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RESEARCH ARTICLE

Oculomotor, vestibular, reaction time, and cognitive (OVRT-C) responses in 7- to 17-year-old children

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Abstract

Several aspects of oculomotor, vestibular, reaction time, and cognitive (OVRT-C) abilities improve throughout childhood at varying rates and become adult-like at different ages. However, developmental testing of these abilities often focuses on limited age ranges and does not elucidate clear developmental trajectories. The present study utilized high-resolution eye-tracking to evaluate 40 children aged 7–17 years on a comprehensive battery of OVRT-C tests to better understand how and when these abilities develop across childhood. As expected, mean responses on OVRT-C tests showed consistent improvement as subject age increased. We report a high prevalence of saccadic intrusions during smooth pursuit in children and adolescents, more self-paced saccades in older children, decreased auditory and visual RT with age, and fewer errors on the anti-saccade test in older children. We also used the Akaike information criterion (AIC) and Bayesian information criterion (BIC) modelling to determine whether a two- or three age group division would be most appropriate for each OVRT-C test. For all key OVRT-C metrics, our data support a separation of children into two age groups as opposed to three. While the age group divide varied by OVRT-C test, these data suggest these abilities mature at differing rates, and optimal separations into two age groups rather than three may reflect a slowing of rapid development as OVRT-C performance becomes more adult-like.

Keywords Eye-tracking · Oculomotor · Development

Introduction

Eye movements have been used clinically as a non-invasive measure of cortical function in adults for decades and have been studied as biomarkers for cortical injury and disease such as concussion, Parkinson's disease, Alzheimer's disease, vestibular migraine, and recently in COVID-19 patients' post-infection (Kelly et al. 2022). Distinct oculomotor deficits have also been observed in children with certain neurological conditions, such as concussion, autism, schizophrenia, and ADHD (Bin Zahid et al. 2020; Wilkes et al. 2015; Ross et al. 2005; Hanisch et al. 2005). Thus, high-quality measurements of eye movements have intrinsic value for clinicians treating both adult and pediatric populations. Oculomotor assessment can also contribute to our understanding of the neural mechanisms and damage that underlie many of these conditions. When combined with simultaneous assessments of vestibular function and reaction time performance, a clinician can conduct a non-invasive yet informative evaluation of a patient's basic brain health (e.g., Hoffer et al. 2017; Mucha et al. 2014; Cochrane et al. 2021).

Characteristics of eye movements develop throughout childhood, for example, showing progressive improvement in saccade and smooth pursuit movements over time. Saccades are rapid eye movements that shift visual fixation of a stationary target onto the fovea, where visual acuity is highest, and can be either voluntary or reflexive. Healthy adults typically initiate saccades within 180–220 ms, with high accuracy (i.e., gain or ratio of target and saccadic amplitude is close to or equal to 1; Collewijn et al. 1988a; Sharpe and Zackon 1987). Saccadic latencies in children are longer than adults' and are

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adult-like by the age of 12 (Fukushima et al. 2000). Saccadic gain and peak velocity, however, become stable and adult-like between 5 and 8 years of age (e.g., Salman et al. 2006a; Sinno et al. 2020; Bucci and Seassau 2012; Hopf et al. 2018).

Smooth pursuit eye movements are used to track a moving target such that it remains on the fovea. Most evidence suggests this system matures at a slower rate than saccades. Nevertheless, while the literature generally supports an increase in smooth pursuit gain across childhood (e.g., Salman et al. 2006b; Ego et al. 2013), the age at which this ability has been determined to reach adult levels varies substantially between studies (e.g., 17–18 years, Katsanis et al. 1998; 5–7 years, Langaas et al. 1998; 7–8 years, Vinuela-Navarro et al. 2019; middle adolescence in the horizontal plane, Salman et al. 2006b).

Other oculomotor tests performed in children to date include optokinetic nystagmus (OKN; Valmaggia et al. 2004); predictive saccades (Lukasova et al. 2018); self-paced saccades (Phillipou et al. 2014); and vergence (Yang et al. 2002). However, these studies are limited in number, and the tested age ranges tend to be large and thus often do not establish a clear developmental trajectory for these abilities.

Studies investigating vestibular function throughout typical development are similarly sparse. Data suggest that subjective visual vertical (SVV) performance in children is less accurate, and their estimations of true vertical are more variable than those of adults (Gaertner et al. 2013; Silva et al. 2022; try Schnabel et al. 2022). To our knowledge, studies of subjective visual horizonal performance in children have not been published. Fixation and gaze in 4- to 15-year-olds become increasingly focused on the center of the visual target and become more stable between the ages of 4 and 15 (Aring et al. 2007). Spontaneous nystagmus is considered a hallmark of vestibular dysfunction in children and has been primarily studied within that context (e.g., Penix et al. 2015).

There are few reports focused solely on measures of reaction time (RT) in children, and most come predominantly from either the sports science or transportation safety literature. As expected, children's RTs decrease with age (Pancar et al. 2016), and become comparable to adults between 15 and 18 years of age (Bucsuházy and Semela 2017). As auditory and visual RTs depend on the processing speed of the central nervous system (CNS), both are used as a gauge of overall brain health and thus are crucial in any comprehensive battery assessing such in children.

The anti-saccade task, in which a subject is instructed not to look at a target stimulus appearing on one side of a screen but to instead generate a volitional saccade in the opposite direction, is widely understood to be a cognitive one that requires the ability to inhibit a reflexive saccade. Given the top-down nature of this task, children under the age of 10 typically find it difficult, with an error rate of around 60% which decreases rapidly until age 15, after which it continues to decline slowly to about 15% by age 20 (Fischer et al. 1997).

Crucially, to our knowledge, no single study has tested children using an extensive and comprehensive battery of OVRT-C tests combined within a single testing session. The goal of the present study was to (1) test 7- to 17-year-old children using a protocol of 18 child-friendly OVRT-C tests; (2) determine which age groupings are the best fit by which to separate children's OVRT-C metrics; (3) compare development of OVRT-C metrics to determine when each measure becomes adult-like.

Materials and methods

Subjects

All research activities were conducted according to the principles described in the Declaration of Helsinki and were approved by the Institutional Review Boards (IRB) at the sites where the research was conducted. Subjects were eligible if they were between the ages of 7 and 17 years of age. Exclusion criteria included history of moderate/severe head injury, concussion within the last 12 months, diagnosis of a severe developmental delay or autism spectrum disorder, history of seizures, and conditions and/or diseases that can affect the cerebrovascular, oculomotor and/or vestibular systems (e.g., vestibular disorders, sudden sensorineural hearing loss, blurred vision, stroke). Both research sites adhered to the same inclusion/exclusion criteria. All subjects and their parent(s) gave informed consent and assent prior to testing. Subjects were 40 children 7–17 years of age (see subject demographics in Table 1) recruited at two research sites: (a) Allegheny Health Network, Pittsburgh, PA, USA (IRB#2019-248), $n = 20$; and (b) University of Miami Miller School of Medicine, Miami, FL, USA (IRB#20,190,888), $n = 20$.

For comparison purposes, we use previously collected and published data (Kullmann et al. 2021a, 2021b). This

Table 1 Demographics characteristics of forty participants

Age				Gender		Race			Hispanic/Latino	
Min	Max	Mean	SD	Female	Male	White	Black	Other	Yes	No
6.8	17.9	11.9	3.46	*Number of subjects (% out of 40)*						
				18 (45.0%)	22 (55.0%)	35 (87.5%)	1 (2.5%)	4 (10.0%)	18 (45.0%)	22 (55.0%)

database was generated from FDA-approved normative data collected from 300 healthy subjects aged 18 to 45 years recruited from two testing sites: Naval Medical Center San Diego (San Diego, CA) and Madigan Army Medical Center (Fort Lewis, Washington). The relevant data we use for the current study refers to 33 young people aged 18–20, of which 21 (63.4%) are men.

Battery of tests

Each subject completed a comprehensive battery of 18 OVRT-C tests (see Table 2 for a list of tests, target stimulus types, output metrics, and length of each test). Of these, the Gaze Horizontal, Spontaneous Nystagmus, Subjective Visual Vertical, and Subject Visual Horizontal tests are designed to evaluate vestibular function. All visual stimuli were displayed at high contrast against a neutral background. Tests were presented consecutively and ranged from 10 to 40 s in length, for a total testing time of approximately 13 min including instructions. Children were tested while seated adjacent to the test administrator and their heads were not stabilized. After testing, children also completed a comfort questionnaire (see Table 3) consisting of the following 5 questions: do the googles look cool?; do the googles fit snugly?; do you see light from the outside coming through the goggles?; are the goggles too heavy for you?; and were you comfortable running these tests for 15 min?

Age-appropriate pictorial stimuli and verbal instructions for each OVRT-C test

A library of age-appropriate pictorial stimuli was developed for each OVRT-C test (see Table 2 for stimuli for each test). To minimize the potential effect of tester's influence, voice instructions for each test were used and are also listed in Table 2.

Hardware and software

All OVRT-C tests were presented using the Spryson (formerly Neurolign) Dx 100, an FDA-approved eye-tracking device manufactured by Spryson America, LLC. The Dx 100 is a compact and portable head-mounted virtual reality goggle device outfitted with two high-speed digital infrared cameras (940 nm with a sampling rate of 100 frames/second) that record high-resolution images of eye movements in response to visual and auditory stimuli. A hand-held apparatus with response buttons was used to record subjects' reaction times and/or responses for those tests that require manual input (i.e., subjective visual vertical/horizontal, auditory and visual RT). Data were collected using I-Portal software, which captures, time stamps (required for synchronization), and analyzes digital images of the eye to calculate horizontal and vertical eye movement data. VEST™ software was used to operate the hardware, collect data, manage stimulus parameters, integrate I-Portal eye-tracking results, and analyze acquired data to generate a set of desired metrics for each subject.

Treatment of artifacts and outlying data samples

Data collected from OVRT-C tests were calibrated for position based on comparisons of eye movements to fixation locations that had a known displacement. VEST™ software identifies and removes a large portion of the artifacts introduced through subject blinking, recording noise, and other interruptions to eye-tracking, as well as outliers in some tests (e.g. visual and auditory reaction time tests). The software also calculates the validity of the data from which it calculates its output metrics, e.g. validity in some tests reflects the amount of data remaining after artifact removal. For some tests, the software selects one eye's data if the other is of poor quality. For some tests, VEST™ alerts the operator during acquisition if the data are invalid (e.g. the data produce computation errors) or the overall data validity is below certain thresholds of acceptability (using algorithms that vary by test type). Other artifacts, such as those caused by shifting of goggles, incorrect responses unrelated to the test, and residual artifacts not automatically detected, were also manually evaluated to separate eye movement signals from recording noise. As a result of these automated and manual processes, some results from individual OVRT-C tests were removed from the final analysis.

Data analysis

Data collected for each OVRT-C test were examined for completion and validity and analyzed using VEST™ software. For completed and validated tests for each child, metrics of OVRT-C performance were retrieved from VEST™ software. See Table 2 for measured metrics for each test.

Methods used for statistical analysis

This study refers to healthy 7- to 17-year-old children and focuses on the ten OVRT-C test metrics listed in Table 5.

