

Eye Movements Detect Differential Change after Participation in Male Collegiate Collision versus Non-Collision Sports

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Abstract

Although neuroimaging studies of collision (COLL) sport athletes demonstrate alterations in brain structure and function from pre- to post-season, reliable tools to detect behavioral/cognitive change relevant to functional networks associated with participation in collision sports are lacking. This study evaluated the use of eye-movement testing to detect change in cognitive and sensorimotor processing among male club collegiate athletes after one season of participation in collision sports of variable exposure. We predicted that COLL (High Dose [hockey], $n=8$; Low Dose [rugby], $n=9$) would demonstrate longer reaction times (antisaccade and memory-guided saccade [MGS] latencies), increased inhibitory errors (antisaccade error rate), and poorer spatial working memory (MGS spatial accuracy) at post-season, relative to pre-season, whereas non-collision collegiate athletes (NON-COLL; $n=17$) would remain stable. We also predicted that whereas eye-movement performance would detect pre- to post-season change, ImpACT (Immediate Post-Concussion Assessment and Cognitive Test) performance would remain stable. Our data showed that NON-COLL had shorter (improved performance) post- versus pre-season antisaccade and MGS latencies, whereas COLL groups showed stable, longer, or attenuated reduction in latency ($p \leq 0.001$). Groups did not differ in antisaccade error rate. On the MGS task, NON-COLL demonstrated improved spatial accuracy over time, whereas COLL groups showed reduced spatial accuracy ($p < 0.05$, uncorrected). No differential change was observed on ImpACT. This study provides preliminary evidence for eye-movement testing as a sensitive marker of subtle changes in attentional control and working memory resulting from participation in sports with varying levels of subconcussive exposure.

Keywords: collision sports; eye tracking; oculomotor; repetitive head trauma; subconcussive

Introduction

Participation in collision sports (e.g., American football, ice hockey, rugby, and soccer) increases a person's exposure to head impacts, which occur when a biomechanical force is imparted on the brain because of a blow to the head or body.^{1,2} A head impact may result in a concussion, in which clinical signs and symptoms are present, such as loss of consciousness, confusion, and amnesia.² More frequently, however, head impacts fall into the category of subconcussive injuries in which no apparent

clinical signs or symptoms are present, but pathophysiological changes in the brain affecting vasculature and white matter may occur and may have cumulative adverse effects over time (although this remains controversial given the infancy of the literature).^{1,3-6} Specifically, chronic exposure to repetitive head impacts, including concussive and subconcussive events, may be associated with increased risk for long-term neurocognitive and psychiatric outcomes, including chronic traumatic encephalopathy, Alzheimer's disease, major depressive

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disorder, and deficits in executive functions, language, and memory.^{4,7-9} Subconcussive impacts are particularly concerning in adolescents because neural circuits critical for higher-order cognitive functions, including attentional control and working memory, develop throughout adolescence and into early adulthood.^{10,11}

Neuroimaging studies assessing subconcussive events over the course of an athletic season have demonstrated longitudinal alterations in white matter structure and functional activation among high school and college athletes.¹²⁻¹⁹ Although neuroimaging methods have detected change associated with subconcussive injuries, it is not financially feasible for tracking change associated with exposure to subconcussive impacts on a large scale, and, more important, structural neuroimaging does not provide information regarding potential cognitive or behavioral consequences associated with cumulative subconcussive impact exposure.

Studies directly examining cognitive effects of subconcussive injury associated with collision athletics participation have yielded mixed findings, with some reporting pre- to post-season decline in processing speed, attention, and memory¹⁹⁻²² and others observing no change over the season.²³⁻²⁶ Given that cognitive change is observed variably in the short term, but more consistently in the long term,⁹ it is possible the cognitive measures currently used to evaluate possible subtle cognitive change associated with subconcussive impacts lack adequate sensitivity. Recently, eye-movement testing has emerged as a promising tool for detecting neurocognitive and sensorimotor change after concussive²⁷⁻²⁹ and subconcussive head trauma among female athletes.³⁰ Eye-movement testing provides an assay to evaluate sensorimotor processing, speed of attentional shifting, executive control, inhibition, and working memory, which are domains often affected by head injury.³¹ Further, eye-movement testing is ideally suited to detect effects of brain trauma given that most aspects of classic saccadic eye-movement task performance have been localized to specific neuroanatomical areas and networks.³²

The primary aim of this study was to evaluate whether eye-movement testing detects change in sensorimotor and cognitive processing after male collegiate athletes' participation in collision sports. We specifically focused on ice hockey and rugby, which have elevated rates of subclinical head trauma exposure.³³⁻³⁵ We compared the longitudinal eye-movement performance of male, collegiate club collision sport athletes (COLL) to male, collegiate club

non-collision sport athletes (NON-COLL). Several classic saccadic eye-movement tasks were used in this study: prosaccade, antisaccade, and the memory-guided saccade (MGS) tasks (see Gallagher and colleagues for further task information).³⁰ Given that saccade tasks assessing executive functions (antisaccade and MGS) were more sensitive to the effects of contact sport participation among female collegiate athletes relative to the less cognitively demanding prosaccade task,³⁰ we expected that the antisaccade and MGS tasks would be more sensitive to the effects of collision sport participation among male athletes, relative to the reflexive visual attention prosaccade task.

In the main analyses of interest, we hypothesized that collision sport athletes would demonstrate the following changes (reflecting reduced executive attentional control and working memory ability) at post-season, relative to pre-season, whereas non-collision sport athletes would demonstrate stability over time: 1) longer antisaccade latency (reaction time); 2) increased antisaccade error rate (inhibitory errors); 3) longer MGS latency (reaction time); and 4) poorer spatial accuracy on the MGS task (spatial working memory).

