An Examination of the Oculomotor Behavior Metrics within a Suite of Digitized Eye Tracking Tests

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Abstract

Eye tracking has recently been used to examine oculomotor behavior (OMB) for visual and neurological health and wellness with promise in determining characteristics of healthy eyes and in turn a healthy brain. Recent research has demonstrated that human eye movements reflect individual and group differences, however, clinical evaluations of eye movements often lack test-retest reliability. The purpose of this study was to examine the reliability of oculomotor behavior metrics in healthy individuals, to determine the normative values through cluster analysis, and to compare oculomotor behavior metrics by age groups in a suite of digitized eye tracking tests. A large sample of 2993 participants completed RightEye tests. These tests demonstrated acceptable or higher reliability on 85% of the eye movement metrics and the clustering analysis distinguished 5 distinct age groups. Furthermore, group differences were found between age clusters. Overall, the findings represent the reliability of a computerized oculomotor behavior measure and the importance to consider individual and group characteristics for clinical applications as well as applied settings.

Vision in humans is the dominant sensory system with specific characteristics and capabilities. The purpose of eye movements within the oculomotor system is to move salient information into the fovea to see it clearly. Oculomotor behavior (OMB) is broadly composed of smooth pursuits, saccades, and fixations (Michael & Benjamin, 2009). Smooth pursuit (SP) occurs when the eyes track a slow-moving stimulus, usually toward its intended target or location, while keeping the object on the fovea (Barnes, 2008; Duchowski, 2007; Poole & Ball, 2005). Saccades are voluntary or reflexive movements of the fovea from one fixation point to the next (Møllenbach, Hansen, & Lilholm, 2013). Finally, fixations represent a pause or stop of the eye on a target of interest (Komogortsev & Karpov, 2013). Given the importance of eye movements, there is a need to incorporate reliable and accurate measures of OMB into clinical practice and in research. As such, the purpose of this project is to test the reliability of OMB metrics from the RightEye tests in a large sample of healthy individuals and to determine the normative values of OMB metrics for healthy individuals. Furthermore, to compare OMB metrics by age. Therefore, the review of literature is meant to serve as a survey of recent work to this end.

Deficits in the oculomotor system can result in lower visual acuity, changes in visual perception, and reduced visual stability (Leigh & Zee, 2015). Furthermore, the oculomotor system can be an indicator of the neurological status of an individual. For example, it is well-known that individuals with traumatic brain injury (TBI) and mild traumatic brain injury (mTBI) suffer from some vision and visual processing dysfunctions, including visual field defect, visual motion sensitivity, and oculomotor deficits (e.g., Contreras, Ghajar, Bahar, & Suh, 2011; Suh, Kolster, Sarkar, Mccandliss, & Ghajar, 2006). Further, oculomotor control differs from many psychiatric and neurological pathologies (Leigh, & Zee, 2015). For example, saccades and smooth pursuit eye movements have been identified as endophenotypes in several neurological and psychiatric conditions including schizophrenia (e.g., McDowell & Clementz, 1997; Sereno & Holzman, 1995), Parkinson's disease (e.g., Gitchel, Wetzel, & Baron, 2012), essential tremor (e.g., Gitchel, Wetzel, & Baron, 2013), attention deficit hyperactivity disorder (ADHD; Munoz, Armstrong, Hampton, & Moore, 2003; Overton, 2008), fetal alcohol spectrum disorder (Paolozza, Titman, Brien, Munoz, & Reynolds, 2013), bipolar disorder (Mueller et al., 2010), borderline personality disorder (e.g., Kaufman, 2007), and anxiety and depression (Jazbec, McClure, Hardin, Pine, & Ernst, 2005). With the proper measurement of eye movements, scientists and clinicians could utilize OMB to indicate certain neurological diseases. Also, eye movement measurement may indicate current disease state and efficacy of therapy even when other measures (such as magnetic resonance imaging (MRI)) fail to indicate a deficit (Bigler, 2013).

OMB is controlled by specific brain structures, starting with ganglion cells in the retina, spanning across each lobe and involving both excitatory and inhibitory neurons through direct and indirect pathways. Depending on the type of eye movement, this behavior can involve components of the following key brain areas: superior colliculus, thalamus (lateral geniculate nucleus), parietal cortex (parietal eye field), frontal cortex (prefrontal cortex, frontal eye field, supplementary eye field), basal ganglia (striatum, globus pallidus, subthalamic nucleus), cerebral cortex, brain stem reticular formation, and cerebellum (Munoz & Coe, 2011; Munoz, & Everling, 2004). Also, saccades directed towards a remembered target involve working memory and will, therefore, require activation of neurocircuitry including the prefrontal cortex, frontal eye field, or supplementary eye field regions (Alvarez, Alkan, Gohel, Ward, & Biswal, 2010; Burke & Barnes, 2006; Ito, Barnes, Fukushima, Fukushima, & Warabi, 2013; Peltsch, Hemraj, Garcia, & Munoz, 2011).

Beyond a potential indicator of neurological disease, OMB has shown to be affected by age. Smooth pursuit eye movements typically decline with age (Leigh & Zee, 2015) and some saccadic behaviors, such as the disjunctive component of eye movements, are also influenced by age. Children demonstrate an increase in vertical conjugate post-saccadic drift after upward saccades with less horizontal vergence (Gaertner & Kapoula, 2015). Vernet et al. (2009), using the gap and overlap paradigms, demonstrated switching latencies are age-dependent in saccadic direction and by paradigm. They also found that frontal eye field layers are optimal in early adulthood and decline with age. Further, these authors demonstrated differences in horizontal and vertical saccades with longer latencies for middle-aged adults. Also, Contreras et al. found that younger participants could synchronize their eye movements better than older participants and that age is a critical factor when comparing impaired groups as well as normative data.

Assessment of OMB is also examined, both directly and indirectly for elite levels of performance, including military, police, and athletic (Laby et al., 1996; Murray, Hunfalvay, & Bolte, 2017; Murray & Hunfalvay, 2017). A superior ability to anticipate the flight of a ball (Croft, Button, & Dicks, 2010) or target an area (Brenton, Muller, & Mansingh, 2015) can, at least in part, be associated with effective, smooth pursuit, saccades, and fixations (Hunfalvay, Orr, Murray, & Roberts, 2017). The OMB form a foundation in which other higher order processing occurs such as superior reaction time (Oudejans, Michaels, & Bakker, 2011), memory (Beilock, Wierenga, & Carr, 2002), information processing speed (Williams, & Ward, 2003), and decision making (Tenenbaum, 2003) even in children as young as eight years old (Verburgh, Scherder, Lange, & Oosterlaan, 2016). Elite level OMB allows for the athlete, officer, or warfighter to be efficient and effective in performance-related environments and in situations that are stressful or time constrained.

