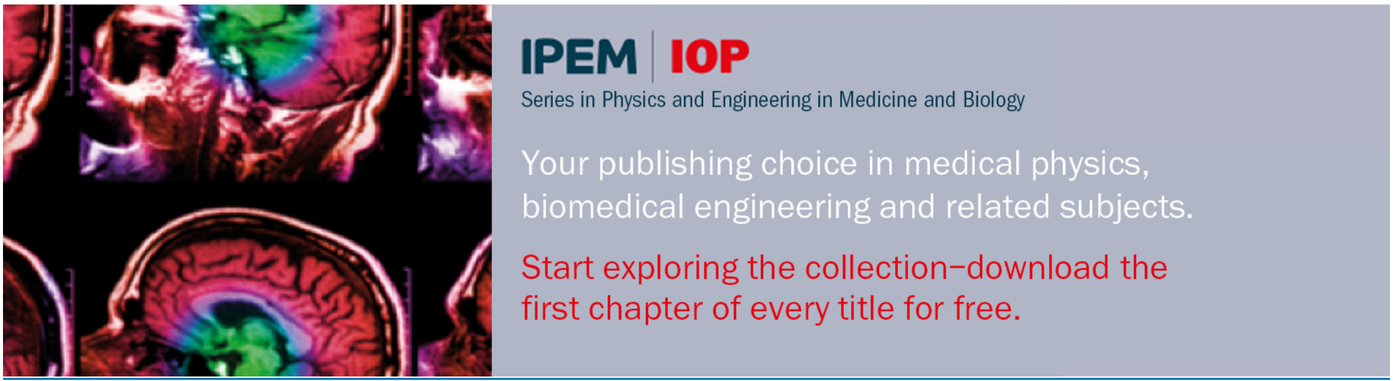
Physiological Measurement

PAPER

Blink duration is increased in concussed youth athletes: a validity study using eye tracking in male youth and adult athletes of selected contact sports

To cite this article: Nadja Snegireva *et al* 2022 *Physiol. Meas.* **43** 075006



IOP Publishing Physiol. Meas. 43 (2022) 075006 https://doi.org/10.1088/1361-6579/ac799b

Physiological Measurement

IPEM Institute of Physics and Engineering in Medicine

RECEIVED
30 December 2021

REVISED
26 May 2022

ACCEPTED FOR PUBLICATION
16 June 2022

PUBLISHED
18 July 2022

PAPER

Blink duration is increased in concussed youth athletes: a validity study using eye tracking in male youth and adult athletes of selected contact sports

Nadja Snegireva[1,*], **Wayne Derman**[2,3], **Jon Patricios**[4] **and Karen Welman**[1]

[1] Movement Laboratory, Department of Sport Science, Stellenbosch University, Stellenbosch, South Africa
[2] Institute of Sport and Exercise Medicine, Faculty of Medicine and Health Sciences, Stellenbosch University, Cape Town, South Africa
[3] International Olympic Committee (IOC) Research Centre, Cape Town, South Africa
[4] Wits Institute for Sport and Health, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa
[*] Author to whom any correspondence should be addressed.

E-mail: nadja.snegireva@gmail.com

Keywords: eye movement measurements, concussion, return to sport, football (soccer), rugby union

Abstract

Objective. Diagnosing a sports-related concussion (SRC) remains challenging, and research into diagnostic tools is limited. This study investigated whether selected eye tracking variables would be a valid tool to diagnose and monitor SRC in adult and youth participants in selected contact sports, such as Rugby Union (rugby) and football (soccer). *Methods.* This prospective cohort study, with 70 concussed and 92 non-concussed adult and youth athletes, assessed the validity of five previously selected eye tracking variables for SRC diagnostics and management. The performance between concussed and age-matched control (non-concussed) athletes, as well as between three successive testing sessions in the concussed athletes were compared. Self-paced saccade count in adult group; blink duration in the memory-guided saccade and sinusoidal smooth pursuit tasks, proportion of antisaccade errors, and gain of diagonal smooth pursuit in the youth group were assessed. *Results.* The youth concussed group had higher blink duration in the fast memory-guided saccades task ($p = 0.001, \eta^2 = 0.17$) and a tendency for higher blink duration in the sinusoidal smooth pursuit task ($p = 0.016, \eta^2 = 0.06$) compared to the youth control group. In both tasks the blink duration in the concussed youth group decreased from session 1 to session 2 by 24% and 18%, accordingly, although statistical significance was not reached. The concussed adult group demonstrated a lower number of self-paced saccades compared to controls ($p = 0.05, \eta^2 = 0.09$), which gradually increased, with the largest difference between session 1 and session 3 ($p = 0.02$). *Conclusions.* Blink duration in youth athletes holds promise as a valid metric for concussion diagnostics and monitoring. It is recommended to focus future studies on comparing eye tracking performance within the same concussed athletes over time rather than comparing them to healthy controls.

Introduction

The awareness and management of sports-related concussion (SRC) have evolved significantly, however the most recent consensus statement on concussion in sport emphasizes that it remains challenging to identify, assess and manage (McCrory *et al* 2017). In most cases, with proper and timely treatment, concussed athletes will recover fully; however, if unrecognized, there may be significant health implications. Not only can the immediate concussive symptoms be debilitating, but there is also an elevated risk of subsequent concussive and musculoskeletal injuries in the period following a SRC, and a spectrum of further possible long-term sequelae (Dashnaw *et al* 2012, Hubertus *et al* 2019). The diagnostic challenge is largely attributed to the absence of a universal objective tool to detect SRC and to determine when it is safe to return to sport (Lynall *et al* 2013, Kenzie *et al* 2017), leading to a heavy reliance on the athlete's self-reporting of symptoms.

