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Validity of low-resolution eye-tracking to assess eye movements during a rapid number naming task: performance of the eyetribe eye tracker

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Abstract

Objective: To evaluate the performance of the EyeTribe compared to the EyeLink for eye movement recordings during a rapid number naming test in healthy control participants.

Background: With the increasing accessibility of portable, economical, video-based eye trackers such as the EyeTribe, there is growing interest in these devices for eye movement recordings, particularly in the domain of sports-related concussion. However, prior to implementation there is a primary need to establish the validity of these devices. One current limitation of portable eye trackers is their sampling rate (30–60 samples per second, or Hz), which is typically well below the benchmarks achieved by their research-grade counterparts (e.g., the EyeLink, which samples at 500–2000 Hz).

Methods: We compared video-oculographic measurements made using the EyeTribe with those of the EyeLink during a digitized rapid number naming task (the King-Devick test) in a convenience sample of 30 controls.

Results: EyeTribe had loss of signal during recording, and failed to reproduce the typical shape of saccadic main sequence relationships. In addition, EyeTribe data yielded significantly fewer detectable saccades and displayed greater variance of inter-saccadic intervals than the EyeLink system.

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Declaration of interest

The authors report no declarations of interest.

Conclusion: Caution is advised prior to implementation of low-resolution eye trackers for objective saccade assessment and sideline concussion screening.

Keywords

Concussion; eye movements; eye movement measurements; king-devick; rapid number naming; saccades; video oculography

Introduction

Vision testing has emerged as an important screening tool for concussion on the sidelines. Notable among screening instruments is the King-Devick (K-D) test, a flip-card or tablet vision-based rapid number naming task that requires a series of fast eye movements (e.g., saccades) for its successful completion (1). Numerous studies in the past decade have demonstrated prolongation of K-D test completion times compared to baseline times in athletes with concussion (2–5). With vision comprising over 50% of the brain pathways (6), the utility of visual tasks in screening for concussion is not surprising; however, until recently the exact mechanism of K-D test time prolongation in concussion was unknown.

Using high-resolution video-oculography (VOG) to record eye movements during the K-D test, eye movement behavior in healthy controls and in patients with a history of concussion has recently been characterized (7,8). Patients with prior concussion demonstrated prolongation of inter-saccadic intervals (ISI), increased total numbers of saccades to complete the task, and greater degrees of saccadic dysmetria (8). These important findings demonstrated the value of eye movement recordings in characterizing the ocular motor underpinnings of K-D test performance in concussion.

Video-oculographic recordings during visual tasks other than the K-D have also been considered for concussion diagnosis, in each case proposing detection of abnormal eye movements as an indicator of subnormal brain function (9,10). One group has developed a portable eye tracker that utilizes a predictive circular visual paradigm to quantify abnormalities in visual tracking. This device is being marketed towards sideline concussion screening and management, albeit only as an investigational device at this time (11,12). With mounting evidence that eye movement abnormalities capturable only via quantified recordings exist in concussion (8,9,13,14), there has been heightened emphasis on the possibility that technology at the sidelines may play an important role in concussion detection in the future. However, a clear limitation to research progress on the sidelines is the expense and poor portability of existing commercially available, high-resolution, research-grade eye trackers.

Portable and economical video-based eye trackers such as the EyeTribe are now available (15–17) and there is increasing interest in using these mobile eye trackers for objective ocular motor recordings on the sidelines. However, prior to their implementation in this context, there is a need to establish their validity and capacity to provide clinically reliable information. Previous studies have evaluated these devices in a research setting (18,19); and concluded that the EyeTribe is suitable for pupillometry and spatial outcome metrics such as accuracy and precision of fixation measurements, but not saccade kinematics or other

temporal metrics due to a low sampling rate. However, findings based on a power spectral analysis of saccade position waveforms have led some to suggest that a sampling rate of 50 Hz (samples per second) is sufficient to accurately measure saccade peak velocities for saccade amplitudes greater than 5 degrees (20). The mobile EyeTribe has a binocular sampling rate of 30–60 Hz, making it a candidate device for recording saccade kinematics based on these findings (20).

