condition appear sufficient to manifest sports-related concussion decrements in performance even when no change in perceptual cue was necessary. Thus, the context of the perceptual cognitive flexibility condition requires participants to maintain control over visuospatial attention amid pseudorandom transitions between relevant perceptual cues and be constantly prepared to shift their attentional focus. These constant attentional demands may optimize the task's ability to manifest sports-related concussion decrements in performance that remained evident well beyond the return to play period. Although the contextual rule−based cognitive flexibility condition similarly presented with slower RTs for the concussed relative to healthy control group across both switch and nonswitch trials, such impairments were present during only the acute phase following concussive injury.

Clearly, however, further research is necessary to better understand the specific characteristics that contribute to concussion-related impairments in cognition persisting beyond the acute phase of injury in response to this perceptual-based, but not the contextual rule−based, cognitive flexibility assessment. Given the repeated-measures approach, it may be that the learned associations required within the contextual-rule condition are more sensitive to practice from the repeated exposure to the task, resulting in both groups' reaching an RT "floor" more rapidly than in the perceptual condition. Because the present investigation attempted to maintain consistency with existing clinically relevant neurocognitive assessment batteries and to maintain greater consistency in the working-memory load between the perceptual- and contextual-rule conditions, the button-response mapping cues were visible on the participants' screen during the task throughout both conditions. Although providing the benefit of allowing participants to regain the stimulus−response pairings if they forgot them, this approach appears to have negated the extent to which differences in response accuracy could be observed within the context of the present investigation. Thus, future research is necessary to examine the potential influence that making the button-response mapping cues available during the task may have had on enabling participants to reach a plateau in performance. Beyond further investigation of the psychometric properties of these cognitive flexibility assessments, it may also be that the observed findings result not from tapping a distinct domain of cognitive flexibility but rather from some other characteristic of the task, such as the perceptual characteristics or attentional demands.

When considered alongside the existing literature, the supposition that attentionally demanding tasks are particularly effective for eliciting sports-related concussion decrements in cognition appears well supported. Indeed, a growing body of literature has demonstrated subtle yet persistent deficits in cognition several years following a concussive injury (Broglio et al., 2009; De Beaumont, Brisson, Lassonde, & Jolicoeur, 2007; Dupuis, Johnston, Lavoie, Lepore, & Lassonde, 2000; Ellemberg et al., 2007; Giza & Hovda, 2001; Guskiewicz et al., 2005; Halterman et al., 2006; Howell et al., 2013; D. R. Moore et al., 2016; R. D. Moore, Broglio, & Hillman, 2014; R. D. Moore, Hillman, & Broglio, 2014). These deficits in cognition appear particularly pervasive in response to more cognitively demanding tasks or task conditions, such as tasks assessing aspects of executive control.

It is interesting that such investigations have typically relied upon modulating the visuospatial attentional demands of the task to increase the cognitive load. For instance, inhibitory control tasks, such as the flanker and Stroop tasks, that require participants to selectively attend to some information while gating out task-irrelevant and conflicting attentional cues have been observed to elicit sports-related concussion decrements in performance in both the acute phase and protracted periods of recovery. Sports-related concussion disruptions to inhibitory control have been exhibited well beyond the return to play period: 2 months following the injury (Howell et al., 2013), 6−8 months following the injury (Ellemberg et al., 2007), and almost three years following a concussive injury (Pontifex et al., 2012; Pontifex, O'Connor, Broglio, & Hillman, 2009). Similarly, although concussed individuals may perform at a level similar to that of healthy controls when tasks are performed individually, persistent impairments in performance have been observed in response to divided attention tasks (Register-Mihalik, Littleton, & Guskiewicz, 2013). Even years following the injury, a concussive impact appears to result in impairments in visual processing (R. D. Moore, Broglio, & Hillman, 2014), as well as impairments in the ability to sustain and modulate attention (D. R. Moore et al., 2016; R. D. Moore, Hillman, & Broglio, 2014). This is not to say that sports-related concussion decrements in cognition occur only in response to visuospatial attentional tasks or when attentional demands are increased. Rather, it would seem that tasks requiring individuals to maintain control over visuospatial attention appear particularly adept at eliciting decrements in cognition following a concussive injury. Ultimately, from a practical perspective, whether as a result of the specific characteristics and limitations of the tasks or the neural processes subserving them, the present investigation observed preliminary evidence suggesting that persistent concussion-related impairments in cognition may be more likely detected through the utilization of tasks requiring shifts of visuospatial attention.