Given the factors that influence OMB and the current standards of assessment, there is a need for objective and reliable measures of OMB. Leigh & Zee (2015), in their classic textbook, describe the clinical examinations of saccades, smooth pursuit, gaze behavior, and eye-head movements among others. Typically, these clinical evaluations involve a “bedside” approach and instruction which include ‘follow the tip of my finger’ and require the physician to detect the salient characteristics of OMB by the naked eye (Bedell & Stevenson, 2013). The recommendations for saccadic eye examinations included naked eye evaluations are aimed at answering such questions as: “Are saccades promptly initiated? Are they of normal velocity? Are they accurate? Do the eyes move together? Do they go straight to the target?” (Leigh & Zee, 2015, p 243). Examinations for smooth pursuit eye movements are similar. In addition to the standard bedside evaluations, the most commonly used protocol by practitioners, recommended by the Neuro-Optometric Rehabilitation Association, is the Vestibular Ocular-Motor Screening Assessment (VOMS; Mucha et al., 2014). This protocol is used in many settings by various professionals from general medical practitioners, to physical therapists, to neurologists, and even athletic coaches. However, several problems exist with this approach. First, the reliability of VOMS is low irrespective of the administrator’s level of experience (Singh et al., 2013; Winters et al., 2012). Second, it is only possible to detect gross eye movement through the naked eye. Third, measuring a change in eye movements over time is difficult when employing the "bedside" or VOMS assessments. It should be noted that these assessments of oculomotor behavior are only one part of a more holistic assessment which often includes short-term memory and balance tests. However, with the knowledge that eye movements are an essential factor in overall health (Bedell & Stevenson, 2013), it is imperative that they are examined with the highest level of accuracy needed to provide reliable data and interpretation.

Eye tracking has recently been used to examine OMB for overall visual and neurological health and wellness (Ciuffreda et al., 2007; Contreras et al., 2008; Samadani et al., 2015; Suh et al., 2006). Eye tracking provides a highly specific, objective measurement especially when the sample rate is high (120-1000 Hz; Komogortsev & Karpov, 2013). Research to date shows promise in the employment of eye tracking devices to measure characteristics indicative of healthy eyes, in turn, provide evidence for a healthy brain (Bedell & Stevenson, 2013).

A current limitation of eye movement research is a lack of data examining the reliability of oculomotor metrics (Pel, Manders, & van der Steen, 2010). Furthermore, many of the psychometrically focused studies have included relatively low sample sizes (e.g., 37, *n* = 39; Contreras et al., 2008, *n* = 45; 50, 2006, *n* = 21; (Vernet et al., 2009), *n* =10), however, there are some notable exceptions (e.g., Bargary et al., 2017, *n* = 1058; Evdokimidis et al., 2002, *n* = 2,006; Lenzenweger & O'Driscoll, 2006, *n* = 300, Murray, Hunfalvay, & Bolte, 2017, n = 416). Therefore, this study has three main purposes. The first purpose was to examine the reliability of OMB metrics from the RightEye tests in a large sample of healthy individuals and to determine the normative values of OMB metrics for healthy individuals and to cluster these normative values by age.

Methods

Participants

For the normative data analysis, 2993 participants completed of the RightEye tests. Participants were between the ages of 5-62 years (*M* = 20.87, *SD* = 12.45); 2030 were males (67.85%), 962 were females (32.15%). Of the 2993 participants, 61.63% were white, 6.85% black, 8.32% Hispanic, 0.20% Native American and 8.96% opted not to report ethnicity.

To establish test-retest reliability, a subset (*n* = 201) completed RightEye tests twice (i.e., Trial1 and Trial2) on two separate days. These participants were between the ages of 5-62 years (*M* = 25, *SD* =17.47); 108 were males (53.73%), 93 were females (46.27%). Of the 201 participants, 66.67% were white, 3% black, 1.5 % Hispanic, and 28.83% opted not to report ethnicity.

Apparatus

Stimuli were presented using the RightEye tests on NVIDIA 24-inch 3D Vision monitor fitted with an SMI 12" 120 Hz remote eye tracker connected to an Alienware gaming system, and a Logitech (model Y-R0017) wireless keyboard and mouse. The participants were seated in a stationary (non-wheeled) chair that could not be adjusted in height. They sat in from of a desk in a quiet, private testing room. Participants' heads were unconstrained.

The accuracy of the SMI eye tracker was 0.4 degrees within the desired headbox of 32cm x 21cm at 60cm from the screen. For standardization of testing, participants were asked to sit in front of the eye tracking system at an exact measured distance of 60cm (ideal positioning within the headbox range of the eye tracker). A nine-point calibration was conducted with points spanning the computer screen.

Oculomotor Tasks

Five RightEye oculomotor tests are described below. From these 5 tests, 54 different metrics of digitized oculomotor behaviors were assessed (for full description see Appendix I).

Circular smooth pursuit test (CSP). In the CSP test, participants were instructed to track a target stimulus, a black dot of 0.2 degrees' diameter at a 10-degree radius at a rate of 0.4Hz, in a clockwise direction, for 15 seconds. The 0.4 Hz = 1 revolution / 0.4 revolutions per sec = 2.5 sec. To find linear velocity, we multiply the angular velocity with the radius which is 10 degrees: $\frac{2^{\circ}\pi}{2.5\ sec} * 10\ deg = 25.13\ deg/sec$. The CSP test provides measures of fixation percentages, saccade percentages, latent smooth pursuit, and smooth pursuit target accuracy.

Horizontal smooth pursuit test (HSP). In the HSP test, participants were asked to focus on a dot (same size and speed as the CSP test) on the screen and follow the dot horizontally across the screen for 25 seconds, moving to the far right, then to the far left, and back to the center. The stimuli moved in a sinusoidal way from the left to right and right to left in a straight line. For a participant to be considered "on target," they were required to follow the stimuli within an error of 2.4 degrees. A participant could also be ahead or behind a stimulus and can still be labeled as 'following' if they are within an error of 4.8 degrees. The HSP test also provides measures of fixation percentages, saccade percentages, latent smooth pursuit, and smooth pursuit target accuracy.

Vertical smooth pursuit test (VSP). The protocol for the VSP test was the same as the protocol for the HSP test. However, the VSP test was in a vertical plane.

Horizontal saccades test (HS). In the HS test, participants were asked to look at a countdown of 3, 2, 1 in the center of the screen before moving their eyes back and forth between 2 dots. Their goal was to “target each dot” on the left and right of the screen as quickly and accurately as possible. The dots on the screen turned green when the participants' eyes hit the targets. The test lasted 10 seconds. The HS test provides measures of fixation percentages, saccade percentages, and target accuracy

Vertical saccades test (VS). The protocol for the VS test was the same as that for the HS test. However, the VS test was in a vertical plane.

Procedure

Participants were recruited through advertisements placed on the internet, social media, bulletin boards, and word of mouth. The study was conducted in accordance with the tenets of the declaration of Helsinki. The study protocols were approved by the Institutional Review Board of East Carolina University. The nature of the study was explained to the participants, and all participants were provided a written University Approved informed consent to participate. Following informed consent, participants were asked to complete a pre-screening questionnaire and an acuity vision screening where they were required to identify four shapes at 4mm in diameter. If any of the pre-screening questions were answered positively and any of the vision screening shapes were not correctly identified, then the participant was excluded from the study.