We also explored whether collision sport athletes would demonstrate longer prosaccade latency, gain (overshooting), prolonged duration, and slower velocity at post-season, relative to pre-season, whereas we expected non-collision athletes to remain stable over time. Given that ImPACT (Immediate Post-Concussion Assessment and Cognitive Test) is the most commonly used tool in the literature to assess cognitive change as the result of exposure to subconcussive impacts, we also compared pre- to post-season change in cognitive abilities as measured by ImPACT.³⁶ We hypothesized that among collision sport athletes, pre- to post-season change would not be observed on ImPACT whereas it would be observed on eye-movement testing.

Methods

Participants and recruitment

Male university club athletes between ages 18 and 25 years who planned to participate in at least 85% of team practices and games were recruited. Exclusion criteria were factors known to influence eye-movement performance such as a lifetime diagnosis of a psychotic disorder,³⁷ a first-degree relative with a psychotic disorder,³⁸ a history of a seizure disorder,³⁹ a concussion within the previous 6 months, or lifetime history of moderate-to-severe head injury.⁴⁰ Because of unforeseen



changes in schedule and participation, male club ice hockey players were assigned to the COLL-High Dose group, and male club rugby players were assigned to the COLL-Low Dose group (see *Schedule of activities* section below). Male club crew, cross-country, swimming (divers excluded), and triathlon athletes were assigned to the NON-COLL group and all denied concurrent participation in intermural or club collision sports. All participants completed an in-person informed consent and were compensated at \$20 per hour for their time. This study was approved by the university's institutional review board.

Procedure

Schedule of activities. Athletes were assessed at two time points (pre- and post-season). For COLL, the pre-season visit was completed before the commencement of pre-season training and was scheduled to maximize the time since the end of the previous competitive season. Pre-season visit procedures for NON-COLL athletes occurred shortly after the start of the regular season competition because of the availability of athletes and research equipment.

Because of unforeseen circumstances, the rugby team's season unexpectedly ended halfway through the season, resulting in decreased playing time than expected (lower dose of exposure) and increased duration between the last game and the post-season assessment (mean = 19.00 days, standard deviation [SD] = 5.07). Post-season visits for COLL-High Dose took place an average of 11.38 days (SD = 14.00) after the most recent competitive match. NON-COLL athletes were scheduled for post-season visits so that the mean duration between pre- and post-season would be the same for both groups. At each visit, participants completed eye-movement testing, questionnaires, and ImPACT testing. Athletes were instructed not to use caffeine, stimulants, or nicotine within 1 h preceding visits to reduce the potential effect of those confounding factors on eye-movement performance.⁴¹

Eye-movement testing. Eye movements were measured in a windowless room using the Eyelink1000 Plus system (SR Research Ltd, Kanata, Ontario, Canada), a state-of-the-art infrared video-recording system that permits for high-resolution (1000 Hz; microsaccade resolution of 0.05 degrees) recording of eye position. Primary eye-movement measurements of interest on the prosaccade task are latency, gain, accuracy, duration, and peak velocity, as detailed in past work.³⁰ On

the antisaccade task, the primary eye-movement measurements of interest are primary saccade latency and antisaccade error rate (error trials/total trials), a measure of executive inhibition and cognitive control. On the MGS task, the primary eye-movement measurements of interest are primary saccade latency, primary saccade accuracy, and resting position accuracy. See Gallagher and colleagues for further details.³⁰

Immediate Post-Concussion Assessment and Cognitive Test. ImPACT is a 25-min computerized cognitive battery designed for ages 12–59, delivered by a secure Web portal.⁴² The test consists of six subtests that yield four normed composite scores: verbal memory, visual memory, visual-motor speed, and reaction time. Test version 3.4.0 was used in this study and was administered by a trained ImPACT administrator in group format in a computer laboratory for the majority of participants; because of scheduling issues, 3 participants completed ImPACT individually in a clinic room, administered by a trained ImPACT administrator, at both pre- and post-season.

Questionnaires. Before in-person study assessments, all participants completed a comprehensive questionnaire regarding demographic, health history (including concussion history), recent athletic participation information, recent substance use (30-day Timeline Followback),^{43–45} educational background, and parental education and occupational history (to yield a total socioeconomic status score).⁴⁶

In addition, participants completed the following questionnaires online (within 24 h of eye-movement testing) at both visits to assess the influence of physical, cognitive, and emotional symptoms on eye-movement performance. The Post-Concussion Symptom Scale (PCSS), a commonly used measure in clinical and research domains, was used to assess presence and severity of physical, cognitive, and emotional symptoms that occur in both concussed and healthy populations.⁴⁷ The PCSS symptom severity score (range, 0–132) was used in analyses. The Beck Depression Inventory-II (BDI-II) is a 21-item self-report questionnaire that was used to assess the characteristic attitudes and symptoms of depression.^{48,49} The State-Trait Anxiety Inventory (STAI), a commonly used 40-item measure of trait and state anxiety, was used to differentiate situational versus dispositional anxiety.⁵⁰ The Perceived Stress Scale (PSS) is a 10-item questionnaire that was used to assess baseline levels of one's ability to handle stress.^{51,52}



Participation and exposure measurement. To grossly estimate exposure to collision sport participation, team captains for COLL teams recorded participant practice and game attendance; players were marked as “not present” if they attended but did not participate in a practice or game. Total minutes of attendance was calculated by summing the athletes’ total number of practices/games and multiplying that sum by practice/game length, respectively. COLL athletes also self-reported the date of the most recent competition they participated in, and COLL and NON-COLL athletes self-reported the dates of the most recent practices they participated in; this information was cross-referenced with attendance logs provided by COLL team captains; attendance logs were not available for NON-COLL athletes.

