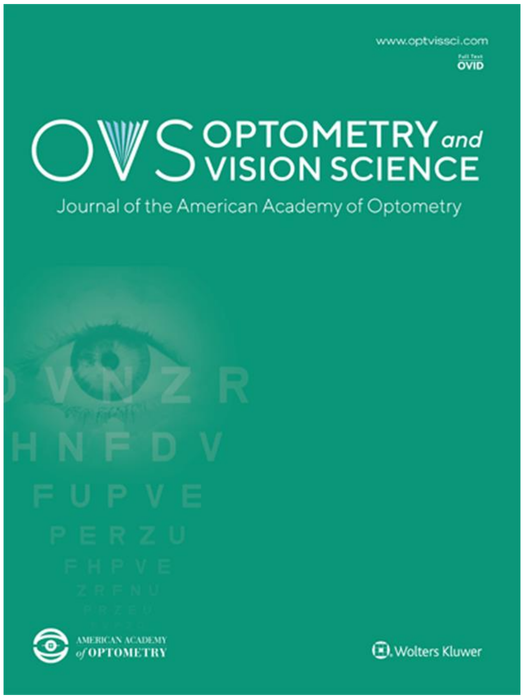

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Authors: Song A, Gabriel R, Mohiuddin O, Whitaker D, Wisely CE, Kim T

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ORIGINAL INVESTIGATION

Automated Eye Tracking Enables Saccade Performance Evaluation of Patients with Concussion History

Ailin Song, MD, MHSc, Rami Gabriel, MD, Omar Mohiuddin, MS, MPH, Diane Whitaker, OD, C. Ellis Wisely, MD, MBA, and Terry Kim, MD

Duke University School of Medicine, Durham, North Carolina (AS), and Department of Ophthalmology, Duke University, Durham, North Carolina (RG, OM, DW, CEW, TK)

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Corresponding author:

C. Ellis Wisely

Ellis.Wisely@duke.edu

ABSTRACT

Significance: Automated eye tracking could be used to evaluate saccade performance of patients with concussion history, providing quantitative insights about the degree of oculomotor impairment and potential vision rehabilitation strategies for this patient population. **Purpose:** To evaluate the saccade performance of patients with concussion history based on automated eye-tracking test results. **Methods:** We conducted a retrospective study of patients with concussion history, primarily from sports participation, who underwent oculomotor testing based on an eye-tracking technology at the Duke Eye Center vision rehabilitation clinic between June 30, 2017 and January 10, 2022. Patients' saccade test results were reviewed, including saccade fixation and saccade speed/accuracy ratio. The outcomes were compared with age-matched normative population data derived from healthy individuals. Multiple linear regression analyses were performed to identify factors associated with saccade performance among patients with concussion history. Results: 115 patients with concussion history were included in the study. Patients with concussion on average had fewer fixations on self-paced horizontal and vertical saccade tests and lower horizontal and vertical saccade speed/accuracy ratios compared with normative ranges. Among patients with concussion history, multiple linear regression analyses showed that older age was associated with fewer fixations on horizontal and vertical saccade tests, while male sex was associated with more fixations on horizontal and vertical saccade tests (all $P<.01$). Additionally, older age was associated with lower horizontal saccade speed/accuracy ratio, after adjusting for sex, number of concussion(s), and time from most recent concussion to oculomotor testing ($P<.001$). **Conclusions:** Patients with concussion history had lower saccade performance based on eye tracking compared with healthy individuals. We additionally identified risk factors for lower saccade performance among patients with concussion history.

These findings support the use of saccade test results as biomarkers for concussion and have implications for post-concussion rehabilitation strategies.

Data from the United States Centers for Disease Control and Prevention (CDC) have indicated that each year, approximately 2.07 million Americans are treated and released from an emergency department as a consequence of traumatic brain injury (TBI).[1] Furthermore, worldwide it is estimated that 50-60 million new TBI cases occur annually.[2] Sport-related concussions, in particular, have created controversy due to the reported association with late cognitive decline, second impact syndrome, and chronic traumatic encephalopathy.[3,4] After TBI, the damage does not always remain static or improve; in fact, studies have shown that up to 50% of patients can have late deterioration visualized by progressive changes on advanced neuroimaging.[5] To make matters more complicated, the detection of sport-related concussion and TBI is difficult as symptoms can be transient and subtle, and visual-motor performance is critically important in sports as seen in numerous studies.[6–15]