A critical step in establishing the validity and usefulness of any new mobile eye tracking technology in concussion screening is to demonstrate a capacity to adequately capture clinically relevant aspects of eye movements in a manner comparable to the performance of established devices for recording visual tasks that might be used on the sidelines. The EyeLink 1000+ is a research-grade, high-resolution, video-based eye tracker with a sampling rate of 500–2000 Hz that has been shown to approach the accuracy of the eye movement field's gold standard, scleral search coil (21,22). Additionally, the EyeLink system is a proven laboratory tool for which data have been reported in over 3000 peer-reviewed publications (23). Thus, it was chosen as the standard to compare eye movement recordings obtained by the EyeTribe.

The purpose of this study was to evaluate the performance and feasibility of the EyeTribe mobile eye tracker for eye movement recordings during a digitized K-D rapid number naming task. We also sought to compare performance and ability to capture saccade characteristics during the K-D using the EyeTribe vs. the EyeLink 1000+.

Materials and methods

Study participants

Study protocols were approved by the Institutional Review Board at New York University School of Medicine. Informed consent was obtained from all study participants who were recruited via a convenience sampling method for this cross-sectional study. Demographic and pertinent health information was obtained by the test administrator using direct questioning. Information regarding previous concussion and neurologic or ophthalmologic disease was collected. Participants were excluded if wearing glasses was necessary to clearly see the tablet screen, since calibration of the EyeTribe was more difficult in this setting (the aim of this study was to test the EyeTribe system under ideal conditions). Participants wearing contact lenses were not excluded, but the presence of contact lenses was noted. Participants for this healthy control study were excluded if they had a history of neurologic disease or ophthalmologic disease other than refractive error.

King-devick test

Eye movement recordings were captured while participants performed a digitized version of the King-Devick (K-D) test, a vision-based rapid number naming task. The test consists of a demonstration card and three test cards. The K-D test is typically administered on a tablet computer screen or as a series of three laminated test cards. Eye movement recordings for this study were analyzed only for the three test cards (excluding the demonstration card). Participants were instructed to read the cards aloud as quickly as possible without making

errors. The resulting K-D summary time score was defined as the total time to complete all 3 test cards (screens), and was saved automatically by test recording systems. For the EyeTribe, two repetitions of the K-D test were performed, but data from only one trial was analyzed. By default, data from the first trial was used unless a problem was identified. Difficulty occurred for one participant whose K-D card #3 data did not record properly; analyses in this case were performed using data from the second trial of the K-D.

Randomization of device testing order

Recording from both devices simultaneously was not feasible; therefore participants were recorded on the EyeTribe and the EyeLink 1000+ separately. The order of the two sessions was randomized such that half of the participants were recorded on the EyeTribe first and the other half of participants were recorded on the EyeLink 1000+ first. In addition, 11 of the 30 original participants were called back for an additional session on the EyeTribe in the 60 Hz mode; this additional recording was always performed after the initial pair of EyeLink and EyeTribe 30 Hz recordings.

Eyetribe system

The EyeTribe (The EyeTribe Tracker Version 1, The EyeTribe, Copenhagen Denmark), was positioned with the manufacturer's mount that was specifically designed for the Surface Pro 3. The combined Surface Pro 3 + EyeTribe mounted unit was placed on a fixed-angle, table-top "book display" stand (Figure 1). Participants were placed in a seated position directly in front of the table, with arms resting on table for stabilization and asked to remain as still as possible. Chair height and distance from the Surface Pro 3 was adjusted as needed until the calibration screen in the EyeTribe user interface indicated that the participant's eyes were in appropriate position. Distance of the participant's eyes from the EyeTribe was estimated to range from 40 to 50 centimeters. Next, calibration was performed using the EyeTribe 9-point calibration, yielding a score from 1 to 5. Every effort was made to achieve the maximum calibration score for all participants; this included adjusting seat height, adjusting distance from screen, reminding the patient to remain still and attempting to minimize any reflections from overhead lighting. However, if this could not be achieved after five attempts at calibration, the score was recorded and the administrator proceeded with the testing. All 30 participants were successfully calibrated in the 30 Hz mode, but only 8 out of 11 participants selected for testing using the 60 Hz mode were successfully calibrated. This was most likely due to the higher sampling rate having a smaller track box (volume of space that the users eyes may be tracked). A custom Java script was used to extract and record the datastream from the EyeTribe during the K-D test.