Participants were excluded from the study if they reported any of the following conditions which may have prevented successful test calibration during the pre-screening process: neurological disorders (such as concussion, traumatic brain injury, Parkinson's Disease, Huntington's Disease, cerebral palsy); vision-related issues (such as extreme tropias (e.g., Niehorster et al., 2017, Renard et al., 2015), phorias (e.g., Han et al., 2010; Renard et al., 2015), static visual acuity of greater than 20/400 (Kooiker et al., 2016), nystagmus (e.g., Holmqvist & Nystrom, 2011; Kooiker et al., 2016), cataracts,eyelash impediments (Holmqvist & Nystrom, 2011); consumption of drugs or alcohol within 24 hours of testing. Participants were also excluded if they were unable to pass a 9-point calibration sequence.

Qualified participants who successfully passed the 9-point calibration sequence completed the RightEye tests. The calibration sequence required participants to fixate one at a time on 9 points displayed on the screen. The participants had to successfully fixate on at least 8 out 9 points on the screen to pass the calibration sequence. For each test, the participant was asked to follow the stimuli as "accurately as possible with their eyes." Written instructions on screen and animations were provided before each test to demonstrate appropriate behavior required in each of the tests.

Data analysis

Given the three aims of this study, we conducted several statistical analyses. First, the reliability of RightEye Test was evaluated using Cronbach's Alpha (CA). The CA indicates the relative reliability and is interpreted using the following criteria CA > .9 specifies excellent reliability above .7 indicates acceptable, and less than .6 represents poor reliability (Fleiss, 1986). The alpha level was set at p<.05 for all statistical test.

Second, to describe the normative features of the data, we performed exploratory data analysis and conducted model-based clustering using expectation–maximization (EM) algorithm analysis. We chose this approach because it has several advantages over k-means or hierarchical clustering approaches. First, both k-means and hierarchical approaches are mainly heuristics thus not model-based and not well suited for inference (Hill & Mukherjee, 2013). Second, a model-based approach uses a density function with an associated weight that will 'suggest' the optimal number of clusters. Lastly, the model approach is based on the Bayesian Information Criterion (BIC) values which help to determine the most appropriate clusters. Third, we examined group differences including age clusters and gender with a series of five multivariate ANOVAs, one for each test (CSP, HSP, VSP, HS, and VS).

Results

Test-Retest Reliability Analysis

All fifty-four eye tracking variables from trials 1 and 2 were analyzed using R (statistical package) reliability procedure. Tables 1-5 presents the means and standard deviations for trials 1 and 2, the Cronbach's Alpha correlations between the Trial 1 and Trial 2, and associated the test-retest reliability decisions. Eighty-five percent of eye tracking variables demonstrated *Acceptable* (.7) to *Excellent* (.9) test-retest reliability. Eight synchronization eye tracking variables were demonstrated *poor reliability* (<.6).

Insert Tables 1-5 about here*

Cluster analysis.

The model-based clustering using EM algorithm analysis created five distinct age group: 5-8, 9-16, 17-28, 29-52, and 53-62. Further, we conducted stability testing to establish that the data sample used for cluster analysis that is representative of the entire population. The stability testing involved sub-sampling 10 individuals from the experimental population for each age group. These sub-samples were then compared against the entire population norm to assess cluster solution (See Figure 1). The comparison of the sample norms and the population norms showed the cluster solution was appropriate in numbers and quality (Calinski-Harabasz Index = 16.61 with average inter-cluster distance = 56.73). The descriptive statistics for all variables derived from the 5 RightEye tests for the 5 clusters are shown in Tables 6-10.

Insert Figure 1 about here

Insert Tables 6-10 about here

Group Differences.

To provide a descriptive indication of the strength of our cluster solution, we conducted a MANOVA on the multivariate effect of the cluster membership (Age) for each test (CSP, HSP, VSP, HS, and VS). All five MANOVAs revealed a significant multivariate effect on cluster membership thus indicating reasonable support for our cluster solution.

CSP Test

The MANOVA for the CSP Test revealed a significant multivariate effect on cluster membership, *Wilks' Lambda = .829,* $F(64, 11{,}374) = 8.69$, $p < .0001$. Descriptive CSP statistics for the five clusters were evaluated by separate one-way analysis of variance. The follow-up ANOVAs revealed significant Age Cluster differences for all circular smooth pursuit variables ($p < .001$). Tukey post hoc analysis for CSP variables indicated there were no significant differences between Age Clusters 17-28 and 29-52 however, these clusters were significantly different from Age Clusters 5-8, 9-16, and 53-62 for E/T VR Error, Fixation (%), On-Target SP, Saccade (%), Latent SP, and Predictive SP. Age Cluster 5-8 significantly differed from each Age Cluster (i.e., 9-16; 17-28; 29-52; and 53-62) for all CSP variables.

HSP Test

Similarly, the MANOVA for the HSP Test demonstrated a significant multivariate effect on cluster membership, *Wilks' Lambda = .729,* $F(32, 7889.837) = 15.845$, $p < .0001$. The follow-up ANOVAs for HSP further supported our cluster solution as significant Cluster differences were found for all HSP variables ($p < .001$). Age Clusters 17-28, 29-52, and 53-62 did not differ for E/T VR, Saccade %, and SP %, however, were significantly different for the remaining Age Clusters (i.e., 5-8, 9-16). Age Cluster 5-8 differed on all clusters for all HSP variables except Fixation %. In this case, Age Cluster 5-8 was not significantly different from Clusters 5-8, 9-16, and 53-62.

VSP Test

Likewise, the MANOVA for the VSP Test also showed a significant multivariate effect on cluster membership, *Wilks' Lambda = .739,* $F(32, 7528.43) = 20.11$, $p < .0001$. The follow-up ANOVAs for VSP also supported our cluster solution as significant Age Cluster differences were found for all VSP variables ($p < .001$) and Tukey's Post Hoc test demonstrated the same findings as the HSP Test.

HS Test

For the Horizontal Saccade Test, the MANOVA revealed a significant multivariate effect on cluster membership, *Wilks' Lambda = .851,* $F(32, 10{,}486.01) = 14.684$, $p < .0001$. Our Cluster solution was support by significant follow-up ANOVA for all HS variables ($p < .001$). Post Hoc test revealed Cluster 5-8 and Cluster 17-28 were significantly different from Clusters 9-16, 29-52, and 53-62 on Fixation %, On-target %, Saccade %, and All Bandwidths.

VS Test

Lastly, the Vertical Saccade Test revealed a significant multivariate effect on cluster membership, *Wilks' Lambda = .817,* $F(32, 7972.35) = 12.956$, $p < .0001$. Similar to the other analyses, follow-up ANOVAs for each VS test demonstrated support for our Cluster solution as all VSP variables were significantly different ($p < .0001$). Post Hoc test revealed the Age Cluster 5-8 was significantly different on all variables. Age Cluster 17-28 differed from the all Age Clusters on All Bandwidths, Saccade, and Fixation %.

Discussion

The purposes of this study were to use an empirical, data-driven approach to examine the reliability of RightEye Neuro Vision and to determine the normative values of OMB metrics for healthy individuals, and to cluster these variables by age through cluster analysis.