Although the present study provides preliminary evidence that dissociable forms of cognitive flexibility exhibit differential trajectories of recovery, the findings are not without limitations that should be addressed by future investigations. In particular, further research is necessary in this area using preconcussion baseline assessments to ensure that the observed findings are indeed reflective of the effects of a sports-related concussion rather than individual differences that may predispose particular subsets of the population to concussive injuries. For instance, it may be that individuals with poorer visuospatial abilities are more susceptible to incurring a concussive injury rather than the visuospatial impairments resulting from sustaining a sports-related concussion. However, such a limitation could similarly be lobbied against much of the existing literature in this area that has used designs similar to those in the present investigation. Further, the present investigation utilized relatively stringent time-frame criteria to examine modulations in cognition following a sports-related concussion. Future investigations may mitigate the attrition rate of participants by using less stringent time-frame criteria. Moreover, given the growing evidence demonstrating modulations in cognition induced by subconcussive impacts (Broglio, Eckner, Paulson, & Kutcher, 2012; Dashnaw, Petraglia, & Bailes, 2012; Gysland et al., 2012), future investigations should examine the extent to which these differences in cognitive flexibility manifest across contact versus noncontact athletes. Although the present investigation did exclude participants with previous severe traumatic brain injury to maximize the generalizability of the participant sample, participants were included even if they had a previous history of a sports-related concussion. Although both the concussion group and the healthy control group had similar proportions of previously concussed participants and any residual impairments associated with the previous concussion would negatively influence the healthy control group as well, further research is necessary to determine the extent to which the present findings are moderated by the number of previous concussions. Given that the athletes utilized in the present investigation were on the milder end of the concussion spectrum, it is also important to acknowledge that the observed findings may not generalize to more severely concussed populations. Moreover, future studies should incorporate additional clinical measures of concussion symptomology, such as posttraumatic amnesia, current symptoms, and emotional function, to determine the extent to which these symptomologies may relate to neurocognitive changes in task performance.

In summary, the present investigation provides early evidence suggesting that the dissociable forms of cognitive flexibility—shifting visuospatial attention and shifting contextual rules—exhibit distinctive patterns of recovery. Specifically, sports-related concussion impairments on a visuospatial attention−based cognitive flexibility assessment appear to persist well beyond the return to play period, whereas impairments on a contextual rule−based cognitive flexibility assessment were observed only within the acute phase of injury (i.e., within 72 hr). Given the growing interest in enhancing the clinical management of concussed athletes, such findings may be particularly important for guiding interpretations of performance on neuropsychological batteries. That is, the present findings suggest that current neurocognitive assessment batteries that predominately rely on contextual-rule response demands—without concurrently taxing visuospatial attention—may not be sufficiently sensitive for detecting persistent cognitive impairments beyond the acute phase of injury. Accordingly, although further research is necessary to determine the clinical feasibility and diagnostic relevance of these findings, the present findings would speculatively suggest that perceptual-based switch tasks may be useful additions for the objective clinical assessment and follow-up after concussive injuries because they would appear to highlight an aspect of cognition that may be more persistently impaired. Because shifting visuospatial attention is a critical ability for attending to task-relevant cues, returning athletes to play while they are still exhibiting impairments in the ability to shift visuospatial attention may increase the likelihood that they will incur further injury.

References

Barth, J. T., Macciocchi, S. N., Giordani, B., Rimel, R., Jane, J. A., & Boll, T. J. (1983). Neuropsychological sequelae of minor head injury. *Neurosurgery, 13,* 529–533. http://dx.doi.org/10.1227/00006123-198311000-00008

Belanger, H. G., & Vanderploeg, R. D. (2005). The neuropsychological impact of sports-related concussion: A meta-analysis. *Journal of the International Neuropsychological Society, 11,* 345–357. http://dx.doi.org/10.1017/S1355617705050411

Broglio, S. P., Eckner, J. T., Paulson, H. L., & Kutcher, J. S. (2012). Cognitive decline and aging: The role of concussive and subconcussive impacts. *Exercise and Sport Sciences Reviews, 40,* 138–144.

Broglio, S. P., Pontifex, M. B., O'Connor, P., & Hillman, C. H. (2009). The persistent effects of concussion on neuroelectric indices of attention. *Journal of Neurotrauma, 26,* 1463–1470. http://dx.doi.org/10.1089/neu.2008.0766

Collins, M. W., Grindel, S. H., Lovell, M. R., Dede, D. E., Moser, D. J., Phalin, B. R., . . . McKeag, D. B. (1999). Relationship between concussion and neuropsychological performance in college football players. *JAMA: Journal of the American Medical Association, 282,* 964–970. http://dx.doi.org/10.1001/jama.282.10.964