Importantly, SRC or even sub-concussive head impacts (List *et al* 2015, Koerte *et al* 2017) manifest with symptoms across a range of domains, including worsened physical symptoms, diminished performance on neurocognitive tests, balance impairment and abnormal eye movements. The prevalence of eye movement deficits following a concussion is estimated at 40%–90% (Kapoor *et al* 2004, Ciuffreda *et al* 2007, Hunt *et al* 2016). Unsurprisingly, camera-based eye tracking technology has increasingly been gaining attention as a possible diagnostic and monitoring tool for SRC as demonstrated by empirical studies (Diwakar *et al* 2015, DiCesare *et al* 2017, Bin Zahid *et al* 2018, Danna-Dos-Santos *et al* 2018, Webb *et al* 2018) and literature reviews (Greenwald *et al* 2012, Ting *et al* 2014, Hunt *et al* 2016, Ventura *et al* 2016, Kontos *et al* 2017, Snegireva *et al* 2018). However, several factors currently make inferences challenging. These include inconsistencies between eye movement metrics and experimental designs, high variability in the time elapsed after the injury at the moment of testing, and lack of uniformity in participant selection. For these reasons, recent studies and commentaries have called for research using a more comprehensive battery of eye tracking measures (Taghdiri *et al* 2018), for studies involving youth athletes (i.e. $\leqslant$ 18 years (McCrory *et al* 2017)) and specifically aged 18–26 years (Samadani *et al* 2017, Bin Zahid *et al* 2018).

Thus, this study was set to investigate whether selected eye tracking variables measured across established tasks would constitute a valid tool to diagnose and monitor SRC in adult and youth participants in such contact sports as Rugby Union (rugby) and football (soccer). This research built on a previous study of reliability of selected eye tracking measures in athletics cohort that identified five variables that may be suited for SRC (Snegireva *et al* 2021). This study evaluated two key hypotheses. Firstly, it was hypothesized that differences would exist between the concussed and control groups in self-paced saccade (SPS) count in the adult group, as well as in blink duration in the memory-guided saccade (MGS) and sinusoidal smooth pursuit (SP) tasks, proportion of antisaccade (AS) errors, and gain of diagonal SP in the youth group. Secondly, these differences were expected to be most pronounced in the early symptomatic stage of a SRC, diminish in the recovery stage, and not be detectable in the post-factum baseline stage. Thereby, the early symptomatic stage of SRC is defined as lasting up to one week post-injury and constituting the period of the neurometabolic cascade within which the SRC symptoms are present but gradually resolve (Henry *et al* 2010, Gardner *et al* 2015). The recovery stage is considered to take place two to four weeks post-injury, usually sufficient for a full neurobiological recovery to take place (Iverson *et al* 2017, Pusateri *et al* 2018). The post-factum baseline stage sets in approximately three months post-injury, subject to being cleared to return to sport by a clinician.

Methods

This prospective cohort study was approved by the Health Research Ethics Committee (Approval #S16/07/129) and adhered to the Declaration of Helsinki. Each participant provided written informed consent or assent (for minor participants) statement; parents of participants under the age of 18 also provided an informed consent statement.

Participants

According to the *a priori* power analysis ($1–\beta = 0.80; \alpha = 0.05; d = 0.50$) conducted using G^*Power 3.1.9.3 for Windows software (Faul *et al* 2007), a target of 51 participants per age group was set. The athletes were recruited from the 'Sports Concussion South Africa schools' program and from rugby and soccer clubs. The inclusion criteria for all participants were: active participation in a contact sport, age between 9 and 35 years, and attending or having attended school. Additionally, for the concussed group, an inclusion criterion was the presence of a recent SRC (not older than one week), whereas for the control group the criteria included the absence of any concussions in the past two years (either sports-related or caused by other factors, e.g. a fall), as well as being age- and sex-matched to the concussed group.

Confirmation of a recent SRC was based on a diagnosis by sports and exercise medicine physicians using the clinical criteria defined at the 5th International Consensus Conference on Concussion in Sport (McCrory *et al* 2017), and verification of a history of previous concussion(s) was based on the self-reports of the participants and/or their parents.

The exclusion criteria for all participants were: major depression (defined as score of 10 or above on Patient Health Questionnaire (PHQ-9) (Manea *et al* 2012, Suzuki *et al* 2015)), poor global cognition (defined as score of 23 or below on the Montréal Cognitive Assessment (MoCA) test (Carson *et al* 2018)), self-reported diagnoses of psychiatric, neurodevelopmental or neurological disorders, ADHD, vision disorders or vision not (corrected-to-) normal, consumption of alcohol or drugs in the past 24 h, antipsychotic, anticonvulsant, or antidepressant medication (Leigh and Zee 2015), orthopaedic injuries or inability to follow the instructions.. In addition, the testing was aborted, and participants were excluded if the tests provoked worsening of concussive symptoms.

Procedure

The apparatus used to record the eye movements, as well as the eye tracking data processing are described in an earlier study (Snegireva *et al* 2021).

The control group participants completed two identical computer-based eye tracking testing sessions by the same trained assessor separated by one week (this time period was selected to approximate the gradual return-to-sport protocol depicted in SCAT5 (Echemendia *et al* 2017)).

The concussed group participants completed three such sessions: in the early stage as soon as possible after the injury (a maximum of one week, hereafter referred to as session 1), in the recovery stage at 2–4 weeks post-injury (session 2), and finally at post-factum baseline stage approximately 3 months post-injury, subject to being symptom-free at rest and exercise, having completed a graded return-to-play program and received clearance for return to sport by a sports physician (session 3).

At each session the Sport Concussion Assessment Tool 5 (SCAT5) (Echemendia *et al* 2017) was also implemented with all participants. The SCAT5 is the latest version of a standardized neuro-cognitive concussion test suitable for individuals above the age of 12 years. It consists of the Glasgow coma scale, Maddocks questions (set of 5 questions that assess game-specific orientation and recent memory), symptom checklist, verbal cognitive tests, a physical examination, a modified Balance Error Scoring System, and a standardized assessment of concussion (Echemendia *et al* 2017). Additionally, at session 1 the researchers conducted a structured interview to obtain demographic information (table 1) and medical history. Furthermore, at the last session, all participants also completed the MoCA for global cognition (only sections not overlapping with the SCAT5) followed by the self-administered PHQ-9 (for depressive mood screening).