Reliability of RightEye Tests

Eighty-five percent of variables resulted in acceptable or higher reliability. Synchronization was the only unreliable metrics within smooth circular pursuit and vertical pursuit. Synchronization analysis, in this study, is modeled by separating the horizontal (x-axis) and vertical (y-axis) components of the eye position in relation to the same components of the target's position, as proposed by Contreras, et al (2011). However, there are no known tests of reliability for synchronization in previous literature, and thus questions group differences usually found using synchronization metrics via this method. Future experiments should analyze all eye movement metrics for reliability and explore other methods of quantifying synchronization such as that outlined by Samadini and colleagues (Samadani et al., 2015). The remaining tests, including circular smooth pursuit, horizontal smooth pursuit, vertical smooth pursuit, vertical saccade, and horizontal saccade, demonstrated strong reliability and potentially represents an acceptable alternative to standard bedside clinical assessment. The circular smooth pursuit (CSP) test is not typically found in clinical practice primarily because it involves recruiting many areas of brain circuitry (Ilg & Their, 2008), the clinical relevance is not entirely clear, and there has been a lack of reliable circular smooth pursuit (CSP) test. With reliable CSP, horizontal smooth pursuit, and vertical smooth pursuit tests, it may be possible to examine how competing signals are affected by brain injury, patient state, or disease state. For example, recent research has demonstrated functional differences in circular smooth pursuit for TBI/concussion (e.g., Hunfalvay, 2017; Zhang, 2014) and others have indicated the influence of drug intervention on smooth pursuit (Naicker, Anoopkumar-Dukie, Grant, & Kavanagh, 2017). Additionally, deficits in smooth pursuit eye movement may be driven by impairments in low-level motion processing [e.g., Chen, 2011; Nagel, Sprenger, Steinlechner, Binkofski, & Lencer, 2012) and/or higher-level predictive mechanisms (Hong et al., 2008; Keedy, Ebens, Keshavan, & Sweeney, 2006). Lastly, for all smooth pursuit test the sampling rate was 120 Hz and recent research has demonstrated this to be a sufficient sampling rate to detect and reliably analyze smooth pursuit (e.g., Gibaldi, Vanegas, Bex, & Maiello, 2017; Naicker et al., 2017).

Vertical saccade and horizontal saccade RightEye are similar to clinical “bedside” evaluation and produced reliable data which is not always seen in clinical practice. A reliable test could be the first line of evaluation rather than a follow-up to suspected saccadic abnormality. As noted before, the “bedside” evaluation involves asking the patient to alternatively fixate on two targets (Leigh & Zee, 2015). This represents not only a shift of attention from one target to another but also a measure of oculomotor performance. As is found here, saccades were measured regarding their accuracy and could indicate lesions in frontal eye fields, motor neurons and oculomotor nerves, Basal Ganglia deficits, etc. (Leigh & Zee, 2015).

Cluster analysis.

The cluster analysis represents a robust method to demonstrate distinct groups by age. We observed 5 distinct clusters which indicate the need to consider age ranges in an oculomotor test. The MANOVAs for circular, vertical, and horizontal smooth pursuit, horizontal saccades, and vertical saccades revealed a significant multivariate effect on cluster membership for Age, thus indicating reasonable support for our cluster solution. Follow-up analysis indicated a majority of the eye tracking variables represent distinct differences for Age. Most measurements demonstrate a curvilinear relationship with peaks occurring for the 17-28 age groups and 29-58 age groups (See Figures 2, 3, 4 and 5 as examples). The results are in-line research indicating saccadic control increases from ages 3-14 and saccade latencies decrease until age 15 (e.g., Irving, et., 2006). In addition, other investigators have noted age-related declines in smooth pursuit and saccades (e.g,, Seferlis et al., 2015) and the underlying age-related changes to the oculomotor nerve (Sharma, Ray, Bhardwaj, Dwivedi, & Roy, 2009). In addition,

The oculomotor behavior develops from childhood and into adulthood. Complex aspect of the visual systems tend to stabilize in later adolescent and remain stable until late adulthood (Luna, Velanova, & Geier, 2008). Evaluation of oculomotor function is a relatively simple and potentially cost-effective approach to assess neurophysiological and neurodegenerative disorders and injury (Lange et al., 2018), however, future research should examine age as factor given a neurological disorder or injury.

Conclusion

Overall, the results demonstrated the RightEye reliable, and the clustering method presented here represents a robust method to demonstrate distinct differences in eye tracking variables by Age. Findings represent the sensitivity OMB measures and the importance to consider individual and group characteristics for clinical applications as well as applied settings. Future studies should also consider normative values for OMB variables to enhance interpretation of findings. Furthermore, group analysis indicates the need to consider individual characteristics in eye tracking research.

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Table 1. Test-retest Reliability of Circular Smooth Pursuit Digitized Eye Tracking Variables

Variable	Trial 1 Mean	Trial SD	Trial 2 Mean	Trial 2 SD	CA	Decision
E/T VR (°) (Left)	14.92	3.13	14.89	2.84	0.9	Acceptable
E/T VR (°) (Right)	14.71	2.49	14.75	2.46	0.9	Acceptable
Fixation (%) (Left)	5.12	6.3	5.6	6.84	0.8	Acceptable
Fixation (%) (Right)	5.3	6.23	5.54	6.86	0.7	Acceptable
Sync X (0-1) (Left)	0.88	0.08	0.87	0.08	0.6	Poor
Sync X (0-1) (Right)	0.88	0.08	0.88	0.08	0.6	Poor
On-Target SP (Left)	62.05	22.56	62.72	24.13	0.7	Acceptable
On-Target SP (Right)	61.01	22.25	61.52	21.48	0.7	Acceptable
Saccade (%) (Left)	5.94	5.29	5.47	5.01	0.8	Acceptable
Saccade (%) (Right)	5.74	5.16	5.44	5.18	0.8	Acceptable
Latent SP (%) (Left)	13.85	14.15	13.77	14.56	0.9	Acceptable
Latent SP (%) (Right)	13.99	13.72	13.93	13.12	0.9	Acceptable
SP (Left) (%)	87.46	12.88	88.26	11.33	0.7	Acceptable
SP (Right) (%)	87.83	11.67	88.38	10.77	0.7	Acceptable
Predictive SP (%) (Left)	5.23	8.45	5.09	8.25	0.9	Acceptable
Predictive SP (%) (Right)	6.77	9.6	6.36	9.52	0.9	Acceptable
Sync Y (0-1) (Left)	0.85	0.09	0.86	0.08	0.5	Unacceptable
Sync Y (0-1) (Right)	0.85	0.08	0.85	0.07	0.4	Unacceptable

E/T VR (°) = eye/target velocity error, SP = Smooth pursuit

Table 2. Test-retest Reliability of Horizontal Smooth Pursuit Digitized Eye Tracking Variables