Evaluation of test result values by age

We examined whether children of different ages react differently to OVRT-C tests. For example, compared to younger children, the mean auditory reaction time latency in older children may be both faster and more stable (i.e., less

Table 2 Tasks, targets, output metrics, and lengths of tests in the OVRT-C testing protocol

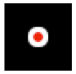
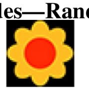
Test and Target	Metrics measured for each test	Voice instructions	Test length (sec)
Focus adjustment	Not Applicable	Not applicable	20
Calibration 	Vertical and horizontal gain	Keep your eye on the dot as it moves, don't let it get away from you!	24
Spontaneous Nystagmus (SN)  Child fixates a light stimulus (cat) placed on the center of the screen for 6 s. The light is turned off and the subject is required to continue to fixate at the spot where the light was for 10 s	Direction and velocity of nystagmus beats and number of square wave jerks for horizontal and vertical nystagmus during fixation and in the dark	When the cat appears look right at it. When the cat disappears keep looking in the same spot to see if it comes back	16
Saccades—Random, Horizontal (SH) and Vertical (SV)  Child follows a flower displayed 16 times at pseudo-randomly distributed times (between 1 to 2 s) and pseudo-random displacements on a horizontal plane (−30 to + 30 degrees)	(a) Latency (s) = time from stimulus presentation until a saccade is initiated. Data are presented as an average of all saccade onset latencies (b) Accuracy (%) = difference between eye position and stimulus position for the main saccade, expressed in per-centage relative to stimulus position. Data are presented as an average of all main saccade accuracies (c) Final Accuracy (%) = difference between eye position and stimulus position for the final position, including corrective saccades, expressed in percentage relative to stimulus position. Data are presented as an average of all saccade accuracies (d) Area Under Main Sequence Fit (AUF) (deg^2/s). Eye velocity is plotted as a function of saccade displacement and fitted with an exponential function. To evaluate the overall velocity and amplitude	Follow the flower as it bounces around, don't let it get away from you!	22 × 2 = 44
Predictive Saccade (PS)  Child is directed to follow a flower as it is displayed. Child is presented with 6 pseudo-random saccade stimuli followed by 21 mirrored saccade stimuli with repeated displacement ± 10 degrees, horizontal, at a constant time interval of 0.65 s	First predicted, total number of predicted saccades, % of predicted saccades	Follow the flower as it bounces around, as fast as you can!	21

Table 2 (continued)

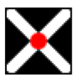
Test and Target	Metrics measured for each test	Voice instructions	Test length (sec)
Smooth Pursuit Horizontal (SPH)  Child follows a planet as it moves sinusoidally horizontally at two different speeds: 0.1 Hz at 10 degrees displacement, stimulus peak velocity 6.28 d/s, 3 cycles; 0.5 Hz at 10 degrees displacement, stimulus peak velocity 31.4 d/s, 6 cycles	(a) Velocity Gain = ratio between the slow phase component of eye velocity and pursuit tracker stimuli. Data are averaged for the leftward and rightward moving stimuli (b) Asymmetry (velocity gain asym-metry) = represents the difference between gain calculated for leftward and rightward moving stimuli (see calculations below the table) (c) Saccadic component (%) = per-centage of eye movement spent on a saccadic movement versus pursuit movement	Follow the red planet as smoothly as you can as it moves from side to side	30 + 12 = 42
Smooth Pursuit Vertical (SPV)  Child follows a rocket as it moves sinusoidally vertical at two different speeds: 0.1 Hz at 10 degrees displacement, stimulus peak velocity 6.28 d/s, 3 cycles; 0.5 Hz at 10 degrees displacement, stimulus peak velocity 31.4 d/s, 6 cycles at	The same as horizontal smooth pursuit tests	Follow the spaceship as smoothly as you can as it bounces up and down	30 + 12 = 42
Vergence Pursuit (VP)  Child is required to follow a white cross with red dot on center that moves towards and away from the subject in a smooth pursuit pattern, 0.1 Hz 3 cycles	(a) Left/Right eye gain = how well the subject tracks the stimulus, calculated for each eye (b) Left–right eyes correlation = how well left–right eye correlate between each anther (c) Saccadic components (%) = per-centage of eye movement spent on a saccadic movement versus pursuit movement	Keep your eyes on the cross as it moves away from and back toward your nose	30
Vergence Step (VS) (saccade)  Child is required to follow a white cross with red dot on center that moves towards and away from the subject in a saccade pattern, 9 repeatable saccades	(a) Left/Right eye inward and outward time constant = how well the subject tracks the stimulus, calculated for each eye (b) Left/Right eyes correlation = how well left–right eye correlate between each other in inward and outward directions (c) Saccadic components (%) = per-centage of eye movement spent on a saccadic movement	Keep your eyes on the cross as it moves away from and back toward your nose	40

Table 2 (continued)

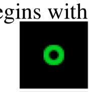
Test and Target	Metrics measured for each test	Voice instructions	Test length (sec)
Optokinetic Horizontal (OKN), 20 and 60 deg/s Child sees a field of white dots on a black background moving on the display first to the right, then to the left, with eye tracking throughout the test with a velocity of 20 and 60 deg/sec. Each test consists of a stimulus rotating for 10 s clockwise (CW) and then 10 s counterclockwise (CCW), with 3 s of rest between CW and CCW rotation	(a) Average eye velocity CW and CCW (deg/sec) = eye velocity during the slow phase of nystagmus for stimuli moving in clockwise (CW) and counterclockwise (CCW) direction (c) Gain = ratio between average eye slow phase velocity and stimulus for CW and CCW segments (d) Gain Asymmetry (%) = represents the difference between gain calculated for CW and CCW segments (see calculat-ions below) (e) Area Under Main Sequence Fit (AUF) (deg^2/sec). Fast phase of OKN nystagmus beats is plotted as a function of the beats length and fitted with an exponential function. To evaluate the overall velocity and amplitude relationship, the software computes the area under the curve = AUF for CW and CCW stimulus movement	You will see a bunch of stars moving by, just look at them and pay attention to them	30 + 30 = 60
Anti-saccade (AS), trial begins with a green fixation dot   on the center of the screen Child is required to fixate on this target for 1.5 to 2.5 s and is then presented with a peripheral target (monster). Child is required to generate an eye movement in the same distance as the target displacement, but in the exact opposite direction. There are 16 anti-saccades with time between saccades randomly selected from 1 to 2 s and random displacement between −30 to + 30 degrees	Error Rate (%) = percentage of pro-saccade errors, i.e., where the subject looks toward rather than away from the stimulus	This is an opposites game! When you see a green dot, look right at it. When you see the monster, don't look at it, look at the same spot on the other side of the screen	33
 **Self-Paced Saccade (SPS)** Child is required to look back and forth between two fixed targets for 10 s	(a) Number of saccades = how many saccades are performed during the test time (b) Eye velocity consistency—eye velocity for left/right eye during test (c) Interval consistency between saccades—time between the saccades; measures consistency and fatigue	You will see two planets. Please look back and forth from one planet to the other as fast as you can	10
 **Visual Reaction Time (VRT)** 18 light stimuli (monster) are presented in the center of the screen, with a random timing. The child is directed to signal their recognition by pressing a button	Latency (msec) = time difference from stimulus presentation until button is pressed	Using the hand with you write with, press the button as quickly as you can when you see the monster	20

Table 2 (continued)

Test and Target	Metrics measured for each test	Voice instructions	Test length (sec)
Auditory Reaction Time (ART) 21 sound stimuli are presented with a random timing. The child is instructed to signal their recognition by pressing a button	Latency (msec) = time difference from stimulus presentation until button is pressed	Using the hand with you write with, press the button as quickly as you can when you hear the buzzer	16
 **Saccade and Reaction Time (SRT)** 16 saccadic stimuli (flower) are randomly projected every 1 to 2 s with a displacement of −30 to + 30 degrees. Child is directed to look at the flower and then press either the left or right button to record whether the stimulus moved to the right or to the left	*Saccade variables*: (a) Latency (s) (b) Accuracy (%) (c) Final Accuracy (%) *Motor reaction time variables*: (d) Latency means (sec)—for left and right Buttons = time difference from stimulus presentation until the left button is pressed	Follow the flower with your eyes as it jumps around. If the flower jumps toward the left, press the left button, if the flower jumps toward the right, press the right button. First look at the flower, then press the button	32
Light Reftex Child is presented with dot on center of vision	Constriction velocity for stimulated vs non-stimulated eyes	Keep your eye on the dot as it appears	31
Subjective Visual Vertical (SVV) Child is presented with a non-vertical line and by using the left and right buttons on the handheld control box, he/she orients the line to the vertical (upright) position	Mean error (deg) = difference between subject's orientation angle and true vertical. Data are presented as a mean of errors of all measurements	You will see a crooked line. Use the left and right buttons to move the line until it points straight up and down. When you have it straight up and down, press the middle button to go on to the next crooked line	15
Test Time (*minutes*)			
Testing time	8.27		
Set-up time	2		
Test Instructions	2		
Total time	12.27		

Table 3 Subjects' responses to the Evaluation of Comfort Level Questionnaire by testing site

Questions	Percentage of subjects who responded *Yes*		
	Alleghany Health Network	University of Miami Miller School of Medicine	Average per trial
Look cool?	95%	95%	95.0%
Is the fit snug?	90%	85%	87.5%
Do you see light coming through the mask?	15%	15%	15.0%
Are the goggles too heavy for you?	30%	65%	47.5%
Is the child able to run tests for 15 min?	100%	100%	100.0%

variable). Below, we describe a statistical methodology to examine this issue.

For each of the test metrics, we divided the subjects into nine age groups, each with an interval of ~ 1.5 years, with an overlap of 0.25 years with the adjacent intervals. For each group we calculated a mean response, and the mean, minimum and maximum age of the children for each interval (see Table 4). The dependence between the mean response and age for these metrics is illustrated in Table 4. Note that the overlaps are intended to create some continuity between adjacent age groups and to avoid "jumps" due to a small number of observations per group (this is a kind of *smoothing*). In addition, a third-degree polynomial curve is added. We note that these are preliminary results which are intended for impression purposes only.

We further quantified the relationship between subject age and test result values using regression analysis, which, depending on the type of response data, includes linear and generalized linear models with and without random effects. The models incorporated subject age, as an independent continuous variable, and individual test responses as dependent variables. In particular, the linear regression model (LM) is used to fit the data for the mean auditory and visual reaction time latency, for the slow horizontal and vertical smooth pursuit (velocity saccade) tests and for optokinetic horizontal (OKN) average gain for both 20°/s and 60°/s (i.e., the first six metrics in Table 5). The first four metrics are fitted using the natural logarithm of the response variable, while the other two are defined on the original (linear) scale. The linear mixed effects model (LMM) is used to fit the data for the saccade and reaction time latency (saccadic and motor response), for the self-paced saccade (velocity and interval intercept) tests, for subjective visual vertical (SVV; mean error) and vergence step (VS; inward time constant). The dependent variables (responses) for these six metrics are defined on the original scale. The proportion of pro-saccade errors (anti-saccade test) are modeled using the logit-linked binomial mixed-effects model, while the number of saccades during the 11 s (self-paced saccade test) is modeled using the log-linked Poisson mixed effects model. The last two models known in the literature as generalized linear mixed effects models (GLMMs). Note that the inclusion of a random effect in the model allows to account for the subject-specific effects when repeated measurements are involved in the analysis. Restricted maximum likelihood (REML; for LM and LMM) and maximum likelihood (ML; for GLMM) estimation methods are used to estimate the model parameters using FITLME and FITGLME functions in MATLAB software (The MathWorks, Inc. USA, version R2015b). Note that in this type of analysis we assume that children's response to the test varies linearly with age (increases or decreases as they get older). In practice, as we will see later, children's response to certain tests can indeed increase (or decrease) with age up to a certain age, but after that age (usually around 12 years) their response stabilizes at a certain level. The next section addresses this issue.