Eye tracking tasks and outcome variables

A detailed description of the experimental design, eye tracking tasks and outcome variables are provided in an earlier study (Snegireva *et al* 2021) that assessed the reliability of 47 pre-specified variables across a range of established paradigms. The variables that demonstrated good or excellent reliability (ICC > 0.75) (Koo and Li 2016, Post 2016, Murray *et al* 2017) along with variables with moderate reliability and percentage mean below 30% were included in the current analysis. The same method was used in an earlier investigation of the oculomotor function in SRC (Cochrane *et al* 2019). Thus, the following five variables were included:

1. Proportion of directional errors in the AS task in the youth group (ICC $= 0.78$). Noteworthy is that this variable in the adult group also demonstrated a moderate level of reliability, however it was below the set ICC threshold (ICC $= 0.68$) and thus not included in the current study.
2. Number of SPS in the adult group (ICC $= 0.86$).
3. Gain of diagonal SP in youth (ICC $= 0.77$).
4. Eye blink duration in the MSG in the youth group (ICC $= 0.99$).
5. Eye blink duration in the sinusoidal SP also in the youth group (ICC $= 0.63$ along with percentage mean of 23%).

Data analysis

Separate statistical analyses were conducted for adult and youth groups using Statistica® 13 (TIBCO Software Inc., Palo Alto, CA, USA) and Excel (Microsoft® Corporation, Redmond, WA, USA). The normality of distribution of each variable was examined using the Shapiro–Wilk test and visually by a statistician (skewness and kurtosis). In accordance with the normality, the descriptive statistics included: means ($\bar{x}$), standard deviations ($\pm$ SD), and 95% confidence intervals (CI) for the normally distributed variables, and medians (MED) with interquartile ranges (IQR) for the non-normally distributed variables.

The differences between the concussed and control groups at session 1, as well as the changes across the testing sessions 1, 2, and 3 within the concussed group were analyzed using a series of independent samples Mann–Whitney U tests and Wilcoxon signed ranks tests (non-normally distributed variables) or repeated measures ANOVA (normally distributed variables). Post-hoc tests were performed on the variables with significant effects identified by the ANOVA. For these comparisons, the alpha level was set at 0.01 following a Bonferroni correction. For all other comparisons (e.g. demographic information) the alpha level was set at 0.05.

The effect sizes (η^2) were calculated based on the Z-score in accordance with the recommendations for non-parametric tests (Fritz *et al* 2012, Grissom and Kim 2012) and considered small ($\eta^2 \geqslant 0.01$), medium ($\eta^2 \geqslant 0.06$) or large ($\eta^2 \geqslant 0.14$) (Lakens 2013).

Finally, a series of correlation analyses (Spearman ρ) were carried out for the results of session 1 to determine whether there was an association between the eye tracking metrics and (1) the severity of the concussive

Table 1. Demographic information of participants reported as $\bar{x} \pm$ SD [95% CI].

	Adult			Youth		
Variables	Concussed	Control	*p*-value	Concussed	Control	*p*-value
Age (*y*)	22.5 ± 3.6 [2.9–4.9]	22.2 ± 2.9 [2.3–3.8]	0.74	14.8 ± 2 [1.7–2.7]	15.4 ± 2.2 [1.8–2.7]	0.23
Height (cm)	179.8 ± 9.3 [7.3–12.8]	177.1 ± 6.7 [5.4–8.9]	0.20	167.9 ± 10.8 [8.6–14.5]	172.4 ± 13.3 [11.2–16.2]	0.12
Weight (kg)	89.2 ± 16 [12.6–21.9]	85.3 ± 12.2 [9.8–16.2]	0.29	62.8 ± 16.4 [13.1–22.1]	64 ± 15.3 [12.9–18.7]	0.74
Sport participation (*y*)	13.7 ± 4.1 [3.2–5.6]	11.9 ± 4.2 [3.4–5.6]	0.10	5.8 ± 2 [1.6–2.8]	6.6 ± 2.7 [2.3–3.3]	0.20
Education (*y*)	13.4 ± 1.9 [1.5–2.6]	13.6 ± 2 [1.6–2.7]	0.73	11.1 ± 1.9 [1.6–2.5]	10.9 ± 2.1 [1.8–2.6]	0.69
Past concussions (*f*)	1.3 ± 1.5* [1.2–2.1]	0.2 ± 0.4* [0.3–0.5]	<0.01	0.8 ± 0.8* [0.7–1.1]	0 ± 0.2* [0.2–0.2]	<0.01
Days since injury	2.7 ± 1.1 [0.9–1.5]			3.3 ± 1.6 [1.3–2.1]		
SCAT symptom severity at first session	27.7 ± 20.9*	10.7 ± 10.8*	<0.01	25.0 ± 23.8*	9.3 ± 8.9*	<0.01
MoCA score (AU, only sections not included in SCAT, max score = 18)	16.6 ± 1.4 [1–2.1]	16.6 ± 1.3 [1–1.7]	0.99	16.7 ± 0.8 [0.5–2]	16.6 ± 1.3 [1.1–1.6]	0.10
PHQ-9 score (AU)	2.4 ± 3.3 [2.5–5]	3 ± 2.4 [1.9–3.2]	0.53	7.2 ± 1.9* [1.2–4.8]	3.5 ± 3* [2.5–3.6]	0.01

Abbreviations: *y*: years; *f*: frequency; $\bar{x}$: mean, SD: standard deviation; CI: confidence interval; MoCA: montreal cognitive assessment; PHQ-9: patient health questionnaire; AU: arbitrary units; *: $p < 0.05$.

Table 2. Between-group differences at session 1 for concussed and control groups in adult and youth participants reported either as $\bar{x}$ [95% CI] or MED {IQR}.