A battery of tests has been developed and employed in the diagnosis of TBI, including the King-Devick test, the Vestibular Ocular Motor Screening test, cognition testing, sleep studies, and even functional magnetic resonance imaging with specific attention to the frontal eye fields and cerebellar vermis.[16] The King-Devick test and the Vestibular Ocular Motor Screening test both highlight the importance of ocular movement for detection of TBI. The King-Devick test utilizes spaced target objects placed on a card for examinees to read aloud in rapid succession to test their speed of saccadic movement, attention, and language.[17] The Vestibular Ocular Motor Screening test also utilizes ocular movement by having patients complete a series of saccades under a set time as well as vestibular-ocular reflex (doll’s head) maneuvers.[18] Patients with TBI were found to have changes in eye movements on these tests.[19,20]

Given the sensitivity and importance of ocular movement in the evaluation of TBI and sport-related concussion, there has been an innovation boom in eye-tracking technology such as Eyelink (SR Research LTD), Pupil Labs (Pupil Labs GmbH), Eyeguide Focus (Eyeguide, Inc), and RightEye (RightEye LLC).[21] These technologies track eye movements in multiple ways including monocular accessories, binocular headsets and advanced cameras.[22] Multiple studies have used eye-tracking technologies to investigate oculomotor deficits in TBI.[23–29] Given that saccade performance has been linked with cognitive abilities,[30] the purpose of this study was to utilize the RightEye equipment to accurately and consistently evaluate the saccade performance of patients with concussion history. Specifically, we used the RightEye technology to assess saccade accuracy and speed to further characterize the differences in patients with concussion history compared with normative ranges, allowing for more descriptive and objective data on saccade performance, compared with tests requiring number or image recognition. Findings from this study may have implications for rehabilitation strategies for patients suffering from symptoms after concussion, for whom vision rehabilitation has been shown to improve outcomes.[31]

METHODS

Study Design

A retrospective study of patients with a history of concussion who underwent oculomotor testing at the Duke Eye Center vision rehabilitation clinic between June 30, 2017 and January 10, 2022 was conducted. Patients with an established history of oculomotor impairment or uncorrectable visual impairment prior to testing were excluded. This research was reviewed by an independent ethical review board and conforms with the principles and applicable guidelines for the protection of human subjects in biomedical research.

Data Collection

Study patients' saccade test results were retrospectively reviewed in the RightEye software (RightEye, LLC., Bethesda, MD, USA). RightEye is a commercially available, validated ocular sensorimotor testing platform using automated eye-tracking technology.[32] We extracted fixation number and speed/accuracy ratio results from horizontal and vertical saccade tests for both eyes of each participant. Figure 1 shows the RightEye system. The RightEye horizontal and vertical saccade tests have been previously described.[23] The angular subtense of the targets used in the saccade tests was 20º (10º in each direction from the center). The accuracy of the eye tracker was 0.4º (standard deviation: 0.1º). Fixation was defined as dispersion of <0.25º for 100 ms. Fixation number was defined as the total number of gaze fixations that occurred during a saccade test, including on-target, overshot, and undershot fixations. RightEye can distinguish between on-target, overshot, and undershot fixations. Speed/accuracy ratio was defined as the ratio of saccade velocity over accuracy. Accuracy was measured by the distance from a participant's fixation point to the target stimulus, so shorter distances represented greater accuracy. In turn, high speed/accuracy ratio values suggest better performance.[23] Additionally, the date of the patient's most recent concussion, total number of concussion(s), age, and sex were collected from the electronic medical record.

Statistical Methods

The primary outcomes were the saccade test results, including fixation numbers on horizontal and vertical saccade tests, horizontal saccade speed/accuracy ratio, and vertical saccade speed/accuracy ratio. These outcomes were compared with age-matched normative population data provided by RightEye, which measured the test performance of healthy individuals across various age groups.[33] Hypothesis testing was not performed as our study was exploratory in nature. Multiple linear regression analyses were performed to identify factors associated with each of the saccade test outcomes. Variables included in the regression analyses were time from most recent concussion, number of concussion(s), age, and sex. For each analysis, assumptions of linear regression were evaluated with residuals vs. fitted values, normal Q-Q, scale-location, and residuals vs. leverage plots. The threshold for statistical significance was set at α=0.05 for two-sided tests. Statistical analysis was performed in R (version 4.1.2) with RStudio (version 1.4.1103).