Variable	Trial 1 Mean	Trial 1 SD	Trial 2 Mean	Trial 2 SD	CA	Decision
E/T VR (°) (Left)	18.91	5.27	18.57	5.14	0.7	Acceptable
E/T VR (°) (Right)	18.84	5.03	18.59	4.87	0.7	Acceptable
Fixation (%) (Left)	8	6.63	7.84	6.71	0.8	Acceptable
Fixation (%) (Right)	7.64	6.27	8.26	6.09	0.7	Acceptable
Sync X (0-1) (Left)	0.95	0.07	0.96	0.06	0.3	Unacceptable
Sync X (0-1) (Right)	0.95	0.07	0.96	0.05	0.3	Unacceptable
Saccade (%) (Left)	4.95	5.23	4.63	5.16	0.8	Acceptable
Saccade (%) (Right)	4.92	5.2	4.74	5.36	0.9	Acceptable
SP (Left) (%)	86.54	10.79	86.38	11.34	0.9	Acceptable
SP (Right) (%)	87.05	9.57	86.6	9.74	0.8	Acceptable

Table 3. Test-retest Reliability of Vertical Smooth Pursuit Digitized Eye Tracking Variables

Variable	Trial 1 Mean	Trial SD	Trial 2 Mean	Trial 2 SD	CA	Decision
E/T VR (°) (Left)	23.17	9.2	22.4	9.82	0.9	Acceptable
E/T VR (°) (Right)	23.11	8.96	22.45	9.79	0.8	Acceptable
Fixation (%) (Left)	23.37	11.38	22.03	11.68	0.7	Acceptable
Fixation (%) (Right)	23.38	11.65	22.61	11.87	0.7	Acceptable
Saccade (%) (Left)	24.6	8.54	25.09	9.27	0.7	Acceptable
Saccade (%) (Right)	25	9.24	25.38	10.13	0.7	Acceptable
SP (Left) (%)	50.21	12.95	51.55	12.99	0.7	Acceptable
SP (Right) (%)	50.06	13.3	51.1	12.81	0.7	Acceptable
Sync Y (0-1) (Left)	0.73	0.08	0.73	0.07	0.4	Unacceptable
Sync Y (0-1) (Right)	0.73	0.08	0.73	0.07	0.4	Unacceptable

Table 4. Test-retest Reliability of Horizontal Saccades Digitized Eye Tracking Variables

Variable	Trial 1 Mean	Trial SD	Trial 2 Mean	Trial 2 SD	CA	Decision
Fixation (#) (Left)	17.75	9.76	20.22	8.58	0.7	Acceptable
Fixation (#) (Right)	17.45	9.39	20.1	8.49	0.7	Acceptable
On-Target (#) (Left)	2.57	2.84	2.88	2.86	0.9	Acceptable
On-Target (#) (Right)	2.15	2.65	2.28	2.61	0.9	Acceptable
Saccade (#) (Left)	18.29	9.53	21.04	8.08	0.7	Acceptable
Saccade (#) (Right)	18.38	9.18	21.15	8.18	0.7	Acceptable
All Bandwidths (#) (Left)	9.42	7.07	10.91	6.55	0.7	Acceptable
All Bandwidths (#) (Right)	8.91	6.31	10.63	6.42	0.7	Acceptable

Table 5. Test-retest Reliability of Vertical Saccades Digitized Eye Tracking Variables

Variable	Trial 1 Mean	Trial SD	Trial 2 Mean	Trial 2 SD	CA	Decision
Fixation (#) (Left)	16.01	6.56	17.76	6.66	0.8	Acceptable
Fixation (#) (Right)	15.21	6.9	16.45	6.76	0.8	Acceptable
On-Target (#) (Left)	3.73	3.87	3.92	4.09	0.7	Acceptable
On-Target (#) (Right)	3.87	4.04	3.84	4.06	0.8	Acceptable
Saccade (#) (Left)	16.49	6.72	17.92	6.91	0.7	Acceptable
Saccade (#) (Right)	16.51	6.8	18.06	7.54	0.7	Acceptable
All Bandwidths (#) (Left)	7.25	5.26	8.18	5.26	0.7	Acceptable
All Bandwidths (#) (Right)	7.31	4.86	7.97	5.36	0.7	Acceptable

Table 6: Descriptive Statistics Circular Smooth Pursuit Clustered by Age

	5 - 8				9 - 16				17 - 28				29 - 52				53 - 62			
Test	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper
E/T VR (°) (Left)	17.45	5.18	16.81	18.09	15.62	3.7	15.32	15.91	14.26	1.84	14.1	14.42	14.38	2.91	14.06	14.69	15.11	1.9	14.74	15.48
E/T VR (°) (Right)	17.56	5.13	16.93	18.18	15.84	4.08	15.51	16.16	14.39	2	14.22	14.56	14.36	1.85	14.16	14.56	15.1	1.74	14.76	15.44
Fixation (%) (Left)	8.65	8.98	7.54	9.75	6.26	8.05	5.62	6.91	4.23	5.95	3.72	4.73	3.93	4.05	3.5	4.37	5.39	5.75	4.26	6.52
Fixation (%) (Right)	9.01	9.5	7.85	10.18	6.55	8.02	5.91	7.19	4.35	6.01	3.83	4.86	4.13	3.98	3.71	4.56	5.4	5.39	4.35	6.46
Sync X (0-1) (Left)	0.86	0.08	0.85	0.87	0.88	0.08	0.87	0.89	0.9	0.05	0.89	0.9	0.89	0.05	0.89	0.9	0.89	0.07	0.87	0.9
Sync X (0-1) (Right)	0.85	0.09	0.84	0.86	0.88	0.08	0.88	0.89	0.9	0.05	0.9	0.9	0.9	0.06	0.89	0.9	0.9	0.05	0.89	0.91
On-Target SP (Left)	56.75	21.23	54.15	59.36	63.64	21.8	61.9	65.38	67.35	20.09	65.63	69.06	64.31	20.98	62.07	66.55	62.53	21.81	58.25	66.8
On-Target SP (Right)	54.06	20.45	51.55	56.57	61.24	21.07	59.56	62.93	65.54	19.61	63.86	67.21	63.37	19.92	61.24	65.5	59.16	18.9	55.45	62.86
Saccade (%) (Left)	8.94	6.76	8.11	9.77	6.4	5.48	5.96	6.84	4.61	4.46	4.22	4.99	5.47	5.8	4.85	6.09	6.46	5.07	5.46	7.45
Saccade (%) (Right)	8.74	6.57	7.93	9.54	6.46	6.11	5.97	6.95	4.48	4.91	4.06	4.9	5.12	5.04	4.59	5.66	6.49	5.49	5.42	7.57
Latent SP (%) (Left)	13.54	13.31	11.9	15.17	14.36	14.98	13.17	15.56	16.89	15.43	15.58	18.21	20.47	18.17	18.53	22.41	17.06	18.51	13.44	20.69
Latent SP (%) (Right)	14.44	13.88	12.73	16.14	14.76	14	13.64	15.88	17.14	15.84	15.79	18.49	20.47	17.26	18.63	22.32	17.32	14.19	14.54	20.1
SP (Left) (%)	82.41	12.44	80.88	83.94	87.34	11.11	86.45	88.23	91.17	8.24	90.47	91.87	90.58	8	89.73	91.44	88.15	8.55	86.48	89.83
SP (Right) (%)	82.25	12.84	80.67	83.83	86.99	11.46	86.07	87.9	91.18	8.53	90.45	91.91	90.74	7.61	89.93	91.56	88.1	8.33	86.47	89.73
Predictive SP (%) (Left)	11.54	12.33	10.03	13.05	8.93	12.02	7.97	9.89	6.88	10.47	5.99	7.77	5.7	10.1	4.62	6.78	8.47	11.78	6.16	10.78
Predictive SP (%) (Right)	13.02	11.88	11.57	14.48	10.63	13.55	9.55	11.71	8.42	12.03	7.4	9.45	6.85	10.57	5.72	7.98	11.42	14.29	8.62	14.22
Sync Y (0-1) (Left)	0.84	0.07	0.83	0.85	0.86	0.07	0.86	0.87	0.87	0.07	0.87	0.88	0.86	0.08	0.85	0.87	0.85	0.08	0.84	0.87
Sync Y (0-1) (Right)	0.83	0.07	0.82	0.84	0.85	0.08	0.84	0.85	0.86	0.07	0.85	0.86	0.86	0.06	0.85	0.86	0.85	0.07	0.83	0.86