Adult					
Stimulus, condition	Variable	Concussed	Control	p-value	η^2
SPS 10°	Saccade count	110.4 [44.5–76.6]	137.3 [44.6–73.3]	0.383	0.06^{M}
Youth					
MGS, fast	Blink duration average	281.9* {236.7–442.1}	209* {183.1–246.1}	0.001	0.17^{L}
SP, sinusoidal	Blink duration average	265.7* {229.6–359.6}	229.1* {188.9–290.6}	0.016	0.06^{M}
SP, diagonal	Gain	171.3 {154–219.9}	164.2 {146.1–227.4}	0.399	0.01^{S}
AS	Directional errors	45.9 [17.5–28.2]	52.4 [15.1–22]	0.056	0.02^{S}

Abbreviations: AS: antisaccades; MGS: memory-guided saccades; SP: smooth pursuit; SPS: self-paced saccades; ^{S}: small effect size ($\eta^2 \geqslant 0.01$); ^{M}: medium effect size ($\eta^2 \geqslant 0.06$), ^{L}: large effect size ($\eta^2 \geqslant 0.14$); CI: confidence interval; IQR: interquartile range; $\bar{x}$: mean, MED: median; η^2: effect size; β:beta (probability of type II error); *: $p < 0.05$

symptoms measured with the SCAT5, as well as (2) self-reported number of previous concussions. Correlation was considered strong ($\rho \geqslant 0.60$), moderate ($0.40 < \rho < 0.60$), weak ($0.2 \leqslant \rho \leqslant 0.40$), or negligible ($\rho < 0.2$) (Portney and Watkins 2009, Akoglu 2018).

Results

Seventy male athletes (34 adult and 36 youth) with a recent SRC and ninety-two male age-matched healthy controls (33 adult and 59 youth athletes) were included in the study and completed session 1. Further five concussed and ten control group participants were initially enrolled in the study, but excluded due to ADHD ($n = 11$), influenza ($n = 1$), age above inclusion criteria ($n = 1$), too long a time after SRC ($n = 1$), and equipment malfunction ($n = 1$). Session 2 was completed by 56 concussed (28 adult and 28 youth athletes) and 70 controls (27 adult and 43 youth athletes), and session 3 was completed by 20 concussed participants (18 adult and 2 youth athletes).

One-third of participants were cleared by a medical specialist to return to sport by session 2, and all participants were cleared by session 3. Concussed participants completed session 1 at 3.0 ± 1.4 d post-injury, session 2 at 19.9 ± 31.6 d, and session 3 at 49.7 ± 19.9 d post-injury. Time that elapsed between sessions 1 and 2 of the control group was 7.0 ± 3.9 d. There were no differences between the control and concussed groups in any of the characteristics except the number of past concussions (table 1).

The between-group differences at session 1 are presented in table 2.

The concussed adult group demonstrated a gradual increase in the number of SPS with the largest difference between session 1 and session 3 ($p = 0.02$). Concussed youth participants at session 1 had the lowest error rates in the AS task (figure 1). Error rate increased in the control youth group from session 1 to session 2 ($p = 0.002$).

Although not statistically significant, the average blink duration in the concussed group decreased from session 1 to session 2 (MGS: MED and IQR 281.9 [236.7–442.1] for session 1 and 232.9 [173.2–325.1] for session 2, $p = 0.35$; diagonal SP: MED and IQR 265.7 [229.6–359.6] for session 1 and 237.3 [193.7–279.1] for session 2, $p = 0.48$).

Several eye tracking variables showed weak correlations in the expected direction with the SCAT symptom severity score and the number of past concussions (table 3).

Discussion

This was the first comprehensive longitudinal study that systematically assessed the validity of eye tracking measures across carefully selected paradigms in heathy and concussed athletes participating in contact sports. Several interesting findings were revealed. Firstly, the trend observed in the saccade count in the SPS task suggests that this metric might indeed be indicative of a SRC in adults, since the concussed group presented a gradual increase in the number of saccades from session to session, with the results of the last session approaching the healthy controls. This confirmed the findings of an earlier meta-analysis (Snegireva *et al* 2018) that demonstrated significantly higher number of saccades in healthy controls. Neuroimaging studies had demonstrated that SPS were associated with the activity of multiple brain areas (Gaymard *et al* 1998, Heitger *et al* 2002, Johnson *et al* 2015, Leigh and Zee 2015, Taghdiri *et al* 2018) and are therefore likely to be affected by a SRC regardless of the location of the impact.

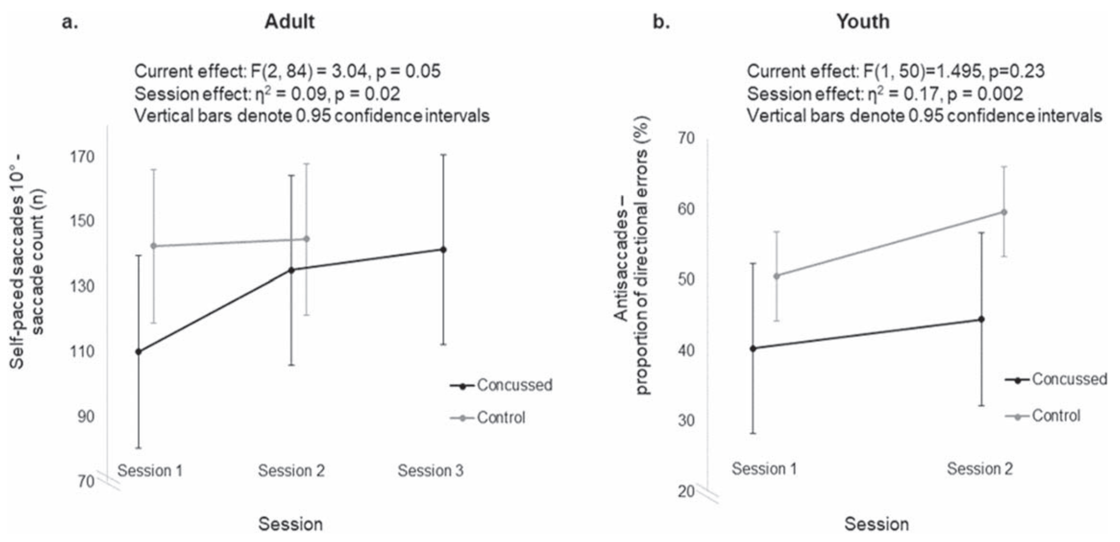


Figure 1. (a) Number of SPS over the sessions for concussed versus control adult groups; (b) Proportion of directional errors for AS over the sessions for concussed versus control youth groups.