Data analyses

See Gallagher and colleagues for eye-movement data scoring and cleaning procedures.³⁰

Statistical analyses. Statistical analyses were performed using IBM SPSS Statistics for Windows (Version 25.0; IBM Corp., Armonk, NY).⁵³ Descriptive analyses were conducted to evaluate group differences in demographic and clinical history information; specific tests included one-way analyses of variance and chi-square tests. General linear mixed modeling of trial-wise data was used to evaluate group differences on eye-movement measures of interest within task. See the Supplementary Materials for further details on eye-movement statistical analyses. Pre- to post-season change on ImPACT performance was conducted using a repeated-measures multi-variate analysis of variance. Alpha thresholds for the five main hypotheses tests (four eye movement, one ImPACT) were corrected for multiple comparisons (Bonferroni corrected, $p=0.01$ [0.05/5]). Effect sizes (d_{poc2}) were calculated for significant main hypotheses testing results; effect sizes reflect the difference in mean pre- to post-season change in eye-movement performance (averaged across conditions) between the COLL-High Dose versus NON-COLL group or between the COLL-Low Dose versus the NON-COLL group, divided by the pooled pre-season SD.⁵⁴

Results

Enrollment, demographic, mood, and substance-use data

The final sample included 8 COLL-High Dose, 9 COLL-Low Dose, and 17 NON-COLL athletes. The NON-COLL group consisted of 9 crew, 3 swimming,

2 triathlon, 2 cross-country, and 1 track athletes. One COLL-High Dose athlete sustained a concussion during the season; the injury was sustained 108 days earlier, and he was cleared for full return to play 87 days before the post-season assessment. All statistical analyses were first completed with the concussed COLL-High Dose player included and then repeated with his data excluded; results were consistent. Therefore, this subject was retained in the sample.

Pre-season assessments among hockey players were conducted an average of 30.89 weeks (SD=3.51, range=22.28–33.29) after the athletes’ most recent competitive game; pre-season assessments among rugby players were conducted an average of 9.86 weeks (SD=0.96, range=8.71–11.29) after the athletes’ most recent competitive game. There were no significant group differences in demographic or health history information; see Table 1. There were significant group differences in pre-season BDI-II total scores and duration between visits, but neither of these factors were associated with eye-movement performance at baseline or change on eye-movement testing from pre- to post-season; see Table 2. There was also no visit (pre- vs. post-season) or group-by-visit effects on mood or symptom ratings (BDI-II, PCSS, STAI, or PSS). Groups differed on mean days since most recent practice participation (COLL-High Dose vs. COLL-Low Dose vs. NON-COLL) and total minutes of game attendance (COLL-High Dose vs. COLL-Low Dose); see Table 2.

Eye movement

See Supplementary Tables S1–S3 for descriptive eye-movement data among groups. See Table 3 for general linear mixed-model results with significant visit-by-group-by-condition and/or visit-by-group interaction effects. Only main effects of interest (visit-by-group-by-condition and visit-by-group) are reported in the Results section. Given the high correlation between saccade gain and accuracy ($r_{(5582)}=0.848$, $p<0.001$), only the results of gain analyses are reported to reduce redundancy.

Prosaccade task. On the reflexive, prosaccade task, there was a visit-by-group-by-condition interaction effect ($F_{(10, 5482)}=7.616$, $p<0.001$), but no visit-by-group effect, such that, post-season, COLL groups demonstrated longer latency on overlap (High Dose, 2.21% increase; Low Dose, 4.85% increase) and, to a lesser extent, no gap trials (High Dose, 1.97% increase; Low



Table 1. Sample Demographic and Health History Information

	Group		
	Collision-High Dose Hockey (n=8)	Collision-Low Dose Rugby (n=9)	Non-collision (n=17)
Age, M (SD)	19.38 (0.92)	19.78 (1.48)	19.47 (0.94)
Race (% Caucasian)	88%	56%	82%
Ethnicity (% Hispanic or Latino)	0%	22%	6%
Socioeconomic status (Hollingshead four-factor, M [SD])	162.88 (18.52)	152.29 (20.70)	131.64 (38.84)
Years of education, M (SD)	13.39 (0.92)	13.11 (1.27)	13.53 (0.94)
Hx of anxiety or depression	13%	22%	6%
Hx of learning disability or ADHD	0%	0%	3%
Hx of one or more previous concussions	38%	33%	24%

Data presented as mean (standard deviation), where indicated, or percentage (%) of group. Hx= self-reported history. Years of education reflects highest year of education completed (13 years= completed freshmen year of college). No significant group differences detected. ADHD, attention-deficit hyperactivity disorder.

Dose, 1.80% increase), but shorter latency on gap trials (High Dose, 6.84% decrease; Low Dose, 1.26% decrease), relative to pre-season performance. NON-COLL, however, demonstrated relative stability over time (percent change, $\leq 1.69\%$ across conditions); see Figure 1. There was also a visit-by-group interaction effect on peak velocity ($F_{(2, 2014)} = 5.208, p = 0.006$), in which NON-COLL and COLL-Low Dose demonstrated faster velocity at post-season by 2.61% and 2.88%, respectively, but COLL-High Dose demon-

strated slower velocity at post-season by 1.58% relative to pre-season performance. There were no visit-by-group effects on prosaccade gain or duration.