The web-based version of the K-D was used during EyeTribe recordings; test card size was calibrated to the tablet screen according to the manufacturer's instructions. After participants were given instructions on how to perform the K-D test, and allowed to practice on the demonstration card, they were asked to close their eyes. The test administrator then opened the eye movement recording program and brought the first test card on the screen. The participant was instructed to open their eyes and to begin reading the test card immediately. After reading the last number on the test card, participants were asked to close their eyes again; the eye movement recording program was closed and the file for that card saved. This

protocol was repeated for all test cards to facilitate accurate discrimination between number-naming data and data acquired during the time between test cards. The total time for all three test cards was automatically calculated by the web-based application based on the amount of time each test card was on the screen; the test administrator was responsible for starting/stopping each test card by clicking on the screen. Total time to complete each test card was not a primary outcome measure of this study, therefore the timing of starting/stopping each test card was not strictly monitored and may have affected total K-D times during EyeTribe trials. Each participant performed two complete trials of the K-D test on the EyeTribe system as described above.

Eyelink system

The EyeLink system (EyeLink 1000+, SR Research, Ontario Canada) consisted of the EyeLink camera mounted on a table top stand positioned below a computer screen (screen dimensions: width 53 cm $\times$ height 70 cm). Participants were placed in a seated position directly in front of the EyeLink system and stabilized with a headrest 60 cm from the computer screen (7). Calibration was achieved using the EyeLink 13 point calibration procedure. Next, a digitized version of the K-D test, consisting of a demonstration card and three test cards (using the identical sequence of digits and digit-spacing as the standard KD test), was sequentially displayed on the computer screen. Binocular eye movement data were recorded during the task for each card, as well as the time to complete each individual test card and total time to complete the three test cards.

Data analysis

Eye position data were analyzed off-line using custom Matlab scripts (7). Velocities of eye movement data recorded from EyeLink system were calculated from position traces using a low-pass differentiator (impulse response $h = F_s * [0.0072 \ 0.0208 -0.0254 -0.1667 -0.2096 \ 0.2096 \ 0.1667 \ 0.0254 -0.0208 -0.0072]$). Velocities of eye movement data acquired from the EyeTribe system were calculated from position traces using two-point central differentiator (impulse response $h = F_s * [-0.5 \ 0 \ 0.5]$). The reason for using different differentiators is the sampling rate F_s of the EyeTribe is much lower than the EyeLink, and hence it is better to apply less smoothing to the EyeTribe data. Accelerations were computed from the calculated velocity using the same differentiator again. Saccades were identified when eye velocity exceeded 30 degree/second and lasted for a minimum duration of 12 milliseconds. Amplitude, duration, peak velocity, peak acceleration, peak deceleration and inter-saccadic interval of identified saccades were extracted for comparison. Main sequence relationships were fit to a decaying exponential using Bayesian parameter estimation with uniform priors. Parameters are reported as best-fit value and 95% confidence interval (CI).

Results

Eye movement recordings were obtained with both the EyeLink and Eye Tribe systems during K-D testing for 30 healthy adult volunteers with a mean age of 32.4 ± 8.7 years. Study participant characteristics are summarized in Table 1. One participant had a history of migraine with aura, but there was otherwise no history of neurologic or ophthalmologic disease. Six participants had remote history of prior concussion (years prior to study), but

there were no participants with acute concussion or symptomatic post-concussive syndromes. Participants who required glasses to read the screen during testing were excluded from the study; however 13 of the 30 participants reported refractive error. Five of those wore soft contact lenses at the time of test administration. Another five participants reported wearing glasses for myopia and three participants for presbyopia; however vision for all participants was sufficiently good to easily perform testing without their glasses. Two participants reported history of refractive surgery (Lasik).