RESULTS

A total of 178 patients underwent oculomotor testing during the study period. We excluded 3 patients who were missing saccade test results, 53 patients with an established history of oculomotor impairment or uncorrectable visual impairment prior to testing, and 7 patients due to lack of documented concussion history in available medical records, yielding a final cohort of 115 patients. Table 1 describes the demographic and clinical characteristics of the included patients. The most common mechanism of injury was sports participation (58.3%), followed by motor vehicle accident (25.2%), and other mechanisms (16.5%).

Saccade Performance of Patients with Concussion History vs. Normative Ranges

Figure 2 compares the saccade performance of our study patients against age-matched normative population data provided by RightEye. Compared with normative ranges, patients with concussion history on average had fewer fixations on the horizontal and vertical saccade tests in each eye. On average, patients also had lower horizontal and vertical saccade speed/accuracy ratios.

Factors Associated with Saccade Performance among Patients with Concussion History

Among the study patients, multiple linear regression analysis showed that older age was associated with fewer fixations on the horizontal saccade test, while male sex was associated with more fixations on the horizontal saccade test in both eyes after adjusting for the number of concussion(s) and time from most recent concussion to oculomotor testing (Table 2).

Similarly, older age was associated with fewer fixations on the vertical saccade test, while male sex was associated with more fixations on the vertical saccade test (Table 3). The number of concussion(s) was also associated with more fixations on the vertical saccade test, after adjusting for age, sex, and time from most recent concussion to oculomotor testing.

Regarding horizontal saccade speed/accuracy ratio, older age was associated with lower ratios in both eyes, after adjusting for sex, number of concussion(s), and time from most recent concussion to oculomotor testing (Table 4). None of these factors were associated with vertical saccade speed/accuracy ratio.

DISCUSSION

This study evaluated the saccade performance of patients with concussion history based on results from automated eye-tracking tests. We found that patients with concussion history had fewer fixations and lower speed/accuracy ratios on self-paced horizontal and vertical saccade tests compared with normative ranges. Additionally, factors associated with study patients' saccade performance were identified.

Our results showed that fixation performance on horizontal and vertical saccade tests was worse for patients with concussion history than for healthy individuals. Previously, several studies have reported changes in eye movements in TBI.[19,20,23–29] Saccade performance has been thought to be a useful biomarker for cognitive abilities,[30] which may be compromised after TBI.[23] However, the literature on mild TBI and more specifically sport-related concussion is limited. Hunfalvay et al. used the RightEye technology to assess self-paced saccades in patients with TBI of varying severity and found that patients with TBI had fewer fixations than healthy individuals.[23] Our study demonstrated results consistent with prior findings and showed that the findings were generalizable to a population of over 100 patients with primarily sports-related concussion history. These findings provide further evidence that saccade performance may be a biomarker for concussion and concussion sequalae.

Furthermore, increasing age was associated with fewer fixations on the horizontal and vertical saccade tests as well as lower horizontal saccade speed/accuracy ratios. The effect of age on saccade performance has been studied previously;[34–39] however, to the best our knowledge, this effect has not been studied among individuals with concussion history. Moreover, age groups included in prior studies were largely heterogeneous.[34–39] Our study included primarily young adults (median age: 21 years). Among this population, our findings suggest that the speed of self-paced saccades likely decreases with age. A previous study examining horizontal saccade dynamics across the human life span found that peak saccade velocity decreased gradually after age 14 years, while saccade accuracy remained stable between age 20 and 49 years.[37] Our study corroborates these findings in a larger cohort (n=115) and suggests that the same trend may exist for vertical saccades. Additionally, our findings have implications for older athletes' oculomotor rehabilitation needs after concussion.

The effect of biological sex on saccade performance is less clear in the literature. Our results showed that male sex was associated with more fixations on horizontal and vertical saccade tests compared with female sex, but there was no significant association between sex and saccade speed/accuracy ratio. These findings suggest that while male patients with concussion history had more self-paced saccades, female patients were more accurate at targeting. Sex differences in smooth pursuit velocity gain and blink rate during fixation have been previously reported,[39] but no study has explored how performance during self-paced saccade tasks may differ with sex. One hypothesis that may explain our findings is that different sports have different ratios of male to female participants, and different sports encourage differing saccade behaviors.[6,7,40] This hypothesis may also explain the positive association between the number of concussions and the number of fixations on the vertical saccade test in this study. However, we unfortunately do not have information for our retrospective cohort on the sport associated with each injury. Future research may elucidate mechanisms behind these associations.