Age group separation

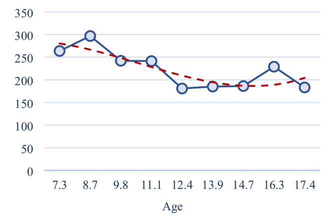
Previous literature in human development identifies several stages, including toddlerhood (age 1–5 years), childhood (3–11 years), and adolescence [12–18 years (Balasundaram and Avulakunta 2024)]. During these stages there are key physical and cognitive changes which can affect OVRT-C task performance. For this reason, we are interested in dividing the subjects into two or three age groups, such that the distribution of results will be similar at the group level and different between different age groups. For this purpose, we need to determine what the optimal division of ages is for the OVRT-C metrics tested. For example, for the 3 age groups, should the first group be in the range of 6–8 years (it is customary to present this range as [6,9), i.e., excluding 9) or perhaps 6 to 9 (which is, [6,10)). See, for example, in Table 6—the first option for the 3-group division is [7, 9), [9,12) and [12,18). In total, we used 10 different age group divisions for the 3-group and 7 for the 2-group.

To find the optimal division, for each of the 14 test metrics, a regression was fitted (according to the previous definition, see columns "model" and "response link" in Table 5) for all 17 division options with the model defined by qualitative (dummy) independent variables for age groups. We

Table 4 Mean response computed for nine intervals each of ~ 1.5 Years

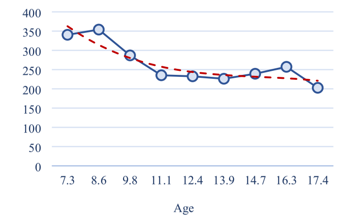
ART, Mean latency (msec)

N	Age			Response
	Min	Max	Mean	
6	6.8	8.1	7.3	263.6
8	8.1	9.3	8.7	296.7
5	9.2	10.7	9.8	242.0
6	10.7	11.5	11.1	241.4
3	11.5	12.9	12.4	180.9
6	12.9	14.3	13.9	185.1
8	14.1	15.4	14.7	186.3
4	15.4	16.8	16.3	229.0
5	16.7	17.9	17.4	183.2



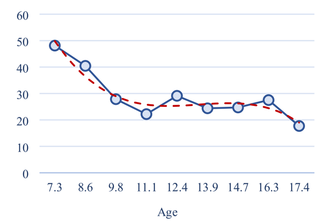
VRT, Mean latency (msec)

N	Age			Response
	Min	Max	Mean	
6	6.8	8.1	7.3	340.4
9	8.1	9.3	8.6	354.0
5	9.2	10.7	9.8	286.9
5	10.7	11.5	11.1	235.3
3	11.5	12.9	12.4	232.6
6	12.9	14.3	13.9	226.3
8	14.1	15.4	14.7	239.2
4	15.4	16.8	16.3	257.2
5	16.7	17.9	17.4	202.7



SPH, 0.1Hz, Velocity saccade (%)

N	Age			Response
	Min	Max	Mean	
6	6.8	8.1	7.3	48.1
9	8.1	9.3	8.6	40.5
5	9.2	10.7	9.8	27.8
6	10.7	11.5	11.1	22.2
3	11.5	12.9	12.4	29.1
6	12.9	14.3	13.9	24.4
8	14.1	15.4	14.7	24.7
4	15.4	16.8	16.3	27.5
5	16.7	17.9	17.4	17.7



SPV, 0.1Hz, Velocity saccade (%)

N	Age			Response
	Min	Max	Mean	
6	6.8	8.1	7.3	43.1
9	8.1	9.3	8.6	45.4
5	9.2	10.7	9.8	43.6
5	10.7	11.5	11.1	39.2
3	11.5	12.9	12.4	52.9
6	12.9	14.3	13.9	30.2
8	14.1	15.4	14.7	27.2
4	15.4	16.8	16.3	25.5
5	16.7	17.9	17.4	16.5

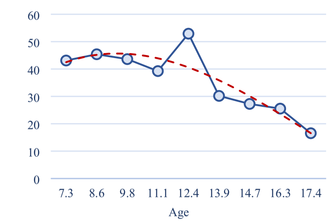
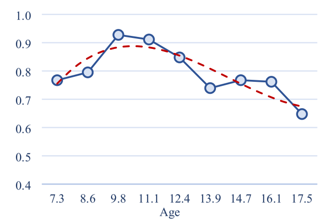


Table 4 (continued)

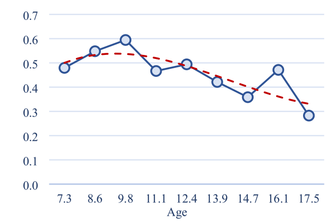
OKN, 20 deg/sec, Average gain

N	Age Min	Age Max	Age Mean	Response
6	6.8	8.1	7.3	0.77
9	8.1	9.3	8.6	0.80
5	9.2	10.7	9.8	0.93
5	10.7	11.5	11.1	0.91
3	11.5	12.9	12.4	0.85
6	12.9	14.3	13.9	0.74
8	14.1	15.4	14.7	0.77
3	15.4	16.7	16.1	0.76
4	16.7	17.9	17.5	0.65



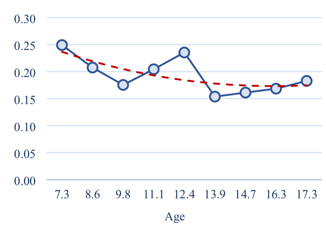
OKN, 60 deg/sec, Average gain

N	Age Min	Age Max	Age Mean	Response
6	6.8	8.1	7.3	0.48
9	8.1	9.3	8.6	0.55
5	9.2	10.7	9.8	0.59
5	10.7	11.5	11.1	0.47
3	11.5	12.9	12.4	0.49
6	12.9	14.3	13.9	0.42
8	14.1	15.4	14.7	0.36
3	15.4	16.7	16.1	0.47
4	16.7	17.9	17.5	0.28



SRT, Saccades, Latency means

N	Age Min	Age Max	Age Mean	Response
12	6.8	8.1	7.3	0.25
18	8.1	9.3	8.6	0.21
10	9.2	10.7	9.8	0.18
10	10.7	11.5	11.1	0.20
6	11.5	12.9	12.4	0.24
12	12.9	14.3	13.9	0.15
16	14.1	15.4	14.7	0.16
8	15.4	16.8	16.3	0.17
8	16.7	17.9	17.3	0.18



SRT, Motor, Latency means

N	Age Min	Age Max	Age Mean	Response
12	6.8	8.1	7.3	0.74
18	8.1	9.3	8.6	0.66
10	9.2	10.7	9.8	0.56
10	10.7	11.5	11.1	0.49
6	11.5	12.9	12.4	0.48
12	12.9	14.3	13.9	0.51
16	14.1	15.4	14.7	0.52
8	15.4	16.8	16.3	0.61
8	16.7	17.9	17.3	0.35

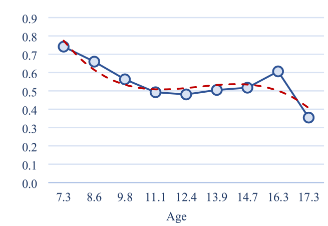
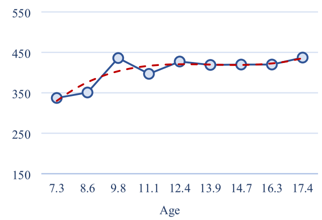


Table 4 (continued)

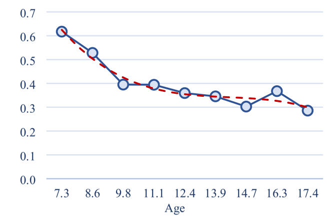
SPS, Velocity intercept

N	Age			Response
	Min	Max	Mean	
12	6.8	8.1	7.3	337.3
18	8.1	9.3	8.6	350.8
10	9.2	10.7	9.8	436.0
10	10.7	11.5	11.1	396.9
6	11.5	12.9	12.4	427.4
12	12.9	14.3	13.9	418.9
16	14.1	15.4	14.7	419.9
7	15.4	16.8	16.3	419.9
10	16.7	17.9	17.4	437.2



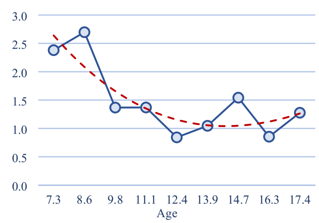
SPS, Interval intercept

N	Age			Response
	Min	Max	Mean	
12	6.8	8.1	7.3	0.62
18	8.1	9.3	8.6	0.53
10	9.2	10.7	9.8	0.39
10	10.7	11.5	11.1	0.39
6	11.5	12.9	12.4	0.36
12	12.9	14.3	13.9	0.35
16	14.1	15.4	14.7	0.30
7	15.4	16.8	16.3	0.37
10	16.7	17.9	17.4	0.29



SVV, Mean error (abs)

N	Age			Response
	Min	Max	Mean	
12	6.8	8.1	7.3	2.38
18	8.1	9.3	8.6	2.70
10	9.2	10.7	9.8	1.37
12	10.7	11.5	11.1	1.37
6	11.5	12.9	12.4	0.84
12	12.9	14.3	13.9	1.05
16	14.1	15.4	14.7	1.54
8	15.4	16.8	16.3	0.85
10	16.7	17.9	17.4	1.28



Vergence Step (VS), Inward time constant

N	Age			Response
	Min	Max	Mean	
10	6.8	7.5	7.2	0.97
16	8.3	9.3	8.7	0.75
10	9.2	10.7	9.8	0.56
10	10.7	11.5	11.1	0.43
6	11.5	12.9	12.4	0.46
12	12.9	14.3	13.9	0.46
16	14.1	15.4	14.7	0.49
8	15.4	16.8	16.3	0.58
10	16.7	17.9	17.4	0.51

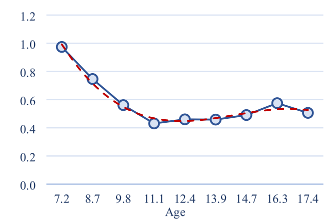
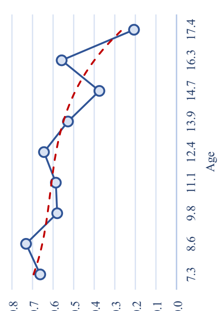
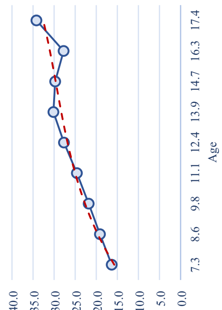


Table 4 (continued)

Antisaccade, % of pro-saccade errors					SPS, Number of saccades				
N	Age			Response	N	Age			Response
	Min	Max	Mean			Min	Max	Mean	
12	6.8	8.1	7.3	0.66	6	6.8	8.1	7.3	16.3
18	8.1	9.3	8.6	0.73	8	8.1	9.3	8.6	19.1
10	9.2	10.7	9.8	0.58	5	9.2	10.7	9.8	21.8
10	10.7	11.5	11.1	0.59	5	10.7	11.5	11.1	24.6
6	11.5	12.9	12.4	0.64	3	11.5	12.9	12.4	27.7
12	12.9	14.3	13.9	0.53	6	12.9	14.3	13.9	30.2
16	14.1	15.4	14.7	0.38	8	14.1	15.4	14.7	29.8
8	15.4	16.8	16.3	0.56	4	15.4	16.8	16.3	27.8
10	16.7	17.9	17.4	0.21	5	16.7	17.9	17.4	34.2





Note: Age interval contains 0.25 Year Overlap with Previous and Next Interval

note that this division should be consistent across the 14 test metrics.