Based on visual inspection of the eye movement tracings, it was noted that the EyeTribe frequently had signal loss as well as tracings that were inconsistent with known eye movement physiology (Figure 2). Therefore, a main sequence analysis was developed to account for subject-specific noise levels in the data when comparing the two systems. A saccadic main sequence describes the stable relationship between saccade amplitude and either saccade peak velocity or duration. Using this method, significant differences in velocity main sequence asymptote (the leveling-off point of peak velocity at high amplitude) and time constant (the rate of rise in peak velocity with increasing saccade amplitude) parameters were found. For peak velocity, the best fit value for the asymptote parameter was 506°/sec (CI: 499, 513°/sec) for the EyeLink vs. 1674°/sec (CI: 1527, 1852°/sec) for the EyeTribe. Similarly, there were significant differences in time constant best fit parameters, with the EyeLink yielding a time constant of 6.1° (CI: 5.29, 6.25°) vs. the EyeTribe yielding a best fit of 102.9° (CI: 93.5, 115.7°; Figure 3A). Main sequence analysis of duration versus amplitude parameters also showed significant differences between exponential fits derived from the EyeLink and EyeTribe data. The duration asymptote was significantly different between the two systems, with the EyeLink having a best fit of 83.2 ms (CI: 82.19–84.35 ms) vs. the EyeTribe best-fit of 62.7 ms (CI: 60.97–64.33 ms). The duration time constant was also significantly different, with the EyeLink data yielding a best-fit of 13.8° (CI: 13.55–14.14) vs. the EyeTribe yielding a best fit of 4.9° (CI: 4.56–5.27°; Figure 3B).

In addition to significant differences in fitted parameters, there were striking differences in the appearance of the EyeLink relative to EyeTribe main sequence plots that were suggestive not only of quantitative statistical differences, but also qualitative differences in the underlying functional relationships. This is particularly noteworthy given that EyeTribe-based and EyeLink-based main sequence plots were derived from the same participants' eye movements. EyeLink-based main sequence plots (Figure 3) showed relatively smooth variation as a function of saccade amplitude with a functional form that is sub-linearly increasing with increasing saccade magnitude, as is typical of main sequence plots (24). In contrast, the EyeTribe main sequence plot describing peak velocity displayed a nearly straight-line relationship (both 30 and 60 Hz data), and with very little indication of the characteristic data-gap in the range of saccade amplitudes between about 10 and 12° found here and in previous studies involving the K-D test recorded with EyeLink (7). The EyeTribe main sequence plot describing saccade duration deviated even further from the qualitative characteristics of a typical main sequence plot, with variation in saccade durations displaying a significantly reduced rank-correlation with amplitude ($r_s = 0.35$) compared to the same plot derived from EyeLink data ($r_s = 0.9$, $p = 0.0005$). These qualitative differences in the shape of EyeTribe-based main sequence plots were evident in both the 30 Hz recordings that were our main focus in this study (the default rate for the system), and also

in the higher-rate 60 Hz EyeTribe recordings (Figure 3). Thus, while the details are different in the two cases, EyeTribe-derived main sequence plots differed just as strongly from those produced by EyeLink recordings whether the EyeTribe sampling rate was 30 or 60 Hz.

Significantly fewer saccades could be detected using the data obtained from EyeTribe recordings, with an average of 110.2 saccades detected in EyeTribe vs. 120.5 saccades per session detected in EyeLink ($p = 0.00007$, Wilcoxon signed rank test) data recordings. Although there was no statistical difference in ISIs measured in data obtained from the two eye trackers (median ISI of 267 ms on the EyeTribe vs. 270 ms on the EyeLink; $p = 0.88$, Wilcoxon signed rank), the ISI values recorded via EyeTribe were significantly more variable than those recorded via the EyeLink system ($p = 0.0001$ Wilcoxon signed rank test performed on by-subject variance estimates, or via the Ansari-Bradley test performed on raw ISI data). Finally, the median K-D time recorded on the EyeTribe was significantly longer than that recorded with the EyeLink (43.5 seconds compared to 41.1 seconds; $p = 0.0023$, Wilcoxon signed rank). However this may be accounted for by the relative imprecision of the web-based K-D measurement used with EyeTribe recordings, which relies on the experimenter's reaction time for starting and stopping the timer; note that measuring a difference in K-D time between systems was not an objective of this study.

Discussion

Overview

Although there were many quantitative differences between the data acquired by the two eye tracking systems, the most notable differences involved the overall qualitative characteristics of the results. First, the mobile EyeTribe had issues with signal loss, likely caused by slight involuntary movements of the participant's head moving the eyes out of range of the system. In addition, the shapes of the main sequence plots derived from EyeTribe data (saccade amplitudes, durations and peak velocities) were clearly different from those normally observed in eye movement recordings of healthy participants (7,8,25). Saccade duration data in particular do not appear to conform to any previously published pattern of results, or to normal ocular motor physiology. Saccade main sequence parameters for both velocity and duration were significantly different between the EyeTribe and EyeLink systems, consistent with previous studies analyzing saccade metrics using the EyeTribe (18).