Antisaccade task. There were significant visit-by-group-by-condition ($F_{(10, 4599)} = 3.970, p < 0.001$) and visit-by-group ($F_{(2, 4599)} = 6.645, p = 0.001$) interaction effects on antisaccade latency. COLL-High Dose demonstrated stable latency (0.02% decrease, averaged across conditions; $d_{ppc2} = 0.231$), COLL-Low Dose

Table 2. Mood, Substance Use, and Participation Data

	Group			p value
	Collision-High Dose Hockey (n=8)	Collision-Low Dose Rugby (n=9)	Non-collision (n=17)	
Visit 1 information				
BDI-II total	2.50 (1.93)	9.22 (9.43)	3.94 (3.61)	0.035
PCSS total	8.38 (8.78)	14.11 (12.21)	12.00 (12.18)	ns
STAI state total	28.63 (3.81)	37.56 (15.15)	35.00 (9.70)	ns
STAI trait total	28.13 (3.56)	40.89 (15.83)	35.47 (9.10)	ns
Perceived stress total	8.88 (3.72)	14.89 (9.27)	12.88 (5.53)	ns
Total days alcohol consumption in previous 30 days	8.88 (6.62)	8.56 (7.80)	5.00 (5.43)	ns
Total servings of alcohol previous 30 days	36.00 (23.82)	35.44 (40.73)	31.00 (37.34)	ns
Average servings alcohol/consumption day	4.30 (0.89)	4.17 (1.33)	5.50 (2.50)	ns
Visit 2 information				
BDI-II	2.75 (2.44)	10.44 (12.84)	4.50 (4.73)	ns
PCSS	11.50 (11.65)	22.56 (24.26)	13.59 (15.95)	ns
STAI state total	28.88 (6.38)	40.44 (17.02)	36.24 (11.49)	ns
STAI trait total	32.25 (8.26)	41.33 (18.11)	35.82 (11.71)	ns
Perceived stress total	10.88 (3.00)	17.44 (8.85)	14.65 (6.54)	ns
Total days alcohol consumption in previous 30 days	8.25 (5.29)	8.78 (7.88)	4.00 (4.29)	ns
Total servings of alcohol previous 30 days	41.38 (32.53)	33.72 (29.97)	23.41 (34.26)	ns
Average servings alcohol/consumption day	4.93 (1.45)	3.75 (2.26)	4.70 (3.25)	ns
Weeks between pre- and post-season visit	20.29 (0.22)	17.32 (0.38)	18.55 (1.44)	<0.001
Participation and exposure information				
Days since most recent practice participation: post-season visit	6.38 (7.11)	19.00 (7.48)	3.35 (5.53)	<0.001
Days since most recent competition participation: post-season visit	11.38 (14.00)	19.00 (5.07)	—	ns
Total minutes of practice attendance	1766.25 (464.77)	1750.00 (607.73)	—	ns
Total minutes of competition attendance	1140.00 (525.03)	89.89 (75.15)	—	<0.001

Data presented as mean (standard deviation), unless otherwise indicated. ns = no significant differences among or between groups. BDI-II, Beck Depression Inventory-II; PCSS, Post-Concussion Symptom Scale; STAI, State-Trait Anxiety Inventory.



Table 3. Significant Group (COLL-High Dose vs. COLL-Low Dose vs. NON-COLL) General Linear Mixed-Model Results

Task	Measure	Predictor	df _{numerator}	df _{denominator}	F	p value	
Prosaccade	Latency	Visit	1	5482	0.823	0.364	
		Condition	2		840.458	<0.001	
		Group	2		0.173	0.841	
		Visit*Group	2		1.862	0.155	
		Visit*Group*Condition	10		7.616	<0.001	
	Peak velocity	Visit	1	2014	5.570	0.018	
		Group	2		0.777	0.46	
		Visit*Group	2	5.208	0.006		
Antisaccade	Latency	Visit	1	4599	26.084	<0.001	
		Condition	2		545.363	<0.001	
		Group	2		0.317	0.729	
		Visit*Group	2		6.645	0.001	
		Visit*Group*Condition	10		3.970	<0.001	
Memory-guided saccade	Latency	Visit	1	3893	0.411	0.522	
		Condition	3		470.716	<0.001	
		Group	2		3.958	0.019	
		Visit*Group	2		20.614	<0.001	
		Visit*Group*Condition	15		3.508	<0.001	
	Primary saccade accuracy	Visit	1	3959	0.002	0.962	
		Condition	3		25.059	<0.001	
		Group	2		0.323	0.724	
		Visit*Group	2		3.061	0.047	
	Resting fixation accuracy	Condition	Visit*Group*Condition	15	4047	1.423	0.127
			Condition	3		5.694	0.001
			Visit*Group	5		2.397	0.035
			Condition	3		5.694	0.001

Only includes analyses with significant visit-by-group or visit-by-group-by-condition interaction effects. Asterisk (“**”) signifies a two- or three-way interaction effect.

COLL, collision; NON-COLL, non-collision.