The Bartlett's, Levene's and Breusch–Pagan tests were used for detecting heteroskedasticity in the residuals from the linear models (LM and LMM). In particular, the Bartlett's test is used for comparing variances of different age groups when normality is assumed, while more robust to non-normal distributions Levene's test computed by performing ANOVA on the squared residuals of the data values from their group means. The Breusch–Pagan Lagrange multiplier ($\mathscr{LM}$) type test is used to test whether the variance of the residuals from a regression are dependent on the values of the independent variables (age group). Similar to Bartlett's test, Breusch-Pagan is also sensitive to the assumption of normality. The heteroskedasticity hypothesis is rejected when the level of significance (p-value) exceeds 5%. Bartlett's and Levene's tests are evaluated using VARTESTN function in MATLAB software. The Breusch-Pagan $\mathscr{LM}$ test is computed using a custom function (written for this study) in MATLAB software. The regression coefficients in the final LM and LMM models are estimated using the generalized least squares (GLS) that accounts for the heteroskedasticity (see Greene, Section 11). Because the results across the three tests are consistent, the findings are presented only for the Breusch-Pagan $\mathscr{LM}$ test (see Table 7).

The Akaike information criterion (AIC) and the Bayesian information criterion (BIC) are used to select the model that best fits the data. A lower value of statistic indicates a better model. The findings according to AIC and BIC are consistent when we compare the models separately for 2 or 3 age groups. However, in order to compare models from a 2- and 3-group division, the BIC criterion should be used because it accounts for the different number of model parameters.

Comparison between young people aged 14–17 and 18–19

We are also interested in whether there is a difference between children approaching the age of 18 and young adults who are slightly over the age of 18, but are technically members of the 18–45 normative adult group. To address this, we compared the test results of 14 children aged 14–17 (of which 8 are males; 57.1%) with those of 58 young adults aged 18–19 (38 are males; 65.5%). The following eight OVRT-C metrics were used for comparison: slow horizontal and vertical smooth pursuit (velocity saccade), saccade and RT latency (saccadic and motor responses), subjective visual vertical (angular error). For each of these metrics, a Two-Sample t-test was used to determine if there is a difference between the mean value of two independent age groups (i.e., 14–17 vs 18–19). The corresponding p-value for mean difference is calculated under two-tail hypothesis. The difference is considered significant when $p \leq 0.05$. To compute the corresponding statistics, we

Table 5 Model estimates for age coefficients and their interpretation

Test/Metrics	Model	Response Link	N Sub	N Obs	Age Coeff	Interpretation of the Age Coefficient *Each year, the …*
ART, Mean latency, msec	LM	log	39	39	−0.042	*mean latency is expected to decrease by 4.2%*
VRT, Mean latency, msec	LM	log	39	39	−0.049	*mean latency is expected to decrease by 4.9%*
SPH, 0.1 Hz, Velocity saccade, %	LM	log	40	40	−0.069	*velocity saccade is expected to decrease by 6.9%*
SPV, 0.1 Hz, Velocity saccade, %	LM	log	39	39	−0.075	*velocity saccade is expected to decrease by 7.5%*
OKN, 20°/s, Average gain	LM	linear	38	38	−0.013	*average gain is expected to decrease by 0.013 units*
OKN, 60°/s, Average gain	LM	linear	38	38	−0.022	*average gain is expected to decrease by 0.022 units*
SRT, Saccades, Latency means	LMM	linear	38	76	−0.007	*latency means is expected to decrease by 0.007 units*
SRT, Motor Resp, Latency means	LMM	linear	38	76	−0.026	*latency means is expected to decrease by 0.026 units*
SPS, Velocity intercept	LMM	linear	39	77	7.899	*velocity intercept is expected to increase by 7.9 units*
SPS, Interval intercept	LMM	linear	39	77	−0.030	*interval intercept is expected to decrease by 0.03 units*
SVV, Mean error (abs)	LMM	linear	40	80	−0.090	*error is expected to decrease by 0.09 degrees*
VS, Inward time constant, sec	LMM	linear	38	76	−0.039	*time constant is expected to decrease by 0.039 s*
AS, Num. of pro-saccade errors	Bin GLMM	logit link	39	78	−0.210	*chance of error is expected to decrease by 19%*
SPS, Num. of saccades per 10 s	Pois GLMM	log link	38	38	0.061	*number of saccades is expected to increase by 6.1%*

Notes: • The models used to estimate the parameters are linear regression models (LM), linear mixed effects models (LMM) and Binomial and Poisson mixed effects models (refer to generalized linear mixed models; Bin and Pois GLMM). The use of mixed models makes it possible to account the subject-specific random effect when there are repeated measurements. • Restricted maximum likelihood (REML; for LM and LMM) and maximum likelihood (ML; for GLMM) estimation was used to estimate the model parameters. • With the exception of OKN 20°/s and SVV, the age coefficients in 12 models are significant at the 5% level

Table 6 Three and Two Age Separation Groups

Model by Group	Group 1			Group 2			Group 3		
	Range	N Sub	N Obs	Range	N Sub	N Obs	Range	N Sub	N Obs
(A) *Three age groups separation*									
1	[7,9)	11	11	[9,12)	10	10	[12,18)	18	18
2	[7,9)	11	11	[9,13)	12	12	[13,18)	16	16
3	[7,9)	11	11	[9,14)	14	14	[14,18)	14	14
4	[7,9)	11	11	[9,15)	19	19	[15,18)	9	9
5	[7,10)	14	14	[10,13)	9	9	[13,18)	16	16
6	[7,10)	14	14	[10,14)	11	11	[14,18)	14	14
7	[7,10)	14	14	[10,15)	16	16	[15,18)	9	9
8	[7,11)	18	18	[11,14)	7	7	[14,18)	14	14
9	[7,11)	18	18	[11,15)	12	12	[15,18)	9	9
10	[7,12)	21	21	[12,15)	9	9	[15,18)	9	9
(B) *Two age groups separation*									
1	[7,9)	11	11	[9,18)	28	28			
2	[7,10)	14	14	[10,18)	25	25			
3	[7,11)	18	18	[11,18)	21	21			
4	[7,12)	21	21	[12,18)	18	18			
5	[7,13)	23	23	[13,18)	16	16			
6	[7,14)	25	25	[14,18)	14	14			
7	[7,15)	30	30	[15,18)	9	9			

Table 7 Breusch-Pagan $\mathscr{LM}$ Test for Heteroskedasticity, Model Estimates for Age Group Effects and Model Selection Criteria

Model	(1) Auditory Reaction Time (ART), Mean latency (s)								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	0.37	*0.83*	5.63	5.46	5.26	*0.13*	*0.06*	14.1	20.8
2	0.67	*0.72*	5.63	5.42	5.27	*0.05*	*0.13*	15.7	22.4
3	0.32	*0.85*	5.63	5.41	5.25	*0.04*	*0.10*	15.6	22.2
4	1.03	*0.60*	5.63	5.35	5.29	*0.01*	*0.53*	17.6	24.2
5	0.63	*0.73*	5.62	5.37	5.27	*0.03*	*0.36*	14.1	20.8
6	0.32	*0.85*	5.62	5.37	5.25	*0.02*	*0.26*	13.9	20.5
7	1.48	*0.48*	5.62	5.31	5.29	*0.00*	*0.82*	14.7	21.3
8	0.15	*0.93*	5.59	5.30	5.25	*0.01*	*0.69*	13.2	19.9
9	2.19	*0.33*	5.59	5.26	5.29	*0.00*	*0.76*	**12.6**	**19.3**
10	2.57	*0.28*	5.55	5.24	5.29	*0.00*	*0.66*	15.4	22.0
1	0.53	*0.47*	5.63	5.33		*0.00*		13.5	18.4
2	0.45	*0.50*	5.62	5.30		*0.00*		10.4	15.4
3	0.06	*0.80*	5.59	5.27		*0.00*		**8.8**	**13.8**
4	0.09	*0.76*	5.55	5.26		*0.00*		12.1	17.1
5	0.31	*0.58*	5.52	5.27		*0.01*		15.2	20.2
6	0.06	*0.81*	5.51	5.25		*0.01*		15.5	20.5
7	0.09	*0.76*	5.45	5.29		*0.14*		20.7	25.6

Model	(2) Visual Reaction Time (VRT), Mean latency (s)								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	0.43	*0.81*	5.84	5.57	5.44	*0.01*	*0.12*	0.1	6.7
2	0.42	*0.81*	5.84	5.54	5.44	*0.00*	*0.25*	1.5	8.1
3	0.90	*0.64*	5.84	5.53	5.44	*0.00*	*0.27*	1.5	8.2
4	3.99	*0.14*	5.84	5.51	5.42	*0.00*	*0.26*	0.2	6.9
5	1.05	*0.59*	5.82	5.47	5.44	*0.00*	*0.74*	−1.4	5.2
6	2.11	*0.35*	5.82	5.47	5.44	*0.00*	*0.70*	−1.8	4.9
7	6.56	*0.04*	5.82	5.47	5.42	*0.00*	*0.51*	**−4.0**	**2.7**
8	2.06	*0.36*	5.77	5.45	5.44	*0.00*	*0.94*	2.9	9.6

Table 7 (continued)

Model	(2) Visual Reaction Time (VRT), Mean latency (s)								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
9	5.50	*0.06*	5.77	5.46	5.42	*0.00*	*0.65*	1.2	7.9
10	3.33	*0.19*	5.73	5.45	5.42	*0.00*	*0.73*	7.0	13.6
1	0.45	*0.50*	5.84	5.48		*0.00*		−2.2	2.7
2	0.05	*0.82*	5.82	5.45		*0.00*		**−6.1**	**−1.1**
3	0.18	*0.68*	5.77	5.44		*0.00*		−1.2	3.8
4	0.12	*0.73*	5.73	5.44		*0.00*		3.8	8.8
5	0.31	*0.58*	5.70	5.44		*0.00*		7.8	12.8
6	0.10	*0.75*	5.68	5.44		*0.01*		9.6	14.6
7	0.21	*0.65*	5.64	5.42		*0.03*		12.0	17.0