Covassin, T., Moran, R., & Wilhelm, K. (2013). Concussion symptoms and neurocognitive performance of high school and college athletes who incur multiple concussions. *American Journal of Sports Medicine, 41,* 2885–2889. http://dx.doi.org/10.1177/0363546513499230

Cremona-Meteyard, S. L., & Geffen, G. M. (1994). Persistent visuospatial attention deficits following mild head injury in Australian Rules football players. *Neuropsychologia, 32,* 649–662. http://dx.doi.org/10.1016/0028-3932(94)90026-4

Dashnaw, M. L., Petraglia, A. L., & Bailes, J. E. (2012). An overview of the basic science of concussion and subconcussion: Where we are and where we are going. *Neurosurgical Focus, 33,* E5. http://dx.doi.org/10.3171/2012.10.FOCUS12284

De Beaumont, L., Brisson, B., Lassonde, M., & Jolicoeur, P. (2007). Long-term electrophysiological changes in athletes with a history of multiple concussions. *Brain Injury, 21,* 631–644. http://dx.doi.org/10.1080/02699050701426931

Delaney, J. S., Lacroix, V. J., Leclerc, S., & Johnston, K. M. (2002). Concussions among university football and soccer players. *Clinical Journal of Sport Medicine, 12,* 331–338. http://dx.doi.org/10.1097/00042752-200211000-00003

DeRenzo, E. G., Conley, R. R., & Love, R. (1998). Assessment of capacity to give consent to research participation: State-of-the-art and beyond. *Journal of Health Care Law & Policy, 1,* 66–87.

Dettwiler, A., Murugavel, M., Putukian, M., Cubon, V., Furtado, J., & Osherson, D. (2014). Persistent differences in patterns of brain activation after sports-related concussion: A longitudinal functional magnetic resonance imaging study. *Journal of Neurotrauma, 31,* 180–188. http://dx.doi.org/10.1089/neu.2013.2983

Dupuis, F., Johnston, K. M., Lavoie, M., Lepore, F., & Lassonde, M. (2000). Concussions in athletes produce brain dysfunction as revealed by event-related potentials. *NeuroReport, 11,* 4087–4092. http://dx.doi.org/10.1097/00001756-200012180-00035

Ellemberg, D., Leclerc, S., Couture, S., & Daigle, C. (2007). Prolonged neuropsychological impairments following a first concussion in female university soccer athletes. *Clinical Journal of Sport Medicine, 17,* 369–374. http://dx.doi.org/10.1097/JSM.0b013e31814c3e3e

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39,* 175–191.

Field, M., Collins, M. W., Lovell, M. R., & Maroon, J. (2003). Does age play a role in recovery from sports-related concussion? A comparison of high school and collegiate athletes. *Journal of Pediatrics, 142,* 546–553. http://dx.doi.org/10.1067/mpd.2003.190

Giza, C. C., & Hovda, D. A. (2001). The neurometabolic cascade of concussion. *Journal of Athletic Training, 36,* 228–235.

Guskiewicz, K. M., Marshall, S. W., Bailes, J., McCrea, M., Cantu, R. C., Randolph, C., & Jordan, B. D. (2005). Association between recurrent concussion and late-life cognitive impairment in retired professional football players. *Neurosurgery, 57,* 719–726. http://dx.doi.org/10.1093/neurosurgery/57.4.719

Gysland, S. M., Mihalik, J. P., Register-Mihalik, J. K., Trulock, S. C., Shields, E. W., & Guskiewicz, K. M. (2012). The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Annals of Biomedical Engineering, 40,* 14–22. http://dx.doi.org/10.1007/s10439-011-0421-3

Halterman, C. I., Langan, J., Drew, A., Rodriguez, E., Osternig, L. R., Chou, L. S., & van Donkelaar, P. (2006). Tracking the recovery of visuospatial attention deficits in mild traumatic brain injury. *Brain: A Journal of Neurology, 129,* 747–753. http://dx.doi.org/10.1093/brain/awh705

Howell, D., Osternig, L., van Donkelaar, P., Mayr, U., & Chou, L. S. (2013). Effects of concussion on attention and executive function in adolescents. *Medicine and Science in Sports and Exercise, 45,* 1030–1037. http://dx.doi.org/10.1249/MSS.0b013e3182814595

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology, 4,* 863.