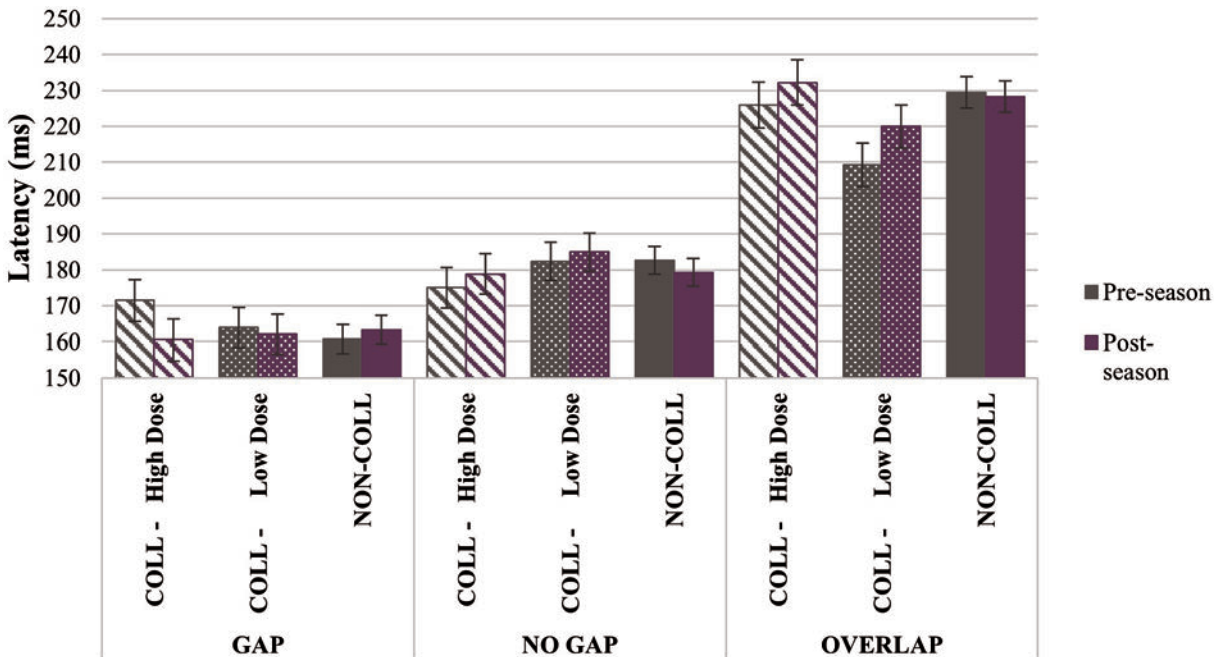


FIG. 1. Prosaccade latency by visit, group, and condition. Compared to pre-season performance, COLL groups demonstrated longer latency on no gap and overlap, but shorter latency on gap at post-season; NON-COLL demonstrated relatively stable latency across conditions from pre- to post-season (visit-by-group-by-condition interaction effect, $p < 0.001$). COLL, collision; NON-COLL, non-collision.



demonstrated intermediary shortened latency (2.03% decrease, averaged across conditions; $d_{ppc2}=0.134$), and NON-COLL demonstrated more-pronounced shortened latency (4.33% decrease, averaged across conditions), at post-season relative to pre-season; greater improvement on latency across groups was observed on the gap condition; see Figure 2. There were no visit-by-group effects on antisaccade error rate.

Memory-guided saccade task

There were significant visit-by-group-by-condition ($F_{(15, 3893)}=3.508, p<.001$) and visit-by-group ($F_{(2, 3893)}=20.614, p<0.001$) interaction effects on MGS latency, in which NON-COLL demonstrated shorter latency at post-season, relative to pre-season (6.48% decrease averaged across conditions), particularly on 1000-, 2000-, and 8000-ms delay conditions ($\geq 5\%$ decrease); COLL-High Dose demonstrated relatively stable latency from pre- to post-season (0.31% mean increase, averaged across conditions; $d_{ppc2}=0.293$, with change on each condition $\leq 1.03\%$); COLL-Low Dose demonstrated

longer latency from pre- to post-season (3.86% increase averaged across conditions; $d_{ppc2}=0.452$), particularly on 2000- (8.45% increase) and 8000-ms (6.76% increase) conditions; see Figure 3.

There were also significant (uncorrected) visit-by-group interaction effects on the accuracy of the primary saccade ($F_{(2, 3959)}=3.061, p=0.047$) and accuracy of the resting fixation position ($F_{(5, 4047)}=2.397, p=0.035$), although there were no visit-by-group-by-condition effects, and these comparisons did not survive Bonferroni's correction. NON-COLL demonstrated improved accuracy of the primary saccade (7.33% decreased error) and the rest position (7.04% decreased error) pre- to post-season, whereas COLL-High Dose and COLL-Low Dose demonstrated decreased accuracy of the primary saccade (3.17% and 3.28% increased error, respectively) and stable accuracy of the rest position over time; see Figure 4. There were no significant visit-by-group-by-condition or visit-by-group effects on delay period errors (i.e., looks to target occurring during the delay period).

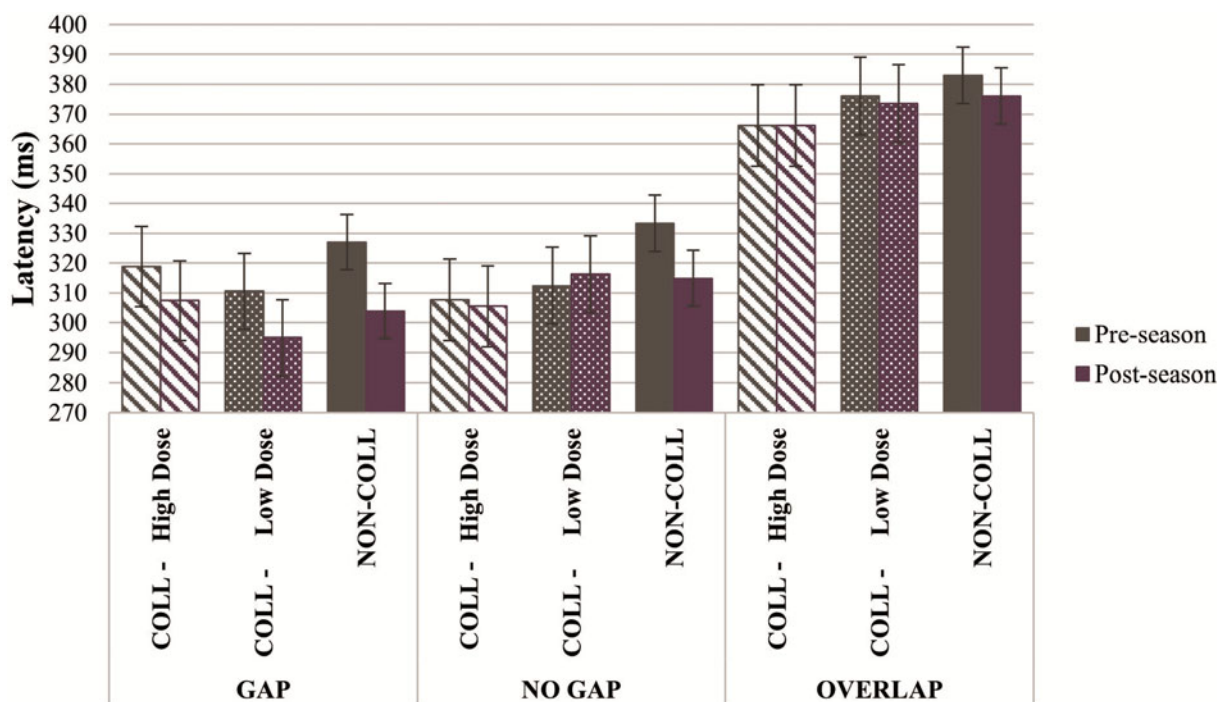


FIG. 2. Antisaccade latency by visit, group, and condition. Compared to pre-season performance, NON-COLL demonstrated shorter latency at post-season across conditions, whereas COLL groups demonstrated relatively stable latency from pre- to post-season averaged across conditions, with greater change observed on gap versus no gap and overlap conditions (visit-by-group-by-condition interaction effect, $p<0.001$; visit-by-group effect, $p=0.001$). COLL, collision; NON-COLL, non-collision.