Table 3. The relationship between eye tracking variables and SCAT5 symptom severity score as well as number of past concussions.

		Adult			
Stimulus, condition	Variable	Symptom severity		Past concussions	
		ρ	p-value	ρ	p-value
SPS, 10°	Saccade count	-0.36^{*}	< 0.01	0.17	0.19
		Youth			
MGS, fast	Blink duration average	0.12	0.36	0.24	0.06
SP, diagonal	Gain	0.26^{*}	0.01	0.25^{*}	0.02
SP, sinusoidal	Blink duration average	0.08	0.45	0.08	0.48
AS	Directional errors	-0.24^{*}	0.02	−0.03	0.80

Abbreviations: ρ: Spearman rho; AS: antisaccades; MGS: memory-guided saccades; SP: smooth pursuit; SPS: self-paced saccades; *: $p < 0.05$.

Secondly, the proportion of directional errors in the AS task in the current study was higher in the youth control group compared to the youth concussed group (even though statistical significance was not reached). The performance of the control group significantly worsened (i.e. the proportion of errors increased) at the second session compared to the first. At first sight, this seems counter to expectations, even though an earlier study had shown similar reductions in error rate of the control group between two sessions conducted one week apart (Ettinger *et al* 2003). However, in the context of the other variables, particularly latency and gain of the primary saccade, it becomes evident that the control group made a speed-accuracy trade-off that is common when decision-making is involved (Gold and Shadlen 2007) and had been observed in the prior studies (Wu *et al* 2010, Lange *et al* 2018). Namely, both latency and gain were the lowest in session 2 of the control group compared to session 1 and to the concussed group. This indicates that the control group in their second session reacted to the target faster but made a trade-off in terms of the number of directional errors they made. Thus, as Leigh and Zee (2015) pointed out, while the AS tasks is a valuable tool for evaluating the function of the brain, it is highly sensitive to confounding and situational factors, and therefore requires careful and standardized approach.

Thirdly, current findings demonstrated that the concussed youth athletes tended to exhibit longer blink durations compared to the healthy controls. This was the first eye tracking study to assess spontaneous blink performance in concussed athletes. Researchers believe that the spontaneous eye blinks are linked to central dopamine activity. In Parkinson's disease, where the dopamine activity in striatum progressively decreases, longer blink durations and reduced blink rates have been observed. Conversely, in schizophrenia, where the striatal dopamine activity is increased, shorter blink durations and increased rates are frequently found (Karson *et al* 1984, Jongkees and Colzato 2016, Abusharha 2017). Since concussions (SRC or non-sports-related) have been previously correlated with the reduction of dopamine levels in striatum (Chen *et al* 2017, Jenkins *et al* 2018), this might explain the findings of this study.

The increase in the blink duration in the concussed athletes was most prominent for the MGS task which also involves working memory and attention (Snegireva *et al* 2018). In a healthy population, longer blink durations had been associated with worse performance on the inhibitory control tasks (Colzato *et al* 2009) and fatigue (Marandi *et al* 2018). Thus, it is possible that impairments in higher executive functions that are characteristic of a youth concussion (Moore *et al* 2016) also affected the blink durations. Additionally, in a heathy population, blinks have been found to be related to age with blink rate and duration increasing from infancy to adulthood and reaching adult levels by the age of 20 (Caplan *et al* 1996, Liu and Shen 2011, Groen *et al* 2017). It is possible, therefore, that blink-related metrics in a youth population show higher sensitivity to a SRC compared to adults. To authors' knowledge there is no research to date that establishes a link between the eye blink durations and SRC, and further investigations are called for to confirm this novel finding.

In agreement with the systematic review that found MGS impairments only in acute (up to 30 d post-injury) SRC (Snegireva *et al* 2018), current results showed a gradual improvement of the eye blink duration from session 1 to session 2: the blink duration decreased by 24% and 18% for MGS and sinusoidal SP, accordingly, although statistical significance was not reached.

In the adult group, there was a weak (approaching moderate) negative correlation between the self-reported severity of SRC symptoms and the number of SPS. This confirmed earlier findings (Heitger *et al* 2009, Taghdiri *et al* 2018) that this variable might reflect the SRC symptom presentation, since this task involves several white matter tracts and cognitive functions that are also associated with SRC symptoms, such as difficulty to concentrate, or feeling in a fog. In the youth group, only weak correlation was found between two variables (gain of the diagonal SP and proportion of AS errors) and the symptom severity. Interestingly, two previous studies (Bin Zahid *et al* 2018, Mani *et al* 2018) had suggested that the eye movement impairments in concussion possibly manifest regardless of the reported symptoms, indicating that eye tracking could be an objective measure largely independent from symptom reporting. Taken together, it is possible that there is a relationship between eye tracking and cognitive symptoms of a SRC, and eye tracking technology can provide the clinicians with further insights in addition to the subjective symptom reports.

Finally, only gain of the diagonal SP demonstrated a weak correlation with the number of past concussions. It is possible that the duration and severity of post-SRC pathophysiology might be affected more by the timing of repeat injuries rather than the previous concussion history alone (Giza and Hovda 2014).