Table 7: Descriptive Statistics Horizontal Smooth Pursuit Clustered by Age

	5 - 8				9 - 16				17 - 28				29 - 52				53 - 62			
Test	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper
E/T VR (°) (Left)	24.29	8.44	23.26	25.33	20.14	6.63	19.61	20.67	16.97	2.92	16.72	17.22	17.06	3.56	16.68	17.44	17.74	2.91	17.17	18.31
E/T VR (°) (Right)	24.31	8.13	23.32	25.31	20.14	6.37	19.63	20.64	17.15	3.7	16.84	17.47	17.2	3.75	16.8	17.6	17.56	2.53	17.06	18.06
Fixation (%) (Left)	10.07	9.77	8.87	11.27	8.87	7.85	8.24	9.49	6.91	5.55	6.44	7.39	7.26	4.81	6.75	7.78	8.08	6.14	6.88	9.29
Fixation (%) (Right)	10.34	8.68	9.27	11.41	8.94	7.91	8.3	9.57	7.13	5.93	6.62	7.63	7.21	5.11	6.66	7.75	8.41	6.44	7.15	9.67
Sync X (0-1) (Left)	0.94	0.06	0.93	0.95	0.96	0.06	0.95	0.96	0.97	0.02	0.97	0.97	0.97	0.02	0.97	0.97	0.97	0.02	0.96	0.97
Sync X (0-1) (Right)	0.94	0.06	0.93	0.95	0.96	0.06	0.95	0.96	0.97	0.02	0.97	0.97	0.97	0.03	0.97	0.97	0.97	0.02	0.97	0.97
Saccade (%) (Left)	10.7	10.56	9.4	11.99	6.27	7.53	5.67	6.87	3.64	5.62	3.16	4.12	3.93	4.08	3.49	4.36	6.13	10.52	4.07	8.19
Saccade (%) (Right)	10.6	10.77	9.28	11.92	6.32	8.08	5.68	6.97	3.63	5.83	3.13	4.12	3.97	4.28	3.51	4.43	5.4	7.67	3.89	6.9
SP (Left) (%)	79.23	15.53	77.32	81.14	84.87	12.37	83.88	85.85	89.45	8.9	88.69	90.21	88.81	7.49	88.01	89.61	85.78	12.33	83.37	88.2
SP (Right) (%)	79.06	14.85	77.24	80.88	84.74	12.44	83.75	85.73	89.25	9.32	88.45	90.04	88.83	7.79	87.99	89.66	86.2	10.86	84.07	88.32

Table 8: Descriptive Statistics Vertical Smooth Pursuit Clustered by Age

	5 - 8				9 - 16				17 - 28				29 - 52				53 - 62			
Test	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper
E/T VR (°) (Left)	35.33	14.5	33.55	37.11	26.76	13.59	25.68	27.85	19.42	8.05	18.73	20.1	20.32	7.57	19.51	21.13	22.7	8.94	20.95	24.46
E/T VR (°) (Right)	35.27	14.09	33.55	37	27.17	14.69	26	28.34	19.76	12.72	18.67	20.84	20.26	7.6	19.45	21.08	22.23	8.56	20.55	23.9
Fixation (%) (Left)	28.24	12.51	26.7	29.77	26	11.88	25.05	26.95	20.16	10.35	19.28	21.04	20.06	8.76	19.13	21	19.49	9.4	17.64	21.33
Fixation (%) (Right)	28.28	13.33	26.65	29.92	25.92	12.02	24.96	26.88	20.76	10.24	19.89	21.63	20.22	9.07	19.25	21.19	20.49	9.05	18.71	22.26
Saccade (%) (Left)	26.72	11.35	25.33	28.11	24.2	8.68	23.51	24.9	24.4	9.52	23.59	25.21	26.46	9.31	25.46	27.45	28.32	11.16	26.13	30.51
Saccade (%) (Right)	26.6	11.35	25.2	27.99	24.42	9.58	23.66	25.18	23.96	9.85	23.12	24.8	26.24	9.61	25.21	27.27	26.69	12.79	24.18	29.19
SP (Left) (%)	45.11	12.35	43.59	46.62	49.79	12.26	48.81	50.77	55.44	12.04	54.41	56.47	53.52	10.83	52.37	54.68	52.09	10.97	49.94	54.24
SP (Right) (%)	45.14	12.85	43.57	46.72	49.65	12.46	48.65	50.64	55.28	12.15	54.25	56.32	53.56	11.28	52.36	54.77	52.74	11.21	50.54	54.94
Sync Y (0-1) (Left)	0.69	0.1	0.68	0.7	0.71	0.08	0.7	0.71	0.74	0.06	0.73	0.74	0.74	0.06	0.73	0.74	0.73	0.06	0.72	0.74
Sync Y (0-1) (Right)	0.69	0.1	0.68	0.7	0.7	0.08	0.7	0.71	0.74	0.06	0.73	0.74	0.74	0.06	0.73	0.74	0.73	0.06	0.71	0.74

Table 9: Descriptive Statistics Horizontal Saccade Clustered by Age

	5 - 8				9 - 16				17 - 28				29 - 52				53 - 62			
Test	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper
Fixation (#) (Left)	12.77	10.14	11.53	14.02	16.31	7.87	15.68	16.94	20.88	9.28	20.09	21.67	16.18	7.6	15.37	16.99	15.58	7.86	14.04	17.12
Fixation (#) (Right)	12.42	7.74	11.47	13.37	16.15	7.4	15.56	16.74	20.73	9.14	19.95	21.5	16.25	7.82	15.41	17.09	15.58	7.9	14.03	17.13
On-Target (#) (Left)	2.14	2.2	1.87	2.41	3.06	2.98	2.83	3.3	3.7	3.47	3.41	4	2.9	3.17	2.57	3.24	2.95	3	2.36	3.54
On-Target (#) (Right)	2.04	2.37	1.75	2.33	2.78	2.68	2.56	2.99	3.43	3.27	3.15	3.71	2.89	2.95	2.57	3.2	2.69	3.11	2.08	3.3
Saccade (#) (Left)	13.85	9.7	12.66	15.05	17.2	7.62	16.6	17.81	21.48	9.02	20.72	22.25	17	7.39	16.21	17.79	16.35	7.46	14.89	17.81
Saccade (#) (Right)	13.63	7.22	12.74	14.51	17.21	7.3	16.62	17.79	21.49	9.06	20.72	22.26	16.91	7.26	16.13	17.68	16.35	7.2	14.94	17.76
All Bandwidths (#) (Left)	5.78	3.9	5.3	6.26	8.23	5.22	7.82	8.65	11.2	6.51	10.65	11.76	8.83	5.63	8.23	9.43	8.07	5.3	7.03	9.11
All Bandwidths (#) (Right)	5.69	3.63	5.25	6.14	8.22	4.96	7.82	8.61	10.83	6.35	10.29	11.37	9.02	5.75	8.4	9.63	7.81	5.82	6.67	8.95