Oculomotor function, including saccade performance, has a critical role in sports performance, leading to the growing trends to develop sports vision training programs.[6–15] Concurrently, sport-related concussions are highly prevalent among athletes.[41] As shown in this study, sport-related concussions affect saccade performance even long after concussion (median time from concussion in our cohort: 169 days). Therefore, athletes experiencing symptoms after concussion may benefit especially from sports vision rehabilitation.[31] Additionally, risk factors for lower saccade performance identified in this study including age and sex may help to guide personalized rehabilitation plans.

Our study has limitations. First, our study was exploratory, and its results should therefore be interpreted as hypothesis-generating and be utilized to guide future research. Importantly, the normative population data used in this study do not differentiate athletes from non-athletes: sports participation may affect saccade performance.[11,42–44] Studies with a prospective cohort design comparing saccade performance of patients with concussion with appropriately matched controls based on both age and sports participation would be important to test the hypotheses generated in this study. We also did not have information regarding the types of sports the patients played or the concussion symptomatology, which may have implications for saccade performance. Additionally, all study patients received oculomotor testing based on an eye-tracking technology at an academic vision rehabilitation clinic located in North Carolina, limiting the generalizability of this study.

Among the strengths of this study are: 1) The use of a state-of-the-art eye-tracking technology allowed us to obtain standardized, reliable, and quantitative information on saccade eye movements. 2) Compared with other studies in this area,[19,20,23–29] our sample of patients with concussion history was large (n=115), and the population was relatively young, enriching the literature on this population. 3) The adjusted r^2 values of our multiple linear regression models were high for models with only four variables, suggesting that the associations detected had meaningful predictive value. 4) While a small number of patients in our study were seen within two weeks after concussion, most patients were seen at a timepoint relatively long after the concussion event (median days after concussion: 169 [IQR: 61.5, 349.5]). The long follow-up period is a unique contribution to the literature.

CONCLUSIONS

This study showed that patients with a history of concussion had lower saccade performance based on eye tracking compared with healthy individuals. We additionally identified risk factors for lower saccade performance among patients with concussion history. These findings support the use of saccade test results as biomarkers for concussion and have implications for post-concussion rehabilitation strategies. Future research could explore how the oculomotor performance changes over time, which may aid in ‘return-to-play’ decision-making for patients with sport-related concussion history.

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Table 1. Characteristics of study patients with concussion history, n=115.

Age (years), median (IQR)	21 (16, 32.5)
Sex, No. (%)	
Female	72 (62.6)
Male	43 (37.4)
Number of concussion(s), median (IQR)	1 (1, 2)
Days from most recent concussion to oculomotor testing, median (IQR)	169 (61.5, 349.5)
Mechanism of injury, No. (%)	
Sports participation	67 (58.3)
Motor vehicle accident	29 (25.2)
Other	19 (16.5)

Table 2. Multiple linear regression models of horizontal saccade fixation.

	Right eye		Left eye	
	Regression coefficient	*P* value	Regression coefficient	*P* value
Sex				
Female	[Reference]	NA	[Reference]	NA
Male	4.24	.003	3.88	.006
Age	-0.24	<.001	-0.24	<.001
Number of concussion(s)	0.86	.092	0.91	.074
Time from most recent concussion to oculomotor testing (years)	0.01	.986	-0.40	.401
Adjusted R^2 (%)	24.86	NA	25.18	NA

NA = not applicable.

Table 3. Multiple linear regression models of vertical saccade fixation.

	Right eye		Left eye	
	Regression coefficient	*P* value	Regression coefficient	*P* value
Sex				
Female	[Reference]	NA	[Reference]	NA
Male	3.69	.003	3.85	.002
Age	-0.16	<.001	-0.17	<.001
Number of concussion(s)	0.95	.033	0.95	.019
Time from most recent concussion to oculomotor testing (years)	0.12	.782	0.12	.777
Adjusted R^2 (%)	18.87	NA	20.69	NA

NA, not applicable.

Table 4. Multiple linear regression models of horizontal saccade speed/accuracy ratio.