Model	(3) Smooth Pursuit—Horizontal (SPH), 0.1 Hz, Velocity saccade (%)								
	Breusch-Pagan		Model Estimates					Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	1.31	*0.36*	−1.01	−1.53	−1.60	*0.04*	*0.77*	80.2	87.0
2	1.09	*0.22*	−1.01	−1.49	−1.63	*0.04*	*0.54*	80.1	86.8
3	2.50	*0.35*	−1.01	−1.60	−1.54	*0.01*	*0.78*	79.9	86.6
4	1.77	*0.46*	−1.01	−1.57	−1.58	*0.01*	*0.95*	80.1	86.9
5	1.13	*0.23*	−1.03	−1.62	−1.63	*0.02*	*0.97*	78.2	84.9
6	2.12	*0.19*	−1.03	−1.74	−1.54	*0.00*	*0.39*	**77.1**	**83.9**
7	1.65	*0.33*	−1.03	−1.66	−1.58	*0.00*	*0.77*	77.9	84.7
8	3.39	*0.01*	−1.15	−1.82	−1.54	*0.02*	*0.34*	79.3	86.1
9	2.11	*0.09*	−1.15	−1.67	−1.58	*0.02*	*0.74*	80.8	87.6
10	0.38	*0.14*	−1.25	−1.61	−1.58	*0.15*	*0.93*	84.5	91.2
1	1.14	*0.36*	−1.01	−1.57		*0.01*		77.3	82.3
2	1.11	*0.26*	−1.03	−1.63		*0.00*		**75.1**	**80.2**
3	0.99	*0.12*	−1.15	−1.63		*0.01*		78.4	83.5
4	0.03	*0.16*	−1.25	−1.60		*0.08*		82.0	87.0
5	0.02	*0.10*	−1.25	−1.63		*0.06*		81.5	86.5
6	0.89	*0.51*	−1.33	−1.54		*0.30*		83.7	88.7
7	0.46	*0.58*	−1.35	−1.58		*0.32*		83.7	88.8

Table 7 (continued)

Model	(4) Smooth Pursuit—Vertical (SPV), 0.1 Hz, Velocity saccade (%)								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	2.03	*0.36*	−1.02	−0.97	−1.51	*0.84*	*0.03*	80.3	87.0
2	3.01	*0.22*	−1.02	−0.96	−1.58	*0.80*	*0.01*	**77.8**	**84.5**
3	2.07	*0.35*	−1.02	−1.14	−1.50	*0.63*	*0.14*	82.6	89.3
4	1.54	*0.46*	−1.02	−1.24	−1.51	*0.35*	*0.29*	83.9	90.6
5	2.91	*0.23*	−0.98	−1.02	−1.58	*0.89*	*0.03*	**77.8**	**84.5**
6	3.33	*0.19*	−0.98	−1.24	−1.50	*0.32*	*0.31*	81.3	88.0
7	2.20	*0.33*	−0.98	−1.32	−1.51	*0.14*	*0.47*	82.3	89.0
8	8.71	*0.01*	−1.04	−1.23	−1.50	*0.53*	*0.40*	79.8	86.4
9	4.75	*0.09*	−1.04	−1.35	−1.51	*0.19*	*0.57*	81.7	88.3
10	4.00	*0.14*	−1.00	−1.50	−1.51	*0.05*	*0.99*	79.4	86.1
1	0.85	*0.36*	−1.02	−1.33		*0.16*		82.4	87.3
2	1.25	*0.26*	−0.98	−1.39		*0.04*		80.3	85.3
3	2.48	*0.12*	−1.04	−1.42		*0.05*		80.1	85.1
4	1.95	*0.16*	−1.00	−1.51		*0.01*		77.5	82.5
5	2.74	*0.10*	−0.99	−1.58		*0.00*		**74.9**	**79.9**
6	0.44	*0.51*	−1.08	−1.50		*0.05*		80.5	85.5
7	0.31	*0.58*	−1.15	−1.51		*0.14*		82.1	87.1

Model	(5) Optokinetic Horizontal (OKN), 20 deg/sec, Average Gain								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	4.46	*0.11*	0.80	0.91	0.74	*0.13*	*0.01*	−9.0	−2.4
2	5.64	*0.06*	0.80	0.90	0.73	*0.14*	*0.01*	**−10.3**	**−3.7**
3	0.76	*0.68*	0.80	0.86	0.74	*0.43*	*0.09*	−4.9	1.6
4	0.89	*0.64*	0.80	0.84	0.70	*0.56*	*0.08*	−5.5	1.0
5	4.00	*0.14*	0.82	0.91	0.73	*0.19*	*0.01*	−9.1	−2.5
6	0.25	*0.88*	0.82	0.86	0.74	*0.60*	*0.13*	−4.4	2.1
7	0.43	*0.81*	0.82	0.83	0.70	*0.77*	*0.11*	−5.0	1.5
8	0.42	*0.81*	0.84	0.79	0.74	*0.56*	*0.54*	−4.9	1.7
9	0.54	*0.76*	0.84	0.79	0.70	*0.46*	*0.29*	−5.6	1.0

Table 7 (continued)

Model	(5) Optokinetic Horizontal (OKN), 20 deg/sec, Average Gain								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
10	0.93	*0.63*	0.85	0.77	0.70	*0.31*	*0.42*	−6.4	0.2
1	0.01	*0.93*	0.80	0.80		*0.96*		−7.2	−2.3
2	0.25	*0.62*	0.82	0.79		*0.66*		−7.4	−2.5
3	0.47	*0.49*	0.84	0.75		*0.14*		−9.5	−4.6
4	1.02	*0.31*	0.85	0.74		*0.07*		−10.7	−5.8
5	1.77	*0.18*	0.85	0.73		*0.04*		**−12.0**	**−7.0**
6	0.22	*0.64*	0.83	0.74		*0.14*		−9.5	−4.6
7	0.42	*0.52*	0.83	0.70		*0.10*		−10.6	−5.7

Model	(6) Optokinetic Horizontal (OKN), 60 deg/sec, Average Gain								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	1.25	*0.54*	0.53	0.52	0.38	*0.91*	*0.06*	−3.9	2.6
2	1.45	*0.48*	0.53	0.52	0.36	*0.88*	*0.03*	−5.1	1.4
3	0.59	*0.74*	0.53	0.50	0.36	*0.64*	*0.07*	−3.6	3.0
4	0.18	*0.91*	0.53	0.46	0.35	*0.36*	*0.15*	−2.5	4.1
5	1.42	*0.49*	0.55	0.48	0.36	*0.41*	*0.12*	**−5.8**	**0.8**
6	0.74	*0.69*	0.55	0.46	0.36	*0.24*	*0.20*	−4.8	1.8
7	0.40	*0.82*	0.55	0.44	0.35	*0.10*	*0.28*	−4.3	2.2
8	0.57	*0.75*	0.52	0.48	0.36	*0.58*	*0.22*	−4.0	2.6
9	0.49	*0.78*	0.52	0.43	0.35	*0.22*	*0.32*	−3.3	3.2
10	0.83	*0.66*	0.53	0.41	0.35	*0.12*	*0.50*	−4.5	2.0
1	0.16	*0.69*	0.53	0.43		*0.13*		−5.5	−0.6
2	0.36	*0.55*	0.55	0.40		*0.02*		−8.3	−3.4
3	0.62	*0.43*	0.52	0.40		*0.04*		−7.4	−2.5
4	0.93	*0.33*	0.53	0.38		*0.02*		−9.0	−4.1
5	1.06	*0.30*	0.52	0.36		*0.01*		**−10.3**	**−5.4**
6	0.50	*0.48*	0.51	0.36		*0.02*		−8.8	−3.8
7	0.13	*0.72*	0.49	0.35		*0.06*		−7.1	−2.2

Table 7 (continued)

Model	(7) Saccade and Reaction Time (SRT), Saccades, Latency means								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathcal{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	1.98	*0.58*	0.24	0.20	0.19	*0.05*	*0.51*	−242.1	−230.5
2	2.94	*0.40*	0.24	0.21	0.18	*0.09*	*0.09*	**−245.7**	**−234.1**
3	1.44	*0.70*	0.24	0.20	0.18	*0.04*	*0.22*	−242.8	−231.1
4	0.88	*0.83*	0.24	0.19	0.18	*0.01*	*0.66*	−241.5	−229.8
5	2.78	*0.43*	0.23	0.22	0.18	*0.46*	*0.07*	−243.4	−231.7
6	2.72	*0.44*	0.23	0.21	0.18	*0.20*	*0.20*	−240.8	−229.2
7	1.25	*0.74*	0.23	0.19	0.18	*0.04*	*0.66*	−239.0	−227.3
8	2.51	*0.47*	0.23	0.21	0.18	*0.45*	*0.25*	−239.7	−228.0
9	0.92	*0.82*	0.23	0.19	0.18	*0.08*	*0.78*	−237.7	−226.1
10	1.84	*0.61*	0.22	0.19	0.18	*0.08*	*0.89*	−238.3	−226.6
1	0.72	*0.70*	0.24	0.19		*0.00*		−249.2	−239.8
2	1.19	*0.55*	0.23	0.19		*0.02*		−246.6	−237.3
3	0.86	*0.65*	0.23	0.19		*0.02*		−245.3	−236.0
4	1.82	*0.40*	0.22	0.19		*0.03*		−245.9	−236.6
5	2.78	*0.25*	0.23	0.18		*0.00*		**−250.7**	**−241.4**
6	0.49	*0.78*	0.22	0.18		*0.02*		−245.9	−236.6
7	0.59	*0.75*	0.21	0.18		*0.18*		−242.4	−233.0

Model	(8) Saccade and Reaction Time (SRT), Motor Response, Latency means								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathcal{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	14.62	*0.00*	0.69	0.54	0.48	*0.04*	*0.38*	**−63.5**	**−54.2**
2	13.60	*0.00*	0.69	0.52	0.49	*0.02*	*0.58*	−60.2	−50.8
3	13.92	*0.00*	0.69	0.50	0.50	*0.01*	*0.95*	−60.5	−51.2
4	14.30	*0.00*	0.69	0.51	0.48	*0.01*	*0.71*	−61.0	−51.7
5	7.79	*0.02*	0.66	0.51	0.49	*0.03*	*0.79*	−55.8	−46.5
6	8.11	*0.02*	0.66	0.48	0.50	*0.01*	*0.73*	−56.3	−47.0
7	8.50	*0.01*	0.66	0.50	0.48	*0.01*	*0.84*	−56.5	−47.2
8	3.63	*0.16*	0.64	0.45	0.50	*0.02*	*0.48*	−51.5	−42.1
9	3.99	*0.14*	0.64	0.49	0.48	*0.02*	*0.98*	−51.1	−41.8

Table 7 (continued)