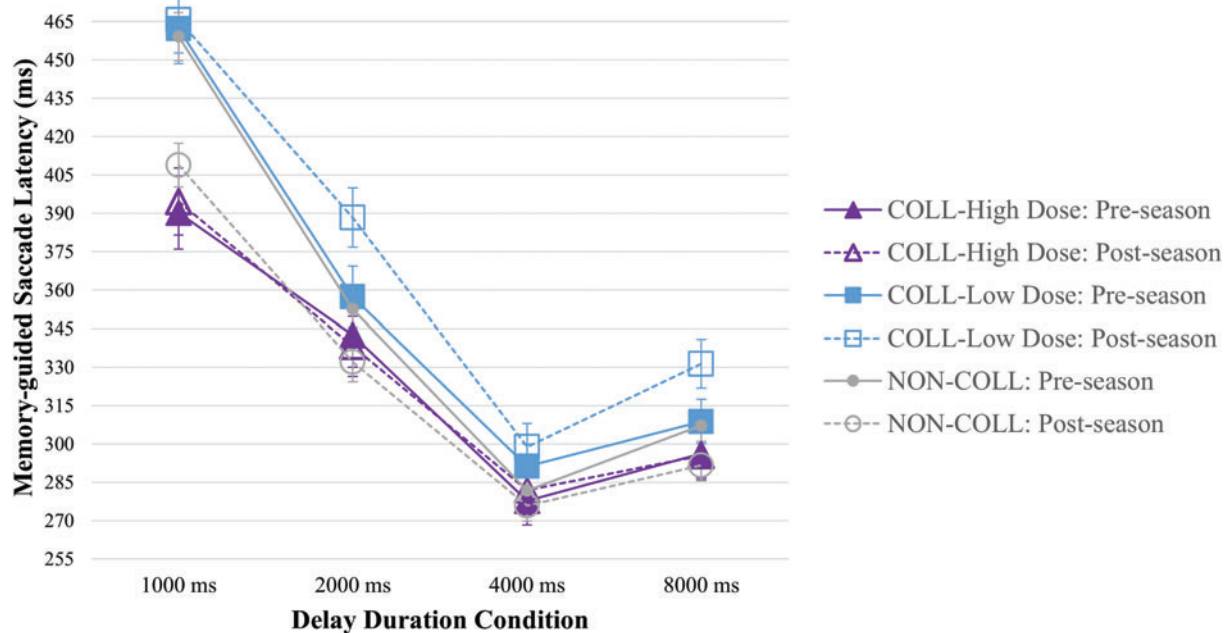


FIG. 3. Memory-guided saccade latency by visit, group, and condition. Compared to pre-season performance, *NON-COLL* demonstrated shorter latency across conditions, particularly on 1000-ms delay duration trials, *COLL-High Dose* demonstrated relatively stable latency, and *COLL-Low Dose* demonstrated longer latency, particularly on 2000- and 8000-ms delay duration conditions, at post-season (visit-by-group-by-condition and visit-by-group interaction effects, $p < 0.001$). COLL, collision; NON-COLL, non-collision.

Immediate Post-Concussion Assessment and Cognitive Test

One NON-COLL athlete from the final eye-movement sample did not attend post-season ImPACT testing and was lost to follow-up (ImPACT NON-COLL, $n = 16$). There was no group-by-time interaction effect on ImPACT composite scores ($F_{(8, 56)} = 0.343$, $p = 0.945$); there was a significant effect of time ($F_{(4, 27)} = 3.524$, $p = 0.019$), driven by visual motor composite score increase (improved performance), at post-season relative to pre-season across all groups ($p < 0.01$); see Table 4.

Discussion

This study evaluated the use of eye-movement testing to detect change related to participation in club collision sports among male collegiate athletes. We found differential change among COLL versus NON-COLL players from pre- to post-season on several eye-movement measures, namely, speeded aspects of reflexive (prosaccade reaction time and velocity) and executive control and working memory (antisaccade and

MGS reaction times) tasks. Broadly speaking, across several reaction-time measures, the COLL-High Dose group did not demonstrate the practice effects that were observed among NON-COLL and, to a lesser extent, COLL-Low Dose athletes. By contrast, no significant differential change among groups was observed on ImPACT—the cognitive measure typically used in the literature to assess cognitive effects of subconcussive hit exposure—from pre- to post-season.