	Right eye		Left eye	
	Regression coefficient (dps/mm)	*P* value	Regression coefficient (dps/mm)	*P* value
Sex				
Female	[Reference]	NA	[Reference]	NA
Male	0.63	.057	-0.11	.76
Age	-0.06	<.001	-0.05	<.001
Number of concussion(s)	0.12	.307	0.20	.142
Time from most recent concussion to oculomotor testing (years)	-0.04	.735	-0.13	.313
Adjusted R^2 (%)	19.94	NA	15.69	NA

dps = degrees per second; NA = not applicable

FIGURE LEGENDS

Figure 1. The RightEye testing system. The screen shows a horizontal saccade test in progress.

Figure 2. Saccade test performance of patients with concussion history vs. reference ranges derived from healthy individuals across age groups. Means and standard deviations are shown. On average, patients with concussion history had fewer horizontal and vertical saccade fixations and lower horizontal and vertical speed/accuracy ratios than healthy individuals. dps = degrees per second.

Figure 1

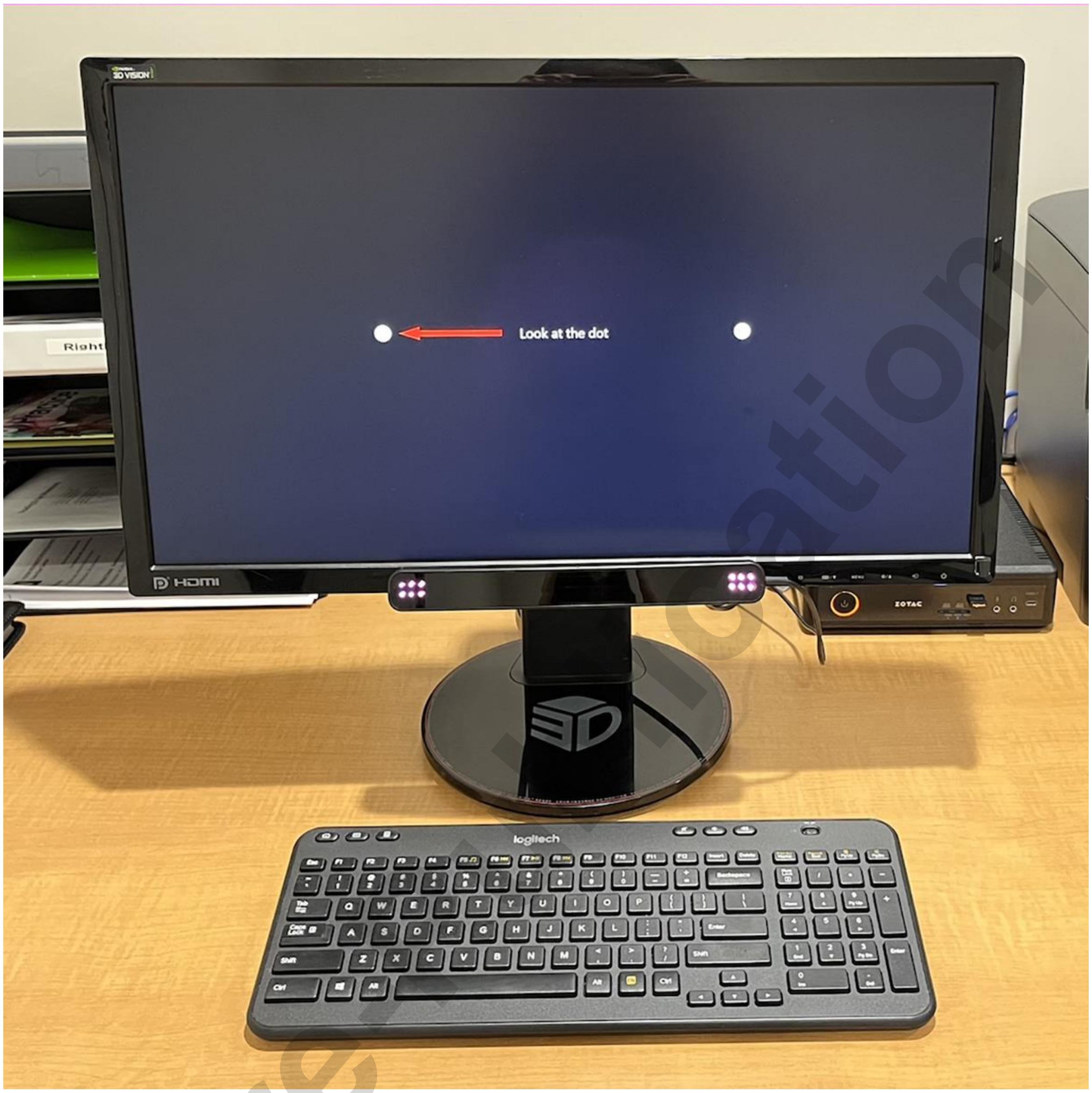
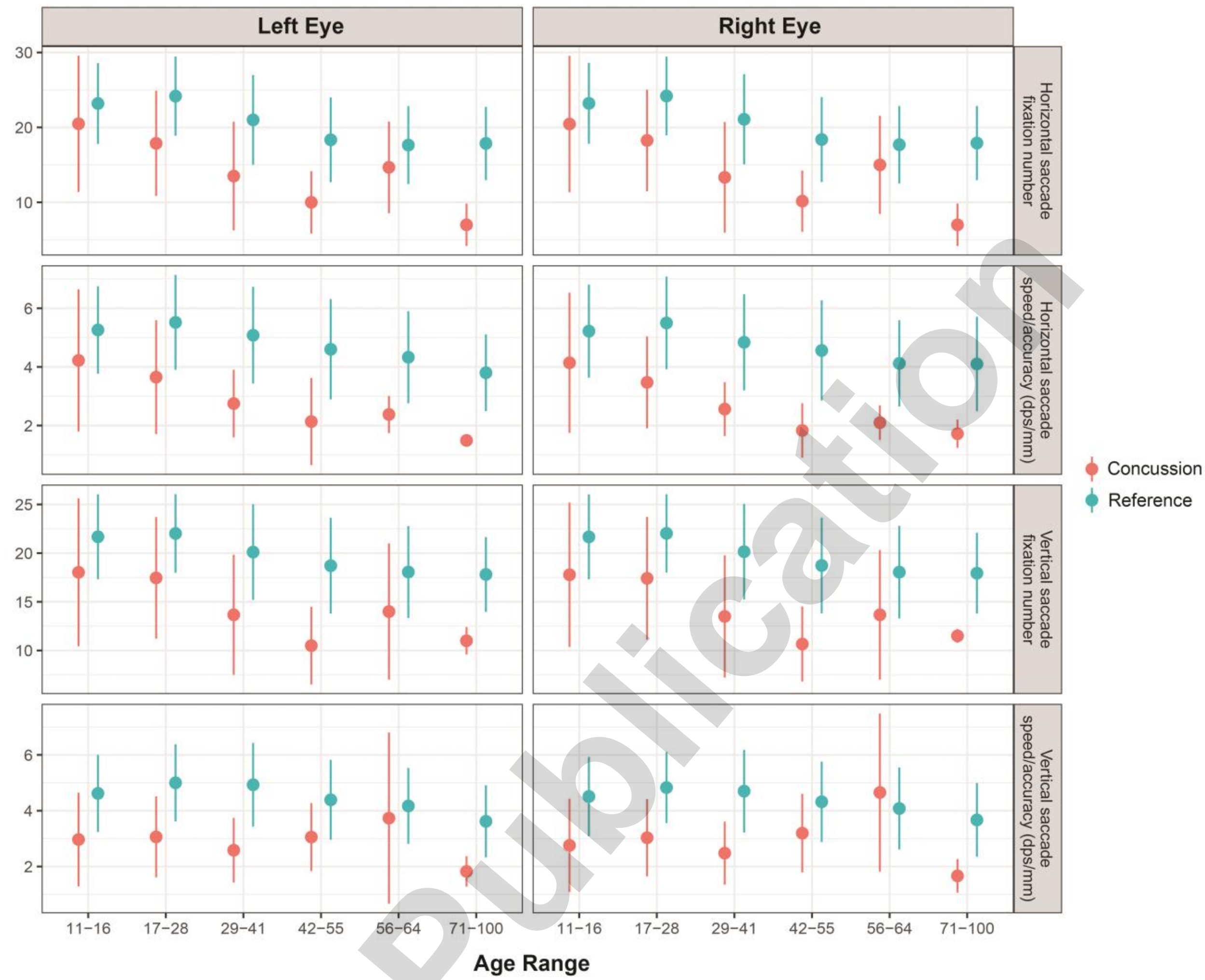


Figure 2



Left Eye
Right Eye
Horizontal saccade fixation number
Horizontal saccade speed/accuracy (dps/mm)
Vertical saccade fixation number
Vertical saccade speed/accuracy (dps/mm)
Concussion
Reference
11–16
17–28
29–41
42–55
56–64
71–100
Age Range