Limitations and future research

A considerable effort was put into assessing the participants at consistent timeframes. However, a certain degree of variability both in the time that had elapsed after the injury at the moment of testing and in the time intervals between sessions 1 and 2 of concussed versus control groups was unavoidable. This variability constitutes a pragmatic clinical reality of standard and accepted practice. However, since some participants might have been further into the recovery process than others, this might have affected the results. Additionally, there was a degree of attrition of participants, since most of the players were cleared to play well before the third scheduled testing session and had little motivation to return.

Cognitive or physical activities that strongly utilize the oculomotor system or promote general fatigue (for example, sports training or studying for exams), as well as further situational factors (e.g. motivation or lighting) might have affected the eye tracking performance in both the concussed and control groups. An even more stringent control for confounding factors, when possible, is highly recommended for future studies: for example, by fixating the head, providing identical sitting conditions and comparable lighting, and adhering to the identical time of the day for all testing sessions. While an assumption was made that the participants were honest in reporting the symptoms and providing information relevant for the inclusion criteria, this cannot be guaranteed.

Very few standardized eye movement assessments in brain disorders exist. To the authors' knowledge, only the Standardized Antisaccades Protocol (Antoniades *et al* 2013) and Saccades Quantification Protocol (Nij Bijvank *et al* 2018) exist (and both were utilized in present study). Therefore, the authors had to rely on single publications in experimental design, which made comparability of the results and studies challenging. Consequently, the protocols utilised may not be fully suitable for SRC assessment, and the ability to reproduce the results of this study needs further investigation. Additionally, in general the eye tracking technology might be susceptible to a range of artefacts caused by the variability of features and algorithms across different devices (Shaikh and Zee 2018), therefore also limiting the generalizability of findings across devices.

This study specifically focused on contact sport athletes in South Africa, therefore the findings might not be representative of non-sporting cohorts or other geographical regions. Also, a sex bias is present, since both concussed and control groups consisted of male athletes. However, it has been established that sex does not affect the saccadic or smooth pursuit performance (Hutton 2008, Sufrinko *et al* 2017). Overall, the findings require confirmation in larger studies comprising further geographic regions, other sports, and both sexes.

Finally, using challenging tasks that are closely related to brain areas involved in executive functions or incorporating a dual-task element may improve the reliability and validity of the eye tracking tests for SRC diagnostics, and further research in this direction is suggested. It is important to recognize that since eye movements are known to be idiosyncratic and related to anatomical (e.g. shape of and length of the eyeball) and personality (impulsivity, anxiety) characteristics (Pearson *et al* 2007, Holmqvist *et al* 2011, Leigh and Zee 2015), future research should focus on comparing concussed individuals to their own pre-injury or post-recovery baseline values rather than comparing them to healthy controls, yet this research design is not without significant challenge.

Conclusion

This pragmatic study based in a clinical setting contributed to recent advancements in research of the tools available for evaluating SRC. While its strengths lie in the very careful selection of variables, unity in the time that elapsed after a SRC at each testing session, and clear stratification by the age group, a broader sample of participants, other combinations of metrics and using athlete's own pre-injury baseline values might create models with better reliability and validity. A novel finding of this study was that blink duration in MGS and sinusoidal SP was increased in concussed children, and future research should focus on inclusion of this metric to further understand this phenomenon.

Acknowledgments

This work was supported by a FIFA Research Scholarship. Special thanks go to Carmen Rogans for assistance with testing, Sewis van Zyl for help with the eye tracking data processing and analysis, as well as Dr James Burger of False Bay RFC, Marc Christian of Cape Town City FC, Norman Titus of Northlink College in Cape Town, as well as the students and staff of St John's College, King Edward VII School, St Stithian's College, and St. David's Marist Inanda, in Johannesburg for assistance with recruitment.

The authors have no conflicts of interest to disclose.

ORCID iDs

Nadja Snegireva https://orcid.org/0000-0003-0659-1887

References

Abusharha A A 2017 Changes in blink rate and ocular symptoms during different reading tasks *Clin. Optom.* **9** 133–8

Akoglu H 2018 User's guide to correlation coefficients *Turk. J. Emerg. Med.* **18** 91–3

Antoniades C *et al* 2013 An internationally standardised antisaccade protocol *Vis. Res.* **84** 1–5

Caplan R, Guthrie D and Komo S 1996 Blink rate in children with attention-deficit-hyperactivity disorder *Biol. Psychiatry* **39** 1032–8

Carson N, Leach L and Murphy K J 2018 A re-examination of montreal cognitive assessment (MoCA) cutoff scores *Int. J. Geriatr. Psychiatry* **33** 379–88

Chen Y-H, Huang E Y-K, Kuo T-T, Miller J, Chiang Y-H and Hoffer B J 2017 Impact of traumatic brain injury on dopaminergic transmission *Cell Transplant.* **26** 1156–68

Ciuffreda K J, Kapoor N, Rutner D, Suchoff I B, Han M E and Craig S 2007 Occurrence of oculomotor dysfunctions in acquired brain injury: a retrospective analysis *Optometry* **78** 155–61

Cochrane G D, Christy J B, Almutairi A, Busettini C, Swanson M W and Weise K K 2019 Visuo-oculomotor Function and Reaction Times in Athletes with and without Concussion *Optom. Vis. Sci.* **96** 256–65

Colzato L S, van den Wildenberg W P M, van Wouwe N C, Pannebakker M M and Hommel B 2009 Dopamine and inhibitory action control: evidence from spontaneous eye blink rates *Exp. Brain Res.* **196** 467–74

Danna-Dos-Santos A, Mohapatra S, Santos M and Degani A M 2018 Long-term effects of mild traumatic brain injuries to oculomotor tracking performances and reaction times to simple environmental stimuli *Sci. Rep.* **8** 4583 Online: (http://nature.com/articles/s41598-018-22825-5)

Dashnaw M L, Petraglia A L and Bailes J E 2012 An overview of the basic science of concussion and subconcussion: where we are and where we are going *Neurosurg. Focus* **33** E5 1–9