We hypothesized that relative to NON-COLL, COLL athletes would demonstrate longer antisaccade and MGS latencies, whereas NON-COLL would remain stable over time. The direction of our hypotheses were partially supported, in that NON-COLL demonstrated shorter latency at post-season, relative to pre-season, on antisaccade and MGS tasks by 4.33% and 6.48%, reflecting possible practice effects in response latency, whereas COLL demonstrated longer, stable, or more attenuated (relative to NON-COLL) shortened latencies over time. Specifically, COLL-High Dose demonstrated stable antisaccade and MGS latencies from pre- to post-season. By contrast, the COLL-Low



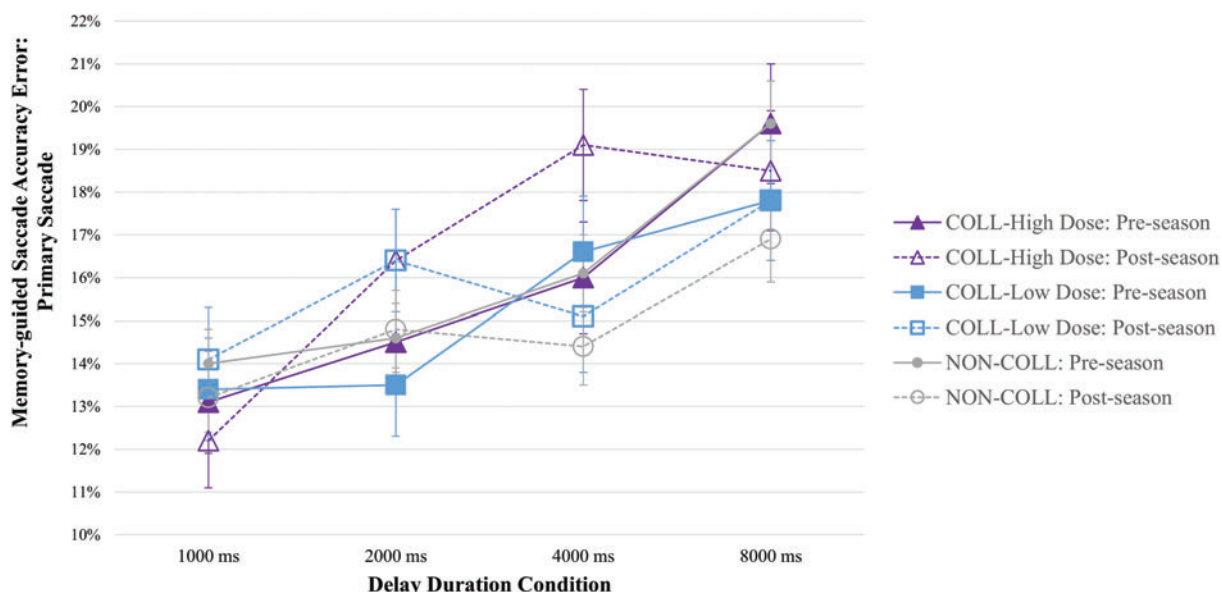


FIG. 4. Memory-guided saccade primary saccade accuracy by visit, group, and condition. Compared to pre-season performance, *NON-COLL* demonstrated decreased spatial error, and *COLL* (both groups) demonstrated increased spatial error on the primary saccade (visit-by-group interaction effects, $p < 0.05$; no visit-by-group-by-condition interaction effects). *COLL*, collision; *NON-COLL*, non-collision.

Dose group demonstrated 4.65% longer MGS latency and 2.03% shorter antisaccade latency from pre- to post-season. It is surprising that the *COLL-Low Dose* group demonstrated more adverse change on MGS latency across time relative to the *COLL-High Dose* group; this may be attributable to small group sizes and intersubject variability. Alternatively, the differen-

tial effect may be attributable to a suspected higher magnitude of hits among rugby players because of the lack of protective helmets.

In sum, it appears that the *COLL* groups demonstrated an attenuated practice effect, relative to *NON-COLL*, on reaction time on eye-movement saccade tasks with executive control demands. Differential

Table 4. ImPACT Composite Data by Group and Visit

		Group		
		Collision-High Dose Hockey (n=8)	Collision-Low Dose Rugby (n=9)	Non-collision (n=16)
Pre-season	Verbal memory	94.00 (4.07)	91.56 (7.52)	90.88 (7.46)
	Visual memory	93.50 (5.18)	83.78 (13.84)	84.19 (8.54)
	Visual motor	48.48 (3.88)	42.08 (6.04)	46.36 (5.47)
	Reaction time	0.57 (0.09)	0.56 (0.06)	0.55 (0.07)
Post-season	Verbal memory	95.38 (7.17)	92.56 (8.92)	90.44 (7.16)
	Visual memory	95.25 (3.62)	87.00 (10.61)	87.94 (6.89)
	Visual motor	49.76 (3.24)	44.15 (5.25)	47.99 (3.46)
	Reaction time	0.54 (0.05)	0.55 (0.05)	0.54 (0.05)

Data presented as mean (standard deviation). Verbal and visual memory composite scores represent the average percentage correct across subtests; visual motor composite score represents a summary score of processing speed performance across subtests; reaction time composite score represents the average reaction time (in seconds) for correct responses across subtests. No significant group-by-time interaction effect was detected. ImPACT, Immediate Post-Concussion Assessment and Cognitive Test.



change from pre- to post-season among collision COLL versus NON-COLL groups is consistent with the post-concussion literature, in that past studies have demonstrated longer antisaccade latency among participants with recent concussion versus controls.^{28,54–56} Further, results from this study are similar to those of a parallel longitudinal study of female soccer players, which showed that those with higher estimated exposure to head impacts demonstrated relative stability over time whereas those with lower estimated head injury exposure and non-contact controls showed faster reaction times at post-season relative to pre-season on antisaccade and MGS tasks.³⁰

Unlike eye-movement testing results, there were no group-by-time effects observed on ImpACT testing in general or on the ImpACT reaction time or visual motor composite scores. Qualitatively, ImpACT composite scores improved from pre- to post-season on memory and visual motor composites among COLL groups and remained stable or improved more modestly among NON-COLL. This suggests the increased sensitivity of executive saccade tasks, relative to ImpACT testing, to changes resulting from participation in collision versus non-collision sports, presumably as a consequence of subconcussive hit exposure.