Model	(8) Saccade and Reaction Time (SRT), Motor Response, Latency means								
Model	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
10	2.16	*0.34*	0.63	0.48	0.48	*0.04*	*0.96*	−48.8	−39.5
1	12.73	*0.00*	0.69	0.50		*0.00*		**−65.6**	**−58.6**
2	7.32	*0.01*	0.69	0.49		*0.00*		−61.5	−54.5
3	3.31	*0.07*	0.69	0.49		*0.01*		−56.4	−49.4
4	1.78	*0.18*	0.69	0.48		*0.01*		−54.1	−47.1
5	2.32	*0.13*	0.66	0.49		*0.04*		−52.7	−45.7
6	1.36	*0.24*	0.66	0.50		*0.16*		−49.2	−42.2
7	0.18	*0.67*	0.66	0.48		*0.18*		−48.1	−41.1

Model	(9) Self-Paced Saccade (SPS), Velocity intercept								
Model	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	3.79	*0.15*	352.4	411.5	427.1	*0.03*	*0.53*	783.8	793.2
2	4.78	*0.09*	352.4	419.7	423.4	*0.01*	*0.88*	783.3	792.7
3	6.11	*0.05*	352.4	417.1	426.4	*0.01*	*0.69*	**781.8**	**791.2**
4	2.47	*0.29*	352.4	413.7	438.5	*0.01*	*0.31*	784.6	793.9
5	4.81	*0.09*	363.4	424.2	423.4	*0.03*	*0.98*	783.7	793.1
6	6.19	*0.05*	363.4	419.9	426.4	*0.03*	*0.80*	**782.1**	**791.5**
7	1.86	*0.40*	363.4	414.9	438.5	*0.03*	*0.36*	786.9	796.2
8	3.47	*0.18*	376.1	417.4	426.4	*0.18*	*0.78*	787.5	796.8
9	0.48	*0.79*	376.1	411.6	438.5	*0.15*	*0.35*	790.3	799.7
10	0.63	*0.73*	377.7	415.8	438.5	*0.14*	*0.45*	790.0	799.4
1	2.43	*0.12*	352.4	421.9		*0.00*		**793.1**	**800.1**
2	1.83	*0.18*	363.4	423.7		*0.00*		795.3	802.3
3	0.22	*0.64*	376.1	423.7		*0.02*		799.2	806.2
4	0.00	*0.96*	377.7	427.1		*0.02*		798.8	805.8
5	0.17	*0.68*	384.6	423.4		*0.07*		800.9	807.9
6	0.80	*0.37*	386.0	426.4		*0.07*		800.3	807.3
7	0.46	*0.50*	389.1	438.5		*0.05*		800.1	807.1

Table 7 (continued)

Model	(10) Self-Paced Saccade (SPS), Interval intercept								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	42.34	*0.00*	0.60	0.40	0.33	*0.01*	*0.28*	−132.7	−121.0
2	42.36	*0.00*	0.60	0.38	0.33	*0.00*	*0.37*	−132.5	−120.8
3	42.80	*0.00*	0.60	0.38	0.32	*0.00*	*0.35*	−138.2	−126.5
4	42.76	*0.00*	0.60	0.35	0.34	*0.00*	*0.85*	−138.7	−127.0
5	34.38	*0.00*	0.57	0.36	0.33	*0.00*	*0.67*	**−141.5**	**−129.8**
6	34.36	*0.00*	0.57	0.36	0.32	*0.00*	*0.61*	−136.8	−125.1
7	34.40	*0.00*	0.57	0.34	0.34	*0.00*	*0.91*	−138.4	−126.7
8	21.40	*0.00*	0.52	0.36	0.32	*0.05*	*0.65*	−124.8	−113.0
9	21.20	*0.00*	0.52	0.33	0.34	*0.01*	*0.86*	−125.6	−113.9
10	16.62	*0.00*	0.51	0.31	0.34	*0.01*	*0.71*	−122.3	−110.6
1	42.33	*0.00*	0.60	0.35		*0.00*		−137.2	−127.8
2	34.10	*0.00*	0.57	0.34		*0.00*		**−138.6**	**−129.2**
3	20.73	*0.00*	0.52	0.33		*0.00*		−123.9	−114.5
4	15.99	*0.00*	0.51	0.33		*0.00*		−119.5	−110.1
5	12.19	*0.00*	0.49	0.33		*0.01*		−114.1	−104.7
6	15.02	*0.00*	0.48	0.32		*0.01*		−123.0	−113.6
7	8.89	*0.01*	0.45	0.34		*0.14*		−115.6	−106.3
Model	(11) Subjective Visual Vertical (SVV), Error Mean (abs)								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	30.34	*0.00*	2.34	1.35	1.30	*0.04*	*0.88*	**263.2**	**272.8**
2	30.36	*0.00*	2.34	1.25	1.37	*0.02*	*0.74*	263.4	273.0
3	30.46	*0.00*	2.34	1.23	1.40	*0.02*	*0.64*	263.6	273.1
4	30.46	*0.00*	2.34	1.28	1.40	*0.01*	*0.76*	263.5	273.0
5	19.62	*0.00*	2.12	1.25	1.37	*0.08*	*0.79*	271.5	281.0
6	19.57	*0.00*	2.12	1.23	1.40	*0.06*	*0.69*	272.2	281.7
7	19.57	*0.00*	2.12	1.29	1.40	*0.05*	*0.81*	272.3	281.8
8	17.65	*0.00*	2.07	0.85	1.40	*0.01*	*0.24*	267.9	277.4
9	17.25	*0.00*	2.07	1.08	1.40	*0.02*	*0.50*	268.9	278.4

Table 7 (continued)

Model	(11) Subjective Visual Vertical (SVV), Error Mean (abs)								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
10	12.13	*0.00*	1.89	1.19	1.40	*0.13*	*0.71*	275.9	285.5
1	30.27	*0.00*	2.34	1.32		*0.01*		**261.1**	**268.2**
2	19.51	*0.00*	2.12	1.33		*0.04*		270.1	277.2
3	16.73	*0.00*	2.07	1.22		*0.02*		267.8	275.0
4	11.84	*0.00*	1.89	1.30		*0.12*		274.7	281.8
5	9.35	*0.00*	1.79	1.37		*0.28*		278.1	285.2
6	6.54	*0.01*	1.74	1.40		*0.40*		281.2	288.4
7	3.02	*0.08*	1.69	1.40		*0.53*		284.5	291.7
Model	(12) Vergence Step (VS), Inward time constant, sec								
	Breusch-Pagan		Model Estimates			*p*-value		Model	
			Age Group Effect			Group (2) vs		Criteria	
	$\mathscr{LM}$	*p*-val	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	14.54	*0.00*	0.85	0.51	0.49	*0.00*	*0.78*	26.9	36.2
2	11.77	*0.00*	0.85	0.51	0.48	*0.00*	*0.74*	31.4	40.7
3	10.42	*0.01*	0.85	0.48	0.50	*0.00*	*0.77*	34.0	43.4
4	8.53	*0.01*	0.85	0.48	0.53	*0.00*	*0.43*	38.0	47.3
5	30.39	*0.00*	0.82	0.44	0.48	*0.00*	*0.33*	6.6	15.9
6	31.50	*0.00*	0.82	0.42	0.50	*0.00*	*0.07*	2.6	11.9
7	32.05	*0.00*	0.82	0.43	0.53	*0.00*	*0.09*	**0.1**	**9.5**
8	21.49	*0.00*	0.73	0.43	0.50	*0.00*	*0.24*	24.7	34.0
9	22.05	*0.00*	0.73	0.44	0.53	*0.00*	*0.18*	19.6	28.9
10	17.58	*0.00*	0.70	0.44	0.53	*0.00*	*0.23*	26.8	36.1
1	7.79	*0.01*	0.85	0.49		*0.00*		34.1	41.1
2	29.45	*0.00*	0.82	0.47		*0.00*		**6.1**	**13.1**
3	20.77	*0.00*	0.73	0.48		*0.00*		24.4	31.3
4	16.51	*0.00*	0.70	0.49		*0.00*		31.7	38.7
5	12.34	*0.00*	0.68	0.48		*0.01*		38.3	45.3
6	9.48	*0.00*	0.65	0.50		*0.05*		45.2	52.2
7	3.55	*0.06*	0.62	0.53		*0.32*		55.1	62.1

Table 7 (continued)

Model	(13) Antisaccade (AS), Number of pro-saccade errors						
	Model Estimates			*p*-value		Model	
	Age Group Effect			Group (2) vs		Criteria	
	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	1.42	0.91	−0.08	*0.35*	*0.06*	240.6	252.4
2	1.42	0.79	−0.12	*0.23*	*0.07*	240.9	252.7
3	1.42	0.79	−0.27	*0.20*	*0.03*	**239.4**	**251.2**
4	1.43	0.56	−0.41	*0.07*	*0.07*	240.9	252.7
5	1.34	0.71	−0.13	*0.25*	*0.13*	241.0	252.8
6	1.34	0.73	−0.27	*0.23*	*0.05*	**239.6**	**251.4**
7	1.34	0.47	−0.41	*0.06*	*0.11*	240.7	252.5
8	1.07	1.16	−0.28	*0.88*	*0.02*	241.0	252.8
9	1.08	0.60	−0.43	*0.34*	*0.09*	243.3	255.1
10	1.20	0.22	−0.41	*0.05*	*0.30*	240.3	252.1
1	1.43	0.25		*0.01*		242.3	251.7
2	1.35	0.15		*0.01*		241.3	250.8
3	1.08	0.16		*0.04*		244.2	253.6
4	1.20	−0.08		*0.00*		239.4	248.9
5	1.12	−0.13		*0.01*		240.4	249.8
6	1.09	−0.28		*0.00*		**239.0**	**248.5**
7	0.90	−0.44		*0.01*		242.2	251.6

Model	(14) Self-Paced Saccade (SPS), Number of saccades						
	Model Estimates			*p*-value		Model	
	Age Group Effect			Group (2) vs		Criteria	
	(1)	(2)	(3)	(1)	(3)	AIC	BIC
1	2.89	3.13	3.39	*0.04*	*0.01*	244.9	251.5
2	2.89	3.17	3.39	*0.01*	*0.02*	246.4	252.9
3	2.89	3.19	3.41	*0.01*	*0.02*	246.4	252.9
4	2.89	3.27	3.37	*0.00*	*0.34*	251.3	257.9
5	2.91	3.24	3.40	*0.00*	*0.11*	243.6	250.1
6	2.91	3.25	3.41	*0.00*	*0.08*	**243.1**	**249.7**
7	2.91	3.33	3.37	*0.00*	*0.66*	246.0	252.6
8	2.97	3.30	3.41	*0.01*	*0.31*	246.2	252.7
9	2.97	3.38	3.37	*0.00*	*0.92*	247.2	253.8

Table 7 (continued)

Model	(14) Self-Paced Saccade (SPS), Number of saccades						
	Model Estimates			*p*-value		Model Criteria	
	Age Group Effect			Group (2) vs			
	(1)	(2)	(3)	(1)	(3)	AIC	BIC
10	3.00	3.41	3.37	*0.00*	*0.73*	249.0	255.5
1	2.89	3.30		*0.00*		250.3	255.2
2	2.91	3.34		*0.00*		**244.2**	**249.1**
3	2.97	3.38		*0.00*		245.3	250.2
4	3.00	3.39		*0.00*		247.1	252.0
5	3.04	3.39		*0.00*		250.7	255.6
6	3.06	3.40		*0.00*		252.2	257.1
7	3.13	3.36		*0.05*		262.1	267.0

Note: Bold indicated the smaller values for AIC and BIC (smaller is better)

used the TTEST2 function in MATLAB software (The MathWorks, Inc. USA, version R2015b) assuming unknown and unequal variances with Satterthwaite's approximation for the effective degrees of freedom.