Additionally, significantly fewer saccades were detected in EyeTribe recordings. This is not surprising considering the EyeTribe's relatively low 30 Hz sampling rate, which may be insufficient to obtain data samples during all saccades (i.e., a complete saccade may occur between 30 Hz data samples) and provide inaccurate temporal data for saccade velocity and duration calculations. This temporal imprecision can be seen in the greater variance of EyeTribe ISI data, and would tend to increase the difficulty of finding a difference between ISI values in healthy versus concussed subject recorded with the EyeTribe. This is particularly troublesome with regard to using a low temporal frequency device as part of a sideline concussion screen, as this key measure was recently found to be prolonged in chronic concussion (8).

As mentioned previously, 60 Hz recordings using the EyeTribe in a subset of participants demonstrated that this sampling rate did not appreciably improve the quality of eye movement recordings. Although it has been previously suggested that a sampling rate of 50 Hz is sufficient for saccade analysis (20), the main sequence plots based on both the 30 Hz and 60 Hz EyeTribe recordings failed to match those based on EyeLink data, even qualitatively. In short, neither EyeTribe recording session showed adequate resolution to accurately characterize saccade kinematics in this study, a finding that is elaborated below.

Measurements of saccade kinematics

The EyeTribe's poor temporal resolution is an important limitation when analyzing saccade kinematics. From a mathematical perspective, it is known that if a sampling frequency is too low, the result is a loss of information known as aliasing (20). This is illustrated in Figure 4, which shows that a saccade waveform (26) captured by a 500 Hz vs. 30 Hz system will have a large impact on the calculated velocity. In Figure 4b, changes in velocity at each data point for the 30 Hz system (large circles) appear quite abrupt compared to those of the 500 Hz recording (small circles). However, any biological motor systems must have a smooth acceleration and deceleration and this is better captured by the 500 Hz system (Figure 4). Furthermore, the 500 Hz system can accurately capture and discriminate saccades of different velocities (Figure 5, Panels a and b). In contrast, the 30 Hz sampling rate for two saccades of different velocities (Figure 5, Panels c and d) does not allow accurate definition of saccade onset and offset (Figure 5, Panel c). This results in inaccurate calculations of all temporal measures, including saccade velocity (Figure 5, Panel d), saccade duration, and ISI. This issue likely contributed to the significant differences seen between the EyeTribe and EyeLink in the saccade main sequence parameters of peak velocity and duration. It is interesting to note that from an historical perspective, VOG has been limited by its slower sampling rate resulting in noisier estimates of saccade parameters when compared to scleral search coil (27), this has only recently been overcome with the higher sampling rates of modern VOG (21,22). Therefore, it is not unexpected that the slow sampling rate of portable video-based eye trackers is not sufficient to accurately measure saccade kinematics.

Low-resolution eye tracking performance

The quality of eye movement tracings obtained by the EyeTribe was highly variable across participants and trials. In general, however, EyeTribe recordings were prone to signal loss and often produced tracings that were inconsistent with known eye movement physiology. One possible explanation for the observed signal loss is participant head movement during testing, which is supported by a recent study demonstrating that non-optimal head positioning during EyeTribe recording results in significant data loss and variation in the inter-sample interval (28). Importantly, because tight control of head positioning in sideline testing is unrealistic, this source of variation in data quality would affect calculation of saccade metrics including the ISI, a measure recently shown to be prolonged in concussion during K-D testing (8).

Eye movement tracings from a representative subject on both the EyeTribe and the EyeLink are shown in Figure 2. In addition to signal loss, it can be appreciated that, due to the lower sampling rate, the EyeTribe data tracing is less dense than that of the EyeLink, resulting in

greater difficulty extracting the details of the eye's movements. Overall, side-by-side comparison of EyeTribe and EyeLink tracings revealed lower quality and consistency in the EyeTribe recordings, findings consistent with the lower temporal resolution of the EyeTribe.