Langlois, J. A., Rutland-Brown, W., & Wald, M. M. (2006). The epidemiology and impact of traumatic brain injury: A brief overview. *Journal of Head Trauma Rehabilitation, 21,* 375–378. http://dx.doi.org/10.1097/00001199-200609000-00001

Marsh, N. V., & Smith, M. D. (1995). Post-concussion syndrome and the coping hypothesis. *Brain Injury, 9,* 553–562. http://dx.doi.org/10.3109/02699059509008214

Mayer, A. R., Mannell, M. V., Ling, J., Elgie, R., Gasparovic, C., Phillips, J. P., . . . Yeo, R. A. (2009). Auditory orienting and inhibition of return in mild traumatic brain injury: A FMRI study. *Human Brain Mapping, 30,* 4152–4166. http://dx.doi.org/10.1002/hbm.20836

Mayr, U., LaRoux, C., Rolheiser, T., Osternig, L., Chou, L.-S., & van Donkelaar, P. (2014). Executive dysfunction assessed with a task-switching task following concussion. *PLoS ONE, 9*(3): e91379. http://dx.doi.org/10.1371/journal.pone.0091379

McCrea, M., Guskiewicz, K. M., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., . . . Kelly, J. P. (2003). Acute effects and recovery time following concussion in collegiate football players: The NCAA Concussion Study. *Journal of the American Medical Association, 290,* 2556–2563. http://dx.doi.org/10.1001/jama.290.19.2556

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167–202. http://dx.doi.org/10.1146/annurev.neuro.24.1.167

Moore, D. R., Pindus, D. M., Raine, L. B., Drollette, E. S., Scudder, M. R., Ellemberg, D., & Hillman, C. H. (2016). The persistent influence of concussion on attention, executive control and neuroelectric function in preadolescent children. *International Journal of Psychophysiology, 99,* 85–95. http://dx.doi.org/10.1016/j.ijpsycho.2015.11.010

Moore, R. D., Broglio, S. P., & Hillman, C. H. (2014). Sport-related concussion and sensory function in young adults. *Journal of Athletic Training, 49,* 36–41. http://dx.doi.org/10.4085/1062-6050-49.1.02

Moore, R. D., Hillman, C. H., & Broglio, S. P. (2014). The persistent influence of concussive injuries on cognitive control and neuroelectric function. *Journal of Athletic Training, 49,* 24–35. http://dx.doi.org/10.4085/1062-6050-49.1.01

Pontifex, M. B., Broglio, S. P., Drollette, E. S., Scudder, M. R., Johnson, C. R., O'Connor, P. M., & Hillman, C. H. (2012). The relation of mild traumatic brain injury to chronic lapses of attention. *Research Quarterly for Exercise and Sport, 83,* 553–559. http://dx.doi.org/10.1080/02701367.2012.10599252

Pontifex, M. B., O'Connor, P. M., Broglio, S. P., & Hillman, C. H. (2009). The association between mild traumatic brain injury history and cognitive control. *Neuropsychologia, 47,* 3210–3216. http://dx.doi.org/10.1016/j.neuropsychologia.2009.07.021

R Core Team. (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from https://www.R-project.org/

Ravizza, S. M., & Carter, C. S. (2008). Shifting set about task switching: Behavioral and neural evidence for distinct forms of cognitive flexibility. *Neuropsychologia, 46,* 2924–2935. http://dx.doi.org/10.1016/j.neuropsychologia.2008.06.006

Register-Mihalik, J. K., Littleton, A. C., & Guskiewicz, K. M. (2013). Are divided attention tasks useful in the assessment and management of sport-related concussion? *Neuropsychology Review, 23,* 300–313. http://dx.doi.org/10.1007/s11065-013-9238-1

Stephens, R., Rutherford, A., Potter, D., & Fernie, G. (2010). Neuropsychological consequence of soccer play in adolescent U.K. school team soccer players. *Journal of Neuropsychiatry and Clinical Neurosciences, 22,* 295–303. http://dx.doi.org/10.1176/jnp.2010.22.3.295

Terry, D. P., Faraco, C. C., Smith, D., Diddams, M. J., Puente, A. N., & Miller, L. S. (2012). Lack of long-term fMRI differences after multiple sports-related concussions. *Brain Injury, 26,* 1684–1696. http://dx.doi.org/10.3109/02699052.2012.722259

van Donkelaar, P., Langan, J., Rodriguez, E., Drew, A., Halterman, C., Osternig, L. R., & Chou, L. S. (2005). Attentional deficits in concussion. *Brain Injury, 19,* 1031–1039. http://dx.doi.org/10.1080/02699050500110363

Wasserman, E. B., Kerr, Z. Y., Zuckerman, S. L., & Covassin, T. (2016). Epidemiology of sports-related concussions in National Collegiate Athletic Association athletes from 2009–2010 to 2013–2014: Symptom prevalence, symptom resolution time, and return-to-play time. *American Journal of Sports Medicine, 44,* 226–233. http://dx.doi.org/10.1177/0363546515610537

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