Results

Evaluation of comfort level questionnaire

After completing the battery of (OVRT-C) tests, each subject was asked 5 questions to evaluate their comfort level. All children in the sample were able to complete the 15-min testing period. Most children reported liking the aesthetics of the goggles and a comfortable fit (see Table 3). Moreover, none of the patients shifted the goggles during the protocol and therefore did not need recalibration.

To understand how age affected comfort level, we split our subjects into three age groups: middle childhood (group 1: 7–10 years); young teen (group 2: 10–14 years); and teenagers (group 3: 14–17 years). Compiled results are shown in Table 3.

Evaluation of test result values by age

For each of the 14 OVRT-C metrics, Table 4 illustrates how the test responses vary with age (computed for the nine age intervals). The mean responses showed consistent change with age, following upward or downward trends across the ages tested. For example, the figures attached to Table 4 illustrate that the mean auditory and visual reaction time latencies decreased as the children get older. However, it is evident that there is some stability in most of the metrics from the age of approximately 12.

Table 5 reports the model estimates for the age coefficients and their interpretation as reflected in the model. With the exception of OKN 20°/s (average gain) and SVV (mean angular error), the age coefficients in 12 of the 14 models are significant at the 5% level. As an example, one of the measures we acquired from smooth pursuit tests is the amount of saccadic, non-pursuit eye movement subjects exhibit during the test. For the slow horizontal smooth pursuit test, the coefficient was −0.069, which indicates an expected decrease in saccadic, non-pursuit eye movements by 6.9% per year, indicating a steady improvement of smooth pursuit function. For slow smooth pursuit vertical tests, the expected improvement was 7.5%. As another example, the amount of error on the anti-saccades test, where subjects are asked to look away from a target, are expected to decrease

Table 8 Age groups determined by modeling with individual OVRT−C test result measures

Test/Metrics	Division into 3 or 2 age groups	Selected model	Age in years										
			7	8	9	10	11	12	13	14	15	16	17
			Average effect by age group										
ART, Mean latency (msec)	3	9	267	267	267	267	192	192	192	192	198	198	198
	2	3	267	267	267	267	194	194	194	194	194	194	194
			Average effect by age group										
VRT, Mean latency (msec)	3	7	335	335	335	238	238	238	238	238	225	225	225
	2	2	335	335	335	233	233	233	233	233	233	233	233
			Percentage effect by age group										
SPH, 0.1Hz, Velocity saccade (%)	3	6	36	36	36	18	18	18	18	21	21	21	21
	2	2	36	36	36	20	20	20	20	20	20	20	20
			Percentage effect by age group										
SPV, 0.1Hz, Velocity saccade (%)	3	2	36	36	38	38	38	38	21	21	21	21	21
		5	37	37	37	36	36	36	21	21	21	21	21
	2	5	37	37	37	37	37	37	21	21	21	21	21
			Average effect by age group										
OKN, 20 deg/sec, Average gain	3	2	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.73	0.73	0.73	0.73
	2	5	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.73	0.73	0.73	0.73
			Average effect by age group										
OKN, 60 deg/sec, Average gain	3	5	0.55	0.55	0.55	0.55	0.48	0.48	0.48	0.36	0.36	0.36	0.36
	2	5	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.36	0.36	0.36	0.36
			Average effect by age group										
SRT, Saccades, Latency	3	2	0.24	0.24	0.24	0.21	0.21	0.21	0.18	0.18	0.18	0.18	0.18
	2	5	0.23	0.23	0.23	0.23	0.23	0.23	0.18	0.18	0.18	0.18	0.18
			Average effect by age group										
SRT, Motor Resp, Latency means (sec)	3	1	0.69	0.69	0.54	0.54	0.54	0.48	0.48	*0.48*	0.48	0.48	0.48
	2	1	0.69	0.69	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
			Average effect by age group										
SPS, Velocity intercept (deg/sec)	3	3	352	352	417	417	417	417	417	426	426	426	426
		6	363	363	363	420	420	420	420	426	426	426	426
	2	1	352	352	422	422	422	422	422	422	422	422	422
			Average effect by age group										
SPS, Interval intercept	3	5	0.57	0.57	0.57	0.36	*0.36*	*0.36*	*0.33*	*0.33*	0.33	0.33	0.33
	2	2	0.6	0.6	0.6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
			Average effect by age group										
SVV, Mean error	3	1	2.34	2.34	2.34	1.35	1.35	1.35	1.30	1.30	1.30	1.30	1.30
	2	1	2.34	2.34	2.34	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
			Average effect by age group										
VS, Outward time constant (sec)	3	7	0.82	0.82	0.82	0.82	0.43	0.43	0.43	0.43	0.43	0.53	0.53
	2	2	0.82	0.82	0.82	0.82	0.47	0.47	0.47	0.47	0.47	0.47	0.47
			Probability of error by age group										
Antisaccade, Number of pro-saccade errors	3	3	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.4	0.4	0.4	0.4
		6	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.4	0.4	0.4	0.4
	2	6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.4	0.4	0.4	0.4
			Average effect by age group										
SPS, Number of saccades	3	6	18	18	18	26	26	26	26	30	30	30	30
	2	2	18	18	18	28	28	28	28	28	28	28	28

Youngest candidate age group is black with white text, oldest is near-white with black text, and middle group for 3-group models is gray with black text

with each additional year.[1] In two tests where the coefficients were not significant, this does not indicate the absence of a relationship. For example, for most of the tests in Table 4, we saw that up to the age of 10–12 years there is a tendency to decrease (or increase), after which the responses stabilize.

Age group separation

For 14 OVRT-C test metrics and for all the 17 split options, Table 7 reports the results of the Breusch-Pagan $\mathscr{LM}$ test for heteroskedasticity, the estimated fixed effects attributed to each of the age groups, the corresponding significance levels, and the AIC and BIC criteria. The results do not suggest that splitting into 3 groups is optimal. For most options (10 models) in all OVRT-C tests analyzed, no significant

[1] In a logistic model, regression coefficients are interpreted in term of *odds ratio* rather than probability. In the context of *Antisaccade*, when *Age* is defined in terms of years, the odds ratio refers to the annual change in the ratio of the probability that a child will make an error, P, to the probability that he or she will not make an error, $1 - P$, that is, the annual change in $odd = P/(1 - P)$. The odds ratio is computed as $\exp\left(\hat{\beta}_{\text{age}}\right) = \exp(-0.21) = 0.81$. An odds ratio lower than 1 indicates that the chance of making an error decreasing each year. It is common to present change in percentages, that is, $\left\{\exp\left(\hat{\beta}_{\text{age}}\right) - 1\right\}100\% = -19\%$.

Table 9 Effect of age and corresponding Confidence Interval (CI) in an optimal 2-division model

Tests/Metrics	Optimal Model	Age Range of Group 1	Age Coeff	95% CI Lower	95% CI Upper
ART, Mean latency, msec	3	< 11	0.316	0.169	0.463
VRT, Mean latency, msec	2	< 10	0.363	0.240	0.486
SPH, 0.1 Hz, Velocity saccade, %	2	< 10	0.600	0.248	0.951
SPV, 0.1 Hz, Velocity saccade, %	5	< 13	0.586	0.220	0.953
OKN, 20°/sec, Average gain	5	< 13	0.122	0.007	0.237
OKN, 60°/sec, Average gain	5	< 13	0.163	0.045	0.280
SRT, Saccades, Latency means	5	< 13	0.051	0.018	0.083
SRT, Motor Resp, Latency means	1	< 9	0.186	0.072	0.300
SPS, Velocity intercept	1	< 9	−69.6	−110.5	−28.6
SPS, Interval intercept	1	< 9	0.247	0.136	0.357
SVV, Mean error (abs)	1	< 9	1.025	0.222	1.827
VS, Inward time constant, sec	2	< 10	0.351	0.187	0.514
AS, Num. of pro-saccade errors	6	< 14	1.368	0.512	2.223
SPS, Num. of saccades per 10 s	2	< 10	−0.437	−0.602	−0.273

Table 10 Comparison normative children and adults using two-sample t-test

Tests/Metrics	Children Aged 14–17			Adults Aged 18–19			*p*-value (*mean diff*)
	N	Mean	SD	N	Mean	SD	
SPH, 0.1 Hz, Velocity saccade, %	14	24.3	13.1	58	16.7	6.5	**0.025**
SPV, 0.1 Hz, Velocity saccade, %	14	25.5	13.9	58	16.9	8.6	**0.025**
SRT, Saccades, Latency means	13	0.18	0.04	58	0.184	0.04	0.708
SRT, Motor Resp, Latency means	13	0.50	0.22	58	0.406	0.11	0.157
SVV, Mean error	14	1.40	0.98	58	1.349	0.99	0.857

difference was found between age groups (2) and (3). Furthermore, for all 10 + 7 models, the BIC criteria are smaller for models split into 2 groups (a lower BIC value indicates a better fitting model). For example, for the mean auditory reaction time latency (ART test), the optimal AIC and BIC values for the 2-group candidates were for separation at 11 years of age (see model 3: group 1 = [6,11), group 2 = [11,18); AIC = 8.8, BIC = 13.8), with a significant difference between the two age groups ($p < 0.001$). When evaluating the 3-group candidate age groupings, the best separation was at 11 and 15 years; however, the difference between the middle and oldest age groups was not significant ($p = 0.76$). We interpret this to mean that the split into two groups produces significantly better age grouping than a split into three groups. However, it should be noted that these results reflect measurements taken on 40 children, spanning an age range of 11 years (7–17). It is possible that participation of more children would allow us to identify statistical differences in measurements across more frequent age split.

Table 8 summarizes the results for the best-fitting candidate age groupings for ten OVRT-C metrics. The results are reported for each year of age in terms of original measurement units. For example, in the case of the anti-saccade test, the table contains estimates of error probabilities for each year of age. According to division into 3 age groups, (two options were chosen), the probability of making an (pro-saccade) error for children aged 7–9 (80%) is slightly higher than for children aged 10–13 (70%), but almost twice as for children aged 14–17 (40%). The division into 2 groups seems more reasonable and is consistent with the findings in Table 7 (when compared according to BIC).