This study further evaluated whether, relative to NON-COLL, COLL athletes would demonstrate increased antisaccade error rate and poorer spatial accuracy on the MGS task at post- versus pre-season. Our results did not reveal group-by-time effects on antisaccade error rate, but did yield significant findings for MGS accuracy, though these findings were not significant after correction for multiple comparisons. Specifically, NON-COLL demonstrated improved primary saccade and resting fixation MGS spatial accuracy, whereas COLL (both groups) demonstrated poorer primary saccade accuracy and stable resting fixation accuracy, at post-season relative to pre-season.

With regard to the reflexive prosaccade task, there were significant group-by-time effects on latency and velocity. Specifically, relative to pre-season performance, NON-COLL demonstrated stable latency at post-season. By contrast, COLL groups demonstrated longer latency on overlap and no gap trials, and shorter latency on gap trials, at post- versus pre-season. The prolonged latency on overlap and no gap trials at post-season relative to pre-season among COLL, compared to stable latency among NON-COLL, suggests change as a result of exposure to collision sport participation on reflexive saccade reaction time. In addition,

compared to pre-season performance, NON-COLL and COLL-Low Dose demonstrated faster velocity (2.61% and 2.88% increase, respectively) on the prosaccade task, whereas COLL-High Dose demonstrated mildly slower velocity (1.58% decrease), at post-season. This implies a potential subtle dose effect, in which athletes with greater relative exposure to subconcussive hits through increased estimated frequency of participation in collision sport competition demonstrate adverse change on prosaccade velocity performance relative to those with lower relative frequency in engagement, or no engagement at all (i.e., NON-COLL), in collision sport competition.

There are several limitations to this study that warrant mention. Although competition attendance data among COLL athletes suggest a disparate potential exposure to subconcussive hits among hockey (High Dose) versus rugby (Low Dose), we do not have individual, quantitative head injury data to conclusively support that differential change among these groups from pre- to post-season is attributable to variable exposure to head injury. Further, differential change among these groups from pre- to post-season may be attributable to differential, though not statistically significant, time since most recent competition and, by extension, rest and recovery from exposure to subconcussive impacts, given that rugby athletes (Low Dose) were assessed an average of 19.00 days post-competition (SD=5.07), whereas the hockey athletes (High Dose) were assessed closer to the most recent competition (M=11.38, SD=14.00). Future studies should include larger sample sizes, quantitatively monitor head injury exposures for each participant to confirm the sensitivity of eye-movement testing to subconcussive-hit dose effects, and conduct follow-up testing at regular intervals to evaluate the extent to which performance may normalize between collision versus non-collision groups after a period of rest from subconcussive impact exposure among collision athletes.

Conclusion

In summary, compared to pre-season performance, NON-COLL demonstrated stable, whereas COLL groups demonstrated longer (slower), prosaccade latency on no gap and overlap trials. NON-COLL demonstrated shorter (faster), whereas COLL groups showed stable, longer, or more attenuated improvements in antisaccade and MGS latencies at post-season relative to pre-season. On the MGS task, NON-COLL demonstrated improved spatial accuracy, whereas



COLL groups showed poorer primary saccade accuracy and stable resting position accuracy at post-season relative to pre-season (though these findings did not survive Bonferroni's correction for multiple comparisons). Finally, whereas NON-COLL and COLL-Low Dose demonstrated faster post-season relative to pre-season prosaccade velocity, COLL-High Dose showed mildly slower post-season velocity. Overall, there were mild dose effects in prosaccade velocity (greater adverse change among High vs. Low Dose COLL) and antisaccade latency (greater improvement among Low vs. High Dose COLL), but not in other eye-movement measures.

In general, our data demonstrated that male athletes exposed to estimated higher doses of subconcussive impacts did not demonstrate the practice effects on eye-movement testing that were observed among non-collision athletes and, to a lesser extent, collision sport athletes exposed to relatively fewer estimated subconcussive head injury. Whereas the aforementioned effects were statistically significant, the magnitude of effects was generally small, which is not surprising given that the collision athletes did not report increased head injury-related symptoms from pre- to post-season. Additionally, no differential change was observed from pre- to post-season on ImPACT performance among groups, and qualitative review of data demonstrated an unexpected direction of change in which COLL groups improve at post-season to a greater degree than NON-COLL groups on memory and visual motor composite scores. This suggests that eye-movement testing has greater sensitivity to change associated with collision sport participation versus ImPACT. Finally, this study provides convergent data regarding the utility of eye-movement testing in detecting subtle cognitive and sensorimotor change associated with collision sport participation, now demonstrated among both male and female athletes.³⁰

Authors' Contributions

Virginia T. Gallagher contributed to the conception of the study, data acquisition and analysis, and manuscript preparation. Prianka Murthy contributed to data acquisition and analysis and manuscript preparation. Jane Stocks contributed to data acquisition and analysis and manuscript preparation. Brian Vecsi contributed to data acquisition and manuscript preparation. Jeffrey Mjaanes contributed to data acquisition and manuscript preparation. Yufen Chen contributed

to conception of the study and manuscript preparation. Hans C. Breiter contributed to manuscript preparation. Cynthia LaBella contributed to study conceptualization and manuscript preparation. Amy A. Herrold and James L. Reilly contributed to conception of the study, data acquisition and analysis, and manuscript preparation.

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Author Disclosure Statement

No competing financial interests exist.

Supplementary Material

Supplementary Table S1
Supplementary Table S2
Supplementary Table S3

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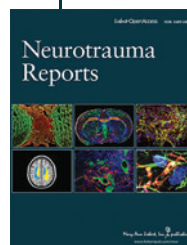
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Abbreviations Used

- BDI-II = Beck Depression Inventory-II
COLL = collision
ImPACT = Immediate Post-Concussion Assessment and Cognitive Test
MGS = memory-guided saccade
NON- = non-collision collegiate athletes
COLL
PCSS = Post-Concussion Symptom Scale
PSS = Perceived Stress Scale
SD = standard deviation
STAI = State-Trait Anxiety Inventory

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