Table 10: Descriptive Statistics Vertical Saccades Clustered by Age

	5 - 8				9 - 16				17 - 28				29 - 52				53 - 62			
Test	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper	Mean	SD	CL Lower	CL Upper
Fixation (#) (Left)	11.44	4.74	10.85	12.02	15.05	6.1	14.56	15.53	19.88	7.23	19.27	20.5	16.74	6.41	16.05	17.42	15.98	7.09	14.59	17.37
Fixation (#) (Right)	11.53	4.74	10.95	12.12	15.03	6.28	14.53	15.53	19.84	7.02	19.24	20.44	16.63	6.26	15.96	17.3	16.12	8.05	14.54	17.7
On-Target (#) (Left)	2.13	2.28	1.85	2.41	3.13	3.04	2.88	3.37	4.59	4.24	4.23	4.95	4.12	3.8	3.71	4.53	3.77	4.18	2.95	4.59
On-Target (#) (Right)	2.12	2.37	1.83	2.41	3.11	3.04	2.87	3.36	4.48	4.26	4.12	4.85	4.34	4.11	3.9	4.78	4.17	4.44	3.3	5.04
Saccade (#) (Left)	12.97	4.82	12.38	13.56	16.22	5.88	15.75	16.69	20.91	6.99	20.31	21.51	17.72	5.98	17.08	18.36	16.81	6.98	15.44	18.18
Saccade (#) (Right)	13.05	4.63	12.48	13.61	16.15	6.16	15.66	16.65	20.95	6.9	20.36	21.53	17.65	6.03	17.01	18.3	16.87	7.41	15.42	18.32
All Bandwidths (#) (Left)	4.9	3.3	4.49	5.3	7.17	4.51	6.81	7.53	10.01	5.59	9.53	10.48	8.05	4.86	7.53	8.57	7.44	4.3	6.6	8.28
All Bandwidths (#) (Right)	4.92	3.27	4.52	5.32	6.92	4.47	6.56	7.27	10.02	5.5	9.56	10.49	8.01	4.72	7.5	8.51	7.12	4.74	6.19	8.05

Figure Caption Page

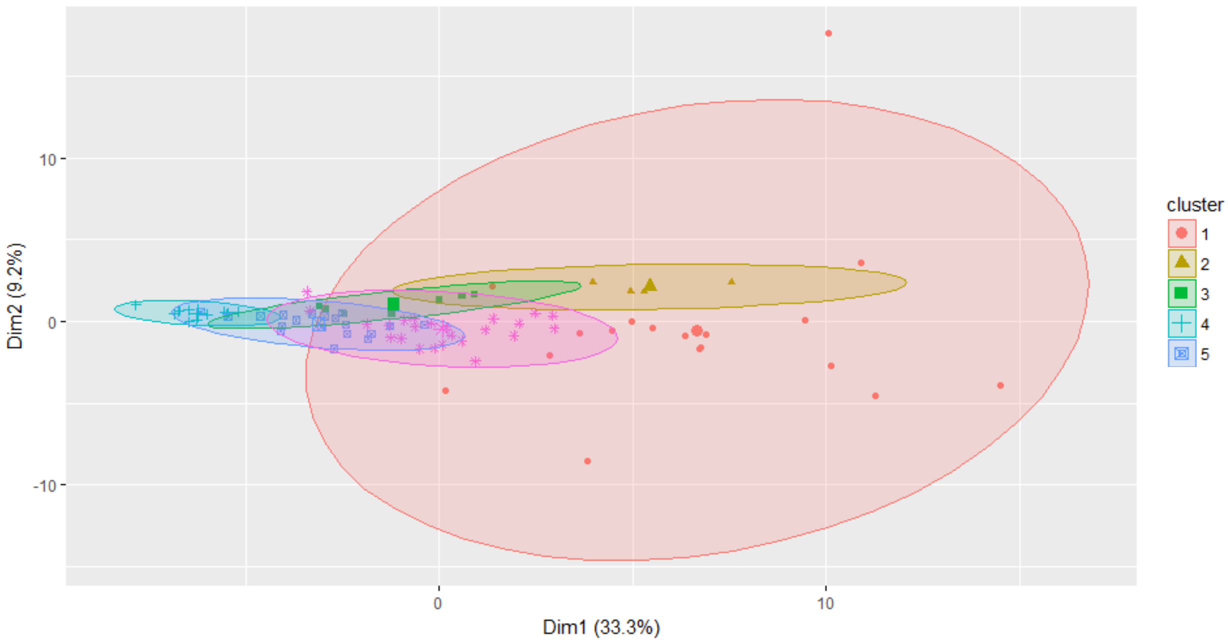
Figure 1: Five Cluster Solution

Figure 2: Circular Smooth Pursuit: Saccades (%)

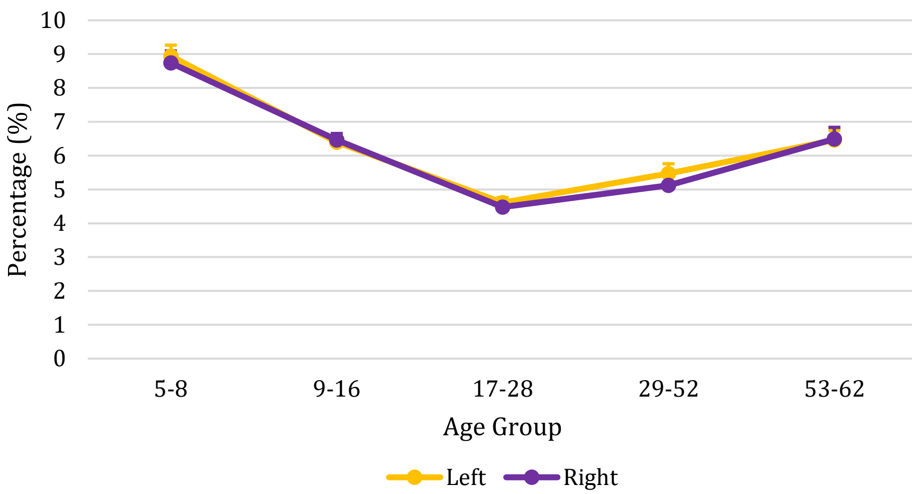
Figure 3: Horizontal Smooth Pursuit: Saccades (%)