Additionally, Table 9 reports the effect of age on the test responses (calculated as the difference between the regression coefficients attributed to age group 1 and 2) based on a 2-division optimal model and the corresponding 95% confidence intervals (95% CI). For example, the mean auditory and visual reaction time (ART and VRT) latency in children under 11 and 10 years of age, respectively, is on average about 32% (95%

CI: 17% to 46%) and 36% (24% to 49%) lower than that of older children (see Table 9). The average gain in the optokinetic horizontal (OKN) 20°/s and 60°/s tests, respectively, is approximately 0.12 (95% CI: 0.01 to 0.24) and 0.16 (0.05 to 0.28) greater in children younger than 12 years. The chance of making an (pro-saccade) error (odds ratio) in children aged 7–13 is almost 4 times higher than in children aged 14–17 [exp(1.37) = 3.94].

In addition to the tests for which results are reported (figures and tables), we briefly discuss additional results for 9 test metrics below.

Area under the main sequence fit (AUF) in optokinetic horizontal (OKN) test with a velocity of 20°/s and 60°/s and AUF for horizontal and vertical saccade (SH and SV) tests. The area under fit in the optokinetic OKN and saccade horizontal and vertical tests do not indicate a difference between the different age groups. Visual inspection did not identify a clear trend in the measurements as a function of the children's age, and similarly, a statistical model did not find a significant difference in 17 models according to the split into 3 or 2. We note that, with a few exceptions, the OKN test results at both 20°/s and 60°/s consistently indicate that different measurements in the same child (for example, when the test results are presented separately for clockwise and counterclockwise) are within the normative limits (in the clinical sense). That is, even if there is a certain difference between the two measurements, the difference is not statistically significant and both measurements are within the normative limit. These results imply that with a high degree of certainty, two different measurements of the same child will be consistent, meaning that they will be placed at the normative limit (or non-normative in both measurements).

Eye constriction velocity in light reflex test. Like OKN, no clear trend can be identified in the eye constriction velocity with age in the light reflex test. There is no clear and explainable difference between different age groups.

Number of predicted saccades in predictive saccades test. In the predictive saccades test, although a certain increase with age in the number of predicted saccades can be seen, there is no uniform trend. Up to and including age 9 years, the prediction rate is low, around 30%, compared to ~ 50–60% for those aged 14 years and older. In the age range of 10–13 years, the results do not align with the results in the groups up to 9 years and older than 13 years, although they are closer to the group 13 years and older.

Outward time constant in vergence step test. In this test, the results are less clear than in *inward time constant*. Although there is a significant difference in the test results between children up to 11 years old and those older than 11, a closer look also reveals that the measurements within the age groups are far from similar (there is high volatility in the test results between children of similar ages).

Saccade horizontal and vertical accuracy. No clear trend can be identified in the accuracy metrics of the two tests.

Comparison between young people aged 14–17 and 18–19

For the five OVRT-C test metrics, Table 10 reports the mean and standard deviation of the responses, separately, for children aged 14–17 and young adults aged 18–19.

Results from the smooth pursuit tracking tests revealed differences between older children (i.e., aged 14–17) and young adults (ages 18–19) for both horizontal (SPH) and vertical (SPV) pursuit, with young adults exhibiting a lower percentage of saccadic intrusions than older children ($p = 0.025$ for both tests).

When saccades and visual reaction time are combined into a saccade and reaction time (SRT) test that requires combined saccadic and motor responses, the motor responses of older children were not significantly different than those of young adults ($p = 0.708$) and no differences in saccade latency were found between the two groups ($p = 0.157$). These findings for SRT are reflected in Table 5, which show that at around the age of 13–14 the motor responses and saccade latencies tend to stabilize.

The angular error from vertical axis of the subjective vertical visual (SVV) test was not significantly different between older children and young adults ($p = 0.857$). These findings are consistent with those in Table 5, which shows a stabilization in the test results around age 12.

We note that in a statistical analysis conducted by Kullmann et al. (2021a), there were no effects of age on the test metrics when the participant data were divided into pediatric (18–21 years, following FDA criteria) and adult (21–45 years) groups.

Discussion

Examining oculomotor functioning in tandem with vestibular abilities and reaction time tasks can provide vital information about a patient's brain health. However, there is a paucity of research in pediatrics, and existing studies are limited in the age ranges included and therefore accurate developmental trajectories can often not be determined. The current study aimed to test 7- to 17-year-old children using a protocol of OVRT-C tests to determine the feasibility of such testing, the age group divisions by which metrics fit best, and assess when the tested OVRT-C metrics become adult-like.

This study demonstrates that a protocol of 18 OVRT-C tests can be administered to 7- to 17-year-old children with all participants being able to complete the 15-min assessment. Most subjects found the goggles aesthetically pleasing, which is important for use in clinical settings, where children may be wary of unfamiliar testing equipment. Administering testing with medical devices that are child-friendly and/or appealing to children may improve motivation and cooperation on the part of subjects. Our subjects also reported that the goggles had a snug fit and light was not entering the goggles for most subjects, which is important for data validity. Notably, 65% of the children from the University of Miami Miller School of Medicine (UM MSOM) group found the goggles to be too heavy, while only 30% of the Alleghany Health Network group reported the same. This finding may be due to the mean age difference between the groups, with the UM MSOM group being younger. Nevertheless, all subjects were still able to complete the assessment without issue or complaint.

Overall, mean responses on all OVRT-C tests showed consistent improvement with increased age (see Tables 4 and 5). For smooth pursuit, the velocity saccade % refers to the amount of eye movement that is saccadic and not pursuit. Our data suggests this amount of saccadic intrusion decreases on average by 6.9% per year for horizontal smooth pursuit, and 7.5% per year for vertical smooth pursuit. While saccadic intrusions in children have not been widely studied, and to our knowledge have not been investigated in the context of smooth pursuit eye movements, their prevalence is high in children and adolescents during fixation and may reflect a less mature visual system (Salman et al. 2008).

To our knowledge, self-paced saccades have only been tested in children with mTBI, with the authors reporting no difference in the number of saccades between patients and age-matched controls (Phillipou et al. 2014). Our best-fitting model indicates that older children make more saccades than younger ones ($p < 0.001$ for 2 age groups, model 2). As the self-paced saccades task is an inherently volitional one requiring refined saccadic control, this result is consistent with what one would expect. Older children's mean number of saccades per second showed a trend of being slightly less than those of young adults, but this difference did not reach statistical significance, indicating that performance on this task becomes adultlike between the ages of 14 and 17.

Our reaction time data indicate that mean auditory and visual reaction time latency decrease over the developmental trajectory. This is consistent with previous research by Bucsuházy and Semela (2017), who demonstrated reductions in visual reaction time across age groups from 3–5 years of age to 15–18 years. Another study investigating visual and auditory RT in 11- to 18-year-olds reported the same pattern; additionally, although this study did not report statistical tests comparing VRT and ART, their graphs indicate a pattern of longer VRTs than ARTs, which is consistent with our findings (Pancar et al. 2016). In the saccade and reaction time (SRT) task, which requires a pro-saccade towards a target combined with a manual button push indicating the target side, we observed a slower motor response latency for older children compared to young adults, but no differences for saccadic latency between the two groups. It is possible that this result reflects subjects prioritizing eye movements over their motor responses.

Differences across age groups were also observed in the anti-saccade task, which requires participants to inhibit a reflexive saccade. Previous research reports that children under the age of 10 have an error rate of approximately 60% (Fischer et al. 1997). Our data demonstrates that children under 14 have an error rate of 70–80%, while those 14–17 have an error rate of 34.8%. Crucially, the 14–17-year-olds in our sample made more errors than young adults, which may reflect the longer development of prefrontal control over inhibitory processes. However, our percent errors findings are higher than those of another study, which found error rates of 41.1%, 15.6%, and 7.5% in 6–7-year-olds, 10–11 year-olds, and 18–26 year-olds, respectively (Klein and Foerster 2001). This difference in results may be due to differences in methodology, such as the aforementioned study including both gap and overlap trials and their subjects performing substantially more antisaccade trials than our participants (i.e., 16 vs 100), which may induce a practice effect that is reflected in fewer errors overall.

For the 14 reported OVRT-C metrics, our data support a separation into two age groups as opposed to three. This is evident because even for the best-fitting three age group splitting, the mean results of the two older groups were not significantly different (see Table 7). Critically, however, the ages at which the optimal models indicate age groups should be separated varies considerably by OVRT-C test. For example, while our results for metrics Saccade + Reaction Time (SRT; motor response, latency means) and Self-Paced Saccades (SPS; velocity intercept) were optimally split into two age groups of [7,9) and [9,18), the optimal two-group age split for other metrics was older, with the oldest optimal split for anti-saccades, which was between [7,14) and [14,18). These results are not surprising, given that more basic/primitive, bottom-up oculomotor systems tend to mature at a faster rate than those that require more advanced frontal-based cognitive function and control, such as the antisaccade and self-paced saccades tasks. At the very least, these data suggest that OVRT-C abilities mature at differing rates, which is expected; however, the preference for two age groups rather than three may reflect a slowing of rapid development as these abilities become closer to adult-like.

While beyond the scope of the present study, future investigations may aim to incorporate more subjects so that groups can be separated by precise ages to more accurately elucidate the developmental trajectory of each OVRT-C metric.

Clinical implications

These data highlight the feasibility of constructing a pediatric database of OVRT-C metrics, a crucial first step in examining brain function in children. In order to be effective, normative data requires a larger sample size than the sample used in this study, in particular for the device to be cleared by the FDA. Previous research in our adult sample consisted of 300 healthy participants which made for a robust normative sample (Kullmann et al. 2021b). Future directions for our team are to build upon this database to create normed reference values across age and gender. Once normative data is established, there are endless research and clinical applications. For example, despite the higher prevalence of mTBI in children and adolescents, most research on mTBI has been conducted in adults. While research has primarily focused on objective measures for adults, the currently available measures remain inadequate for diagnosing mTBI. Specifically, most of the measures lack sensitivity and specificity, require a baseline assessment before the time of injury, or are self-report and therefore may not represent true symptomology or deficits. Objective measures of mTBI diagnosis are important as returning to school/play too early can result in significant negative outcomes (e.g., poor school performance, second impact injury). A pediatric OVRT-C database will aid in the objective diagnosis of pediatric mTBI in a non-invasive, non-biased, efficient manner. Furthermore, diagnosis of other childhood neurological conditions (e.g., autism) can involve extensive testing and are largely based on parent reports and standardized assessments that include observation. OVRT-C assessments may enable more accurate and efficient diagnosis of childhood neurological conditions. Moreover, longitudinal analysis of OVRT-C functioning can illuminate trajectories of disease progression and may provide critical data which can be used to develop interventions and improve treatment management.

Conclusions

This study is the first to examine OVRT-C functioning in a wide age range of children simultaneously. Results demonstrate distinct patterns of metrics according to age groups. These data are important in developing a larger normative pediatric OVRT-C database which can then be used in research and clinical settings to examine overall brain health and functioning in children. Moreover, examining developmental trajectories of OVRT-C functioning can further in-depth study of neurological conditions as well as contribute to the development of treatment interventions.

Data availability All data collected for this study will be made available upon request.

Declarations

Conflict of interest Authors AK, LCG, RCA, and AB are employees of Spryson America Inc. Authors AK and RCA are financial stakeholders in Spryson America Inc. All other authors have no conflicts of interest to report.

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