DiCesare C A, Kiefer A W, Nalepka P and Myer G D 2017 Quantification and analysis of saccadic and smooth pursuit eye movements and fixations to detect oculomotor deficits *Behav. Res. Methods* **49** 258–66

Diwakar M, Harrington D L, Maruta J, Ghajar J, El-Gabalawy F, Muzzatti L, Corbetta M, Huang M-X and Lee R R 2015 Filling in the gaps: Anticipatory control of eye movements in chronic mild traumatic brain injury *NeuroImage Clin.* **8** 210–23

Echemendia R J *et al* 2017 The sport concussion assessment tool 5th edition (SCAT5) *British Journal of Sports Medicine* **51** 848–50

Ettinger U, Kumari V, Crawford T J, Davis R E, Sharma T and Corr P J 2003 Reliability of smooth pursuit, fixation, and saccadic eye movements *Psychophysiology* **40** 620–8

Faul F, Erdfelder E, Lang A-G and Buchner A 2007 G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences *Behav. Res. Methods* **39** 175–91

Fritz C O, Morris P E and Richler J J 2012 Effect size estimates: current use, calculations, and interpretation *J. Exp. Psychol. Gen.* **141** 2–18

Gardner A, Iverson G L, Levi C R, Schofield P W, Kay-Lambkin F, Kohler R M N and Stanwell P 2015 A systematic review of concussion in rugby league *Br. J. Sports Med.* **49** 495–8

Gaymard B, Rivaud S, Cassarini J F, Dubard T, Rancurel G, Agid Y and Pierrot-Deseilligny C 1998 Effects of anterior cingulate cortex lesions on ocular saccades in humans *Exp. Brain Res.* **120** 173–83

Giza cc and Hovda D A 2014 The new neurometabolic cascade of concussion *Neurosurgery* **75** S24–33

Gold J I and Shadlen M N 2007 The neural basis of decision making *Ann. Rev. Neurosci.* **30** 535–74

Greenwald B D, Kapoor N and Singh A D 2012 Visual impairments in the first year after traumatic brain injury *Brain Inj.* **26** 1338–59

Grissom R J and Kim J J 2012 *Effect Sizes for Research: Univariate and Multivariate Applications* (New York: Routledge)

Groen Y, Börger N A, Koerts J, Thome J and Tucha O 2017 Blink rate and blink timing in children with ADHD and the influence of stimulant medication *J. Neural Transm.* **124** 27–38

Heitger M H, Anderson T J and Jones R D 2002 Saccade sequences as markers for cerebral dysfunction following mild closed head injury *Progress in Brain Research* **140** 433–48

Heitger M H, Jones R D, Macleod A D, Snell D L, Frampton C M and Anderson T J 2009 Impaired eye movements in post-concussion syndrome indicate suboptimal brain function beyond the influence of depression, malingering or intellectual ability *Brain* **132** 2850–70

Henry L C, Tremblay S, Boulanger Y, Ellemberg D and Lassonde M 2010 Neurometabolic changes in the acute phase after sports concussions correlate with symptom severity *J. Neurotrauma* **27** 65–76

Holmqvist K, Nystrom M, Andersson R, Dewhurst R, Jarodzka H and Weijer J van de 2011 *Eye Tracking: a Comprehensive Guide to Methods and Measures* (Oxford: Oxford University Press)

Hubertus V, Marklund N and Vajkoczy P 2019 Management of concussion in soccer *Acta Neurochir. (Wien)* **161** 425–33

Hunt A W, Mah K, Reed N, Engel L and Keightley M 2016 Oculomotor-based vision assessment in mild traumatic brain injury: a systematic review *J. Head Trauma Rehabil.* **31** 252–61

Hutton S B 2008 Cognitive control of saccadic eye movements *Brain Cogn.* **68** 327–40

Iverson G L, Gardner A J, Terry D P, Ponsford J L, Sills A K, Broshek D K and Solomon G S 2017 Predictors of clinical recovery from concussion: a systematic review *Br. J. Sports Med.* **51** 941–8

Jenkins P O *et al* 2018 Dopaminergic abnormalities following traumatic brain injury *Brain J. Neurol.* **141** 797–810

Johnson B D, Zhang K, Hallett M and Slobounov S M 2015 Functional neuroimaging of acute oculomotor deficits in concussed athletes *Brain Imaging Behav.* **9** 564–73

Jongkees B J and Colzato L S 2016 Spontaneous eye blink rate as predictor of dopamine-related cognitive function—a review *Neurosci. Biobehav. Rev.* **71** 58–82

Kapoor N, Ciuffreda K J and Han Y 2004 Oculomotor rehabilitation in acquired brain injury: a case series *Arch. Phys. Med. Rehabil.* **85** 1667–78

Karson C N, Burns R S, LeWitt P A, Foster N L and Newman R P 1984 Blink rates and disorders of movement *Neurology* **34** 677–677

Kenzie E S, Parks E L, Bigler E D, Lim M M, Chesnutt J C and Wakeland W 2017 Concussion as a multi-scale complex system: an interdisciplinary synthesis of current knowledge *Front. Neurol.* **8** 1–17

Koerte I K *et al* 2017 Impaired cognitive performance in youth athletes exposed to repetitive head impacts *J. Neurotrauma* **34** 2389–95

Kontos A P, Deitrick J M, Collins M W and Mucha A 2017 Review of vestibular and oculomotor screening and concussion rehabilitation *J. Athl. Train.* **52** 256–61

Koo T K and Li M Y 2016 A guideline of selecting and reporting intraclass correlation coefficients for reliability research *J. Chiropr. Med.* **15** 155–63

Lakens D 2013 Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs *Front. Psychol.* **4** 863 Online: (http://journal.frontiersin.org/article/10.3389/fpsyg.2013.00863/abstract)