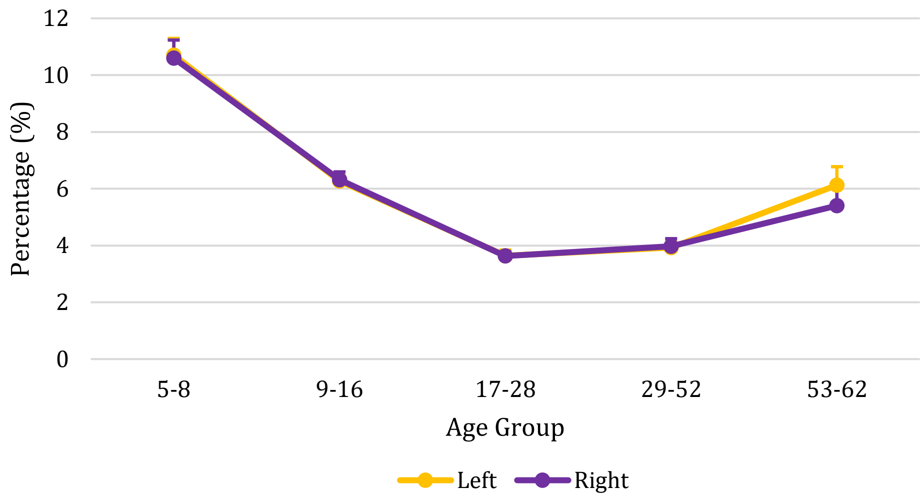
Figure 4: Horizontal Saccade: Saccades (%)

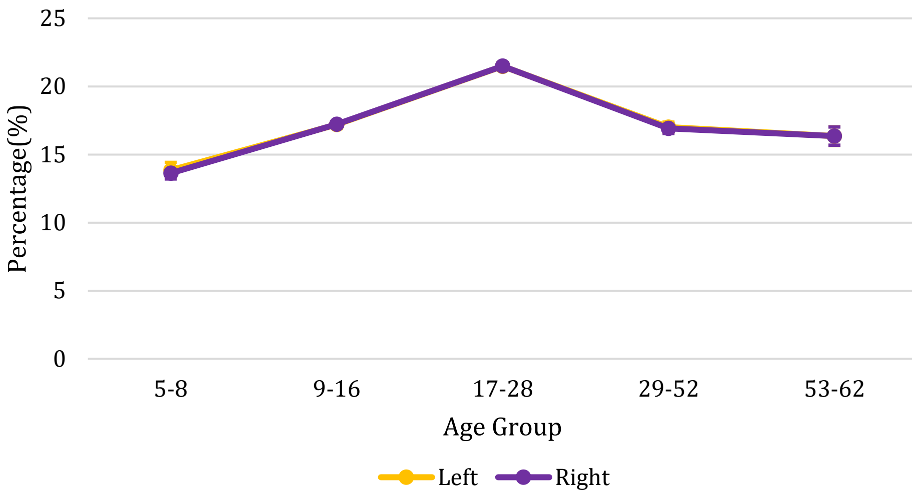
Figure 5: Vertical Saccades: Saccades (%)

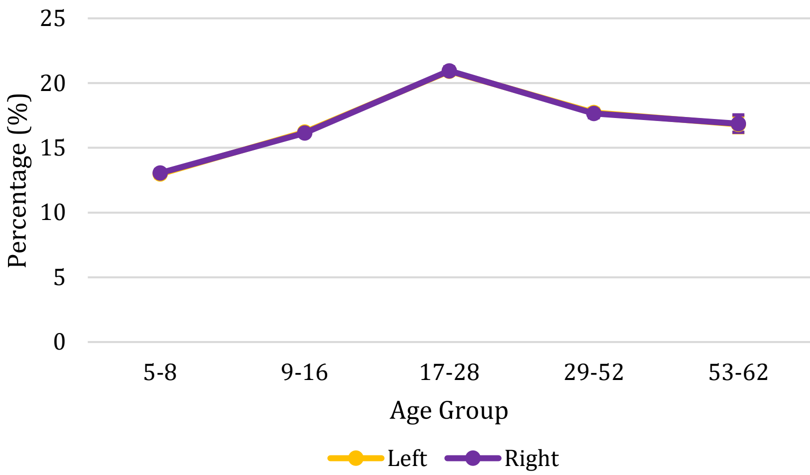


cluster
1
2
3
4
5
Dim2 (9.2%)
10
0
-10
0
10
Dim1 (33.3%)


10
9
8
7
6
5
4
3
2
1
0
Percentage (%)
5-8
9-16
17-28
29-52
53-62
Age Group
Left
Right


12
10
8
6
4
2
0
Percentage (%)
5-8
9-16
17-28
29-52
53-62
Age Group
Left
Right


25
20
15
10
5
0
Percentage(%)
5-8
9-16
17-28
29-52
53-62
Age Group
Left
Right


25
20
15
10
5
0
Percentage (%)
5-8
9-16
17-28
29-52
53-62
Age Group
Left
Right

Appendix I

SMOOTH PURSUIT
Smooth Pursuit (%): are eyes movements that follow the target within a velocity range of the target and are reported as a percentage of the test time.
Saccade (%): are fast eye movements, that move the eyes from one point of interest to the next. They are calculated outside (above or below) the velocity range of the target and reported as a percentage of test time.
Fixation (%): is a stopping point of the eye that allows the user to see in detail. Fixations are reported as a percentage of the test time.
Eye/Target Velocity Error (°/s): refers to how far the user's eyes were away from the target (non-directional). This metric is calculated by subtracting the location of the stimuli and the user's eyes at same sample time, and reported as degrees per second.
Horizontal synchronization SPEM (0-1): refers to how far off on the X plane (co-ordinate) the user's eyes were during the test. Perfect synchronization is a score of 1.0.
Vertical Synchronization SPEM (0-1): refers to how far off on the Y plane (co-ordinate) the user's eyes were during the test. Perfect synchronization is a score of 1.0.
On Target Smooth Pursuit (%): refers to the user's eyes within a velocity range of the target and positioned on the stimuli within and 2cm and reported as a percentage.
Predictive Smooth Pursuit (%): refers to the user's eyes within a velocity range of the target and positioned ahead or in-front-of the stimuli between 2 and 5cm and reported as a percentage.

Latent Smooth Pursuit (%): refers to the user’s eyes within a velocity range of the target and positioned behind the stimuli between 2 and 5cm and reported as a percentage.
SACCADES
Saccade (#): are fast eye movements that cross from the left to right side of the screen or from the right to the left side of the screen. Saccades are tallied throughout the duration of the test and reported as the total number of saccades.
Fixation (#): are stopping points or about-turn of the user's gaze. Fixations are tallied throughout the duration of the test and reported as the total number of fixations.
On-Target (9mm, #): are a tally of x, y coordinates within the left and right targets. These “hits” are tallied across the length of the test and are reported as a total number of target hits.
All Bandwidths: are a tally of x, y coordinates that appear between the on-target 9mm and the 36 millimeters. These “hits” are tallied across the length of the test and are reported as a total number.
Missed (#): a target miss is only recorded if one or both eyes pass through the center line twice and do not hit any other target.