Inter-saccadic interval, saccade frequency and implications for sideline concussion screening

In chronic concussion, it has recently been demonstrated that during the K-D test there is an average prolongation of 38 ms for the ISI, which correlates with increases in total K-D testing time. Therefore, the ISI would be an important candidate measure for sideline concussion screening (8). However, as we showed previously, a low temporal resolution VOG system is not able to characterize the precise onset and offset of saccades, as saccades last <100 ms. Thus, we would expect that the EyeTribe would not be able to accurately capture the ISI: a prediction borne out by the significantly inflated ISI variances derived from EyeTribe recordings.

In addition, there were significantly fewer saccades recorded by the EyeTribe system than by the EyeLink. As discussed earlier, this is most likely due to the low sampling rate recordings failing to capture some saccades, especially smaller saccades with shorter durations. This is important to note in the context of concussion screening, as it was recently shown that in chronic concussion there is a significant increase in the total number of saccades necessary to complete the K-D, with an increase in smaller amplitude saccades (8). Therefore, the inability of the EyeTribe to accurately record the total number of saccades, especially smaller saccades, may be relevant in concussion and is an important limitation when considering use of this and similar low-resolution devices for sideline concussion screening.

Limitations

Eye movement tracings from the EyeTribe system often had data loss from failure of the system to reliably locate a participant's eyes during the course of the task. One potential reason for this loss of data included participant head movement as discussed previously. In addition, data loss frequently occurred during the second half of the trial, when the participant would be looking at the lower half of the screen, which may be explained by the slight closure of the eyes that occurs when looking down.

During calibration for the EyeTribe, many participants required multiple trials for a 5-star calibration to be achieved. This would be especially problematic should it occur during a sideline screen, where a participant's ability to follow instructions that involved sitting still and paying attention might be compromised. Potential participant differences leading to more difficulty calibrating some individuals include differences in height, eye size, eye shape, or ability to stay still during testing. Although every effort was made to standardize EyeTribe recordings for all participants, differences in set-up and the environment may have also had an influence.

A limitation of portable eye trackers is they require proper set-up prior to each testing, which can introduce additional human error and variability, as noted in previous studies (19). Furthermore, participants often complained of screen glare with the EyeTribe system. These limitations are important to note when considering this device for sideline concussion

testing, where the testing environment and injury status of the population under study will introduce additional challenges when attempting to control and standardize testing, particularly with regard to factors such as consistent equipment set-up, ambient lighting, and participant head movement and attention.

Conclusions

The portable EyeTribe eye tracking device had issues with signal loss, and was found to produce data-traces inconsistent with physiologic eye movement behavior when compared to data derived using the EyeLink 1000+. Saccade main sequence parameters for both velocity and duration were significantly different between the EyeTribe and EyeLink systems, indicating the EyeTribe could not accurately capture saccade kinematics. An additional consideration in the use of portable eye tracking systems in a sideline concussion screen is that the eye position data generated by such systems requires filtering, conversion and interpretation by computational scientists and other experts, expertise not typically available to athletic trainers, team physicians or sports parents. Findings of this investigation demonstrate that care should be taken prior to implementation of commercially available, low-resolution, portable eye movement recording devices for use in obtaining objective ocular motor recordings.

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References

1. Galetta KM, Liu M, Leong DF, Ventura RE, Galetta SL, Balcer LJ. The King-Devick test of rapid number naming for concussion detection: meta-analysis and systematic review of the literature Concussion. 2016; 1(2):cnc.15.8. 10.2217/cnc.15.8.
2. Galetta MS, Galetta KM, McCrossin J, Wilson JA, Moster S, Galetta SL, Balcer LJ, Dorshimer GW, Master CL. Saccades and memory: baseline associations of the King-Devick and SCAT2 SAC tests in professional ice hockey players J Neurol Sci. 2013; 328(1):28–31. 10.1016/j.jns.2013.02.008. [PubMed: 23499425]
3. King D, Brughelli M, Hume P, Gissane C. Concussions in amateur rugby union identified with the use of a rapid visual screening tool J Neurol Sci. 2013; 326(1–2):59–63. 10.1016/j.jns.2013.01.012. [PubMed: 23374885]
4. Galetta KM, Brandes LE, Maki K, Dziemianowicz MS, Laudano E, Allen M, Lawler K, Sennett B, Wiebe D, Devick S. The King-Devick test and sports-related concussion: study of a rapid visual screening tool in a collegiate cohort J Neurol Sci. 2011; 309(1–2):34–39. 10.1016/j.jns.2011.07.039. [PubMed: 21849171]
5. Galetta KM, Barrett J, Allen M, Madda F, Delicata D, Tennant AT, Branas CC, Maguire MG, Messner LV, Devick S. The King-Devick test as a determinant of head trauma and concussion in