Lange B, Hunfalvay M, Murray N, Roberts C-M and Bolte T 2018 Reliability of computerized eye-tracking reaction time tests in non-athletes, athletes, and individuals with traumatic brain injury *Optometry and Visual Performance* **6** (3) 119–29 https://uwe-repository.worktribe.com/output/863868/reliability-of-computerized-eye-tracking-reaction-time-tests-in-non-athletes-athletes-and-individuals-with-traumatic-brain-injury

Leigh R J and Zee D S 2015 *The Neurology of Eye Movements* (Oxford: Oxford University Press)

List J, Ott S, Bukowski M, Lindenberg R and Flöel A 2015 Cognitive function and brain structure after recurrent mild traumatic brain injuries in young-to-middle-aged adults *Front. Hum. Neurosci.* **9** 1–9

Liu C-J and Shen M-H 2011 The influence of different representations on solving concentration problems at elementary school *J. Sci. Educ. Technol.* **20** 621–9

Lynall R C, Laudner K G, Mihalik J P and Stanek J M 2013 Concussion-assessment and -management techniques used by athletic trainers *J. Athl. Train.* **48** 844–50

Manea L, Gilbody S and McMillan D 2012 Optimal cut-off score for diagnosing depression with the patient health questionnaire (PHQ-9): a meta-analysis *CMAJ Can. Med. Assoc. J.* **184** E191–6

Mani R, Asper L and Khuu S K 2018 Deficits in saccades and smooth-pursuit eye movements in adults with traumatic brain injury: a systematic review and meta-analysis *Brain Inj.* **32** 1315–36

Marandi R Z, Madeleine P, Omland Ø, Vuillerme N and Samani A 2018 Eye movement characteristics reflected fatigue development in both young and elderly individuals *Sci. Rep.* **8** 1–10

McCrory P *et al* 2017 Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016 *British Journal of Sports Medicine* **51** 838–47

Moore D R, Pindus D M, Raine L B, Drollette E S, Scudder M R, Ellemberg D and Hillman C H 2016 The persistent influence of concussion on attention, executive control and neuroelectric function in preadolescent children *Int. J. Psychophysiol.* **99** 85–95

Murray N, Hunfalvay M and Bolte T 2017 The reliability, validity, and normative data of interpupillary distance and pupil diameter using eye-tracking technology *Transl. Vis. Sci. Technol.* **6** 2–2

Nij Bijvank J A, Petzold A, Balk L J, Tan H S, Uitdehaag B M J, Theodorou M and van Rijn L J 2018 A standardized protocol for quantification of saccadic eye movements: DEMoNS ed A Anderson *PLoS One* **13** e0200695

Pearson B C, Armitage K R, Horner C W M and Carpenter R H S 2007 Saccadometry: the possible application of latency distribution measurement for monitoring concussion *Br. J. Sports Med.* **41** 610–2

Portney L G and Watkins M P 2009 *Foundations of Clinical Research: Applications to Practice* (Upper Saddle River, N.J: Prentice Hall)

Post M W 2016 What to do with 'moderate' reliability and validity coefficients? *Arch. Phys. Med. Rehabil.* **97** 1051–2

Pusateri M E, Hockenberry B J and McGrew C A 2018 Zurich to Berlin-'Where' Are We Now with the Concussion in Sport Group? *Curr Sports Med Rep.* **17** 26–30

Samadani U, Zahid A B, Lockyer J, Dammavalam V, Grady M F, Nance M, Scheiman M and Master C L 2017 Eye tracking a biomarker for concussion in the paediatricpediatric population *British Journal of Sports Medicine* **51** A5 https://bjsm.bmj.com/content/51/11/A5.2

Shaikh A G and Zee D S 2018 Eye movement research in the twenty-first century—a window to the brain, mind, and more *Cerebellum* **17** 252–8

Snegireva N, Derman W, Patricios J and Welman K 2018 Eye tracking technology in sports-related concussion: a systematic review and meta-analysis *Physiol. Meas.* **39** 12TR01

Snegireva N, Derman W, Patricios J and Welman K 2021 Eye tracking to assess concussions: an intra-rater reliability study with healthy youth and adult athletes of selected contact and collision team sports *Exp. Brain Res.* **239** 3289–302

Sufrinko A M, Mucha A, Covassin T, Marchetti G, Elbin R J, Collins M W and Kontos A P 2017 Sex differences in vestibular/ocular and neurocognitive outcomes following sport-related concussion *Clin. J. Sport Med. Off. J. Can. Acad. Sport Med.* **27** 133–8

Suzuki K, Kumei S, Ohhira M, Nozu T and Okumura T 2015 Screening for major depressive disorder with the patient health questionnaire (PHQ-9 and PHQ-2) in an outpatient clinic staffed by primary care physicians in japan: a case control study *PLoS One* **10** e0119147

Taghdiri F *et al* 2018 Decreased number of self-paced saccades in post-concussion syndrome associated with higher symptom burden and reduced white matter integrity *J. Neurotrauma* **35** 719–29

Ting W K-C, Perez Velazquez J L and Cusimano M D 2014 Eye movement measurement in diagnostic assessment of disorders of consciousness *Front. Neurol.* **5** 1–9

Ventura R E, Balcer L J, Galetta S L and Rucker J C 2016 Ocular motor assessment in concussion: current status and future directions *J. Neurol. Sci.* **361** 79–86

Webb B, Humphreys D and Heath M 2018 Oculomotor executive dysfunction during the early and later stages of sport-related concussion recovery *J. Neurotrauma* **35** 1874–81

Wu C-C, Kwon O-S and Kowler E 2010 Fitts's law and speed/accuracy trade-offs during sequences of saccades: Implications for strategies of saccadic planning *Vis. Res.* **50** 2142–57

Zahid A B, Hubbard M E, Lockyer J, Podolak O, Dammavalam V M, Grady M, Nance M, Scheiman M, Samadani U and Master C L 2018 Eye tracking as a biomarker for concussion in children *Clin. J. Sport Med.* **30** 433–43