- boxers and MMA fighters *Neurology*. 2011; 76(17):1456–62. 10.1212/WNL.0b013e31821184c9. [PubMed: 21288984]
6. Felleman DJ, Van Essen DC. Distributed hierarchical processing in the primate cerebral cortex *Cereb Cortex*. 1991; 1(1):1–47. 10.1093/cercor/1.1.1. [PubMed: 1822724]
 7. Rizzo J-R, Hudson TE, Dai W, Desai N, Yousefi A, Palsana D, Selesnick I, Balcer LJ, Galetta SL, Rucker JC. Objectifying eye movements during rapid number naming: methodology for assessment of normative data for the King-Devick test *J Neurol Sci*. 2016; 362:232–39. 10.1016/j.jns.2016.01.045. [PubMed: 26944155]
 8. Rizzo J-R, Hudson TE, Dai W, Birkemeier J, Pasculli RM, Selesnick I, Balcer LJ, Galetta SL, Rucker JC. Rapid number naming in chronic concussion: eye movements in the King-Devick test *Ann Clin Transl Neurol*. 2016; 3:801–11. 10.1002/acn3.345. [PubMed: 27752515]
 9. Maruta J, Suh M, Niogi SN, Mukherjee P, Ghajar J. Visual tracking synchronization as a metric for concussion screening *J Head Trauma Rehabil*. 2010; 25(4):293–305. 10.1097/HTR.0b013e3181e67936. [PubMed: 20611047]
 10. Samadani U, Li M, Qian M, Laska E, Ritlop R, Kolecki R, Reyes M, Altomare L, Sone J-Y, Adem A. Sensitivity and specificity of an eye movement tracking-based biomarker for concussion *Concussion*. 2015; 1(1):2056–3299. eISSN.
 11. *SyncThink [Internet]*. Palo Alto, CA: SyncThink; 2017 [accessed 2017 Mar 7]. <http://www.syncthink.com/>.
 12. Sussman E, Ho A, Pendharkar A, Ghajar J. Clinical evaluation of concussion: the evolving role of oculomotor assessment *Neurosurg Focus*. 2016; 40(4):E7. 10.3171/2016.1.FOCUS15610.
 13. Heitger MH, Jones RD, Dalrymple-Alford JC, Frampton CM, Ardagh MW, Anderson TJ. Motor deficits and recovery during the first year following mild closed head injury *Brain Inj*. 2006; 20(8):807–24. 10.1080/02699050600676354. [PubMed: 17060148]
 14. Cifu DX, Wares JR, Hoke KW, Wetzel PA, Gitchel G, Carne W. Differential eye movements in mild traumatic brain injury versus normal controls *J Head Trauma Rehabil*. 2015; 30(1):21–28. 10.1097/HTR.0000000000000036. [PubMed: 24695263]
 15. *TheEyeTribe [Internet]*. Copenhagen, Denmark: The EyeTribe; 2014 [accessed 2016 Sept 26]. <http://theeyetribes.com/>.
 16. *Tobii Pro X2–30 screen-based eye tracker [Internet]*. Stockholm, Sweden; 2015 [accessed 2016 Sept 26]. <http://www.tobii.com/product-listing/tobii-pro-x2-30/>.
 17. *SensoMotoric Instruments RED250mobile [Internet]*. Teltow, Germany: SensoMotoric Instruments; 2016 [accessed 2016 September 26]. <http://www.smivision.com/en/gaze-and-eye-tracking-systems/products/red250mobile.html>.
 18. Dalmaijer E. Is the low-cost EyeTribe eye tracker any good for research? *PeerJ Preprints*. 2014 10.7287/PEERJ.PREPRINTS.585V1.
 19. Ooms K, Dupont L, Lapon L, Popelka S. Accuracy and precision of fixation locations recorded with the low-cost Eye Tribe tracker in different experimental set-ups *J Eye Mov Res*. 2015; 8(1) 10.16910/JEMR.8.1.5.
 20. Wierts R, Janssen MJA, Kingma H. Measuring saccade peak velocity using a low-frequency sampling rate of 50 Hz *IEEE Trans Biomed Eng*. 2008; 55(12):2840–42. 10.1109/TBME.2008.925290. [PubMed: 19126467]
 21. Kimmel DL, Mammo D, Newsome WT. Tracking the eye non-invasively: simultaneous comparison of the scleral search coil and optical tracking techniques in the macaque monkey *Front Behav Neurosci*. 2012; 6:49. 10.3389/fnbeh.2012.00049. [PubMed: 22912608]
 22. McCamy MB, Otero-Millan J, Leigh RJ, King SA, Schneider RM, Macknik SL, Martinez-Conde S, Paterson K. Simultaneous recordings of human microsaccades and drifts with a contemporary video eye tracker and the search coil technique *PLoS One*. 2015; 10(6):e0128428. 10.1371/journal.pone.0128428. [PubMed: 26035820]
 23. *SR Research-Publications [Internet]*. Ontario, Canada: SR Research; 2016 [accessed 2016 Sept 26]. <http://www.sr-research.com/publications.html>.
 24. Leigh RJ, Zee DS. *The Neurology of Eye Movements*. 5th ed Oxford: Oxford University Press; 2015.

25. Ramat S, Leigh RJ, Zee DS, Optican LM. What clinical disorders tell us about the neural control of saccadic eye movements *Brain*. 2007; 130(Pt 1):10–35. 10.1093/brain/awl309. [PubMed: 17121745]
26. Dai W, Selesnick IW, Rizzo J-R, Rucker JC, Hudson TE. A parametric model for saccadic eye movement *IEEE Signal Proc Med Bio Symp*. 2016 10.1109/SPMB.2016.7846860.
27. Van Der Geest JN, Frens MA. Recording eye movements with video-oculography and scleral search coils: a direct comparison of two methods *J Neurosci Methods*. 2002; 114(2):185–95. 10.1016/S0165-0270(01)00527-1. [PubMed: 11856570]
28. Niehorster DC, Cornelissen THW, Holmqvist K, Hooge ITC, Hessels RS. What to expect from your remote eye-tracker when participants are unrestrained *Behav Res Methods*. 2017 10.3758/s13428-017-0863-0.

Figure 1. Components of the EyeTribe system. The EyeTribe was positioned using the manufacturer's mount on a Surface Pro 3 and placed on a tabletop bookstand as shown. A wireless keyboard and mouse were used by the test administrator to control the system. Participants were instructed to sit directly in front of the EyeTribe system and place arms on desk to minimize movement during testing.

Figure 2.

Representative eye movement tracings for a single participant while performing test card 2 of the K-D on the EyeLink (a) and EyeTribe (b) systems. The EyeTribe (b) position tracings are noisier, have a lower sampling resolution depicted by the thinner black line and tracings inconsistent with eye movement physiology between 15 and 20 seconds. Furthermore, saccade velocities represented by the green line on both plots show that even when the EyeTribe position tracing looks comparable to the EyeLink, the calculated saccade velocities are very different.

Figure 3.

Main sequence analysis of saccade maximum velocity (A) and duration (B) for the EyeLink vs. the EyeTribe. Data from both 30 Hz (black) and 60 Hz (grey) sampling are shown in the EyeTribe main sequence plots. Dashed lines show best exponential fits.

Figure 4. Illustration of one simulated saccade waveform sampled at 30 Hz and 500 Hz (a), and velocities calculated from these data (b).

Figure 5.

Illustration of two saccades with different velocities. Simulated saccade waveforms sampled at 500 Hz (a), are plotted alongside velocities calculated from these simulated data (b).

Identical saccade waveforms sampled at 30 Hz (c) and corresponding calculated velocities (d).

Table 1.

Demographics and baseline characteristics of participants (n = 30).

Age, years (SD)	32.4 (8.7)
Female Sex, n (% Female)	19 (63%)
Wearing Contacts During Testing, n (%) Refractive Error, n (%)	5 (17%)
Myopia	5 (17%)
Presbyopia	3 (10%)
History of Lasik Surgery, n (%)	2 (7%)
Remote History of Concussion, n (%)	6 (20%)
Previously Performed EyeLink, n (%)	17 (57%)