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CHANGES IN HORIZONTAL SACCADES WITH AGE

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Previous studies have demonstrated that saccadic eye movements are slow and imprecise in infants; however, by age 7, they are close to the adult levels. Saccadic eye movement efficiency peaks in adolescence, and after age 50, peak velocity and accuracy begin to decline due to age-related changes in the brain. Different studies have demonstrated the age effect on the reflexive and antisaccade task performance, e.g., a decrease in latency and peak velocity scores with age. The current study aims to explore age-related changes in saccadic eye movement latency, peak velocity, and accuracy in reflexive and antisaccade tasks in school-age children. Saccadic eye movement targets for antisaccade and reflexive saccade tasks were presented at one spatial position. Eye movements were recorded with a Tobii Pro Fusion video-oculograph to analyse peak velocity, latency, and accuracy (120 Hz). The results demonstrate a significant age effect only on the peak velocity measurements in the antisaccade task, i.e., a decrease in the peak velocity with age was observed only for the antisaccades directed to the right. No significant age effect on the latency and accuracy measurements in both antisaccade and reflexive saccade tasks was observed. The obtained results demonstrate that there are no age-related effects on the parameters of rightward directed reflexive saccades (latency, peak velocity, and accuracy) and antisaccades (latency and accuracy).

Keywords: *Age, antisaccades, saccadic eye movements, saccadic eye movement parameters, reflexive saccades.*

1. INTRODUCTION

The primary function of saccadic eye movements is to reposition the images of objects from the peripheral and parafoveal areas to the central area of the retina, known as the fovea. The foveal region, which spans the central 2° of the visual angle around the fixation point, enables high visual acuity and the recognition of fine details in objects. The parafoveal region extends approximately 5° of visual angle in each direction from the fixation point, and the peripheral region encompasses everything beyond the parafoveal area, where visual acuity is reduced, impeding fine detail recognition [1].

The saccadic eye movement system provides gaze transfer and continuous information acquisition, therefore learning about the processes of the surrounding world. Saccades are driven by two streams of information, i.e., bottom-up, which ensures stimulus-driven saccades, and top-down, which ensures saccades driven by internal factors. Both of these information streams are essential for saccadic generation and often operate simultaneously. Task and stimulus properties are combined to determine the plan for the next saccade, taking into account the importance assigned to the information and its relevance to the task [2].

Saccadic eye movement analysis provides an objective insight into human perceptual processes, motor skills, and cognitive functions. Considering that the saccadic eye movement system plays an essential role in the process of reading, sports and other everyday activities, eye tracking can be applied in developmental studies to understand the role of age in the saccadic eye movement performance [3]–[5]. The good news is that that studies involving eye movement analysis are not limited to adult participants, but eye tracking is also extensively applied in children and infant studies [6]. However, in the later cases, we have to take into account that the oculomotor system stabilises during the first years of life, which is a significant factor when designing an experiment involving eye tracking in children [7].

Several studies have previously explored the age effect on various saccadic eye movement parameters. Longer saccadic reaction times to peripheral visual targets have been observed in children comparing to adults. Likely related to reduced control of peripheral visual information in children, leading to difficulties in perceiving important object details, and therefore affecting the reaction times of saccadic eye movements [8]. Infants younger than 42 months make more hypometric saccades compared to older children, and by the age of 8, children's accuracy improves [9]. Yang & Kapoula (2003) concluded that saccadic amplitude in 4–12-year-old children was relatively similar to that in adults [10], and Helo et al. (2014) demonstrated an increase in the average saccade amplitude with age, reaching an average saccade length comparable to that of adults by the age of 6 [11].

On the contrary, Aring et al. (2007) reported an increase in fixation duration between the ages of 4 and 15, indicating that the ability to maintain attention and control reflexive saccades develops from childhood through the adolescence [12]. Helo et al. (2014) indicated that children with slower saccadic eye movement programming and lower cognitive resources may exhibit longer fixation times before making the next saccade, resulting in insufficient time to process visual information [11]. Fukushima et al. (2000) explored the saccadic eye movement parameters of children and adults in non-reading tasks by examining the peak velocity and latency of reflexive and anti-saccades. The results indicated a decrease of saccadic reaction time with increasing age. Regarding the amplitude in the anti-saccade task, the study found no significant differences between the saccadic eye movement amplitude of children and adults. Therefore, it concluded that only the latency and peak velocity of anti-saccades decreased with age [3]. Yep et al. (2022) studied participants ranging in age from 5 to 93 years to evaluate saccadic eye movement performance. The study found that children aged 5 years and older exhibited longer saccade reaction times and a higher rate of directional errors in anti-saccade tasks. However, performance improves with age, with significant advancements observed during childhood and adolescence, peaking between the ages of 12 and 15 years. Optimal performance is achieved between the ages of 18 and 25, characterised by consistently short reaction times and low directional error rates in anti-saccade tasks. As adults continue to age, there is a gradual decline in the performance of saccadic eye movements, marked by increased reaction times and a higher frequency of directional errors in anti-saccade tasks [13].

Mazumrad et al. (2019) found that age influenced saccadic reaction time, i.e., the reaction time increased with age [5]. Similarly, Irving et al. (2006) found age-dependent dynamics of horizontal saccades, including the saccadic reaction time, accuracy, and peak velocity, each of which followed a specific age-related trajectory associated with brain structures [4]. Saccades showed fast responses and high velocity in childhood and early adolescence, stabilising in middle age, after which all parameters decreased significantly. It is clear that the saccadic eye movement system rapidly develops during the first years of life, but the question arises: At what age does the saccadic performance stabilise? Is it the age of 6–8 years when children start going to school or is it early adolescence? Currently, there is no consensus on which parameters of saccadic eye movements change with age and which have already stabilised in primary school age. Therefore, the aim of the current study is to evaluate the changes in accuracy, latency, and peak velocity of reflexive and anti-saccades with age in school-aged children (7–12 years old).

2. EXPERIMENTAL

2.1. Participants

295 children between the ages of 7 and 12 (9.3 ± 1.7 years) – 140 boys and 155 girls – from four Latvian primary schools voluntarily participated in the study. All participants underwent a general assessment of visual functions, and only the participants who had near visual acuity (65 cm) of at least 0.4 decimal units, uncorrected or corrected with contact lenses were enrolled in the subsequent study. None of the children were reported to have any eye diseases or other functional disorders that could affect eye movement parameters.

The study was carried out in accordance with the requirements of the Declaration of Helsinki. The study was approved by the Life and Medical Sciences Research Ethics Commission of the University of Latvia (13 June 2022). All participants participated in the study on a voluntary basis, which was confirmed by the written consent of the child's parents or legal guardians. Participants were informed about the progress of the study, the equipment applied, and their responsibilities and rights throughout the study.

2.2. Stimuli

Visual stimuli were designed in Microsoft PowerPoint for consistency and clarity. The shape and size of the stimulus were either a circle or a star of 0.72°. Given that the reflexive and anti-saccade tasks were consecutive and had a similar stimulus arrangement, it was decided to present different stimulus for each task to reduce the cognitive load caused by confounding instructions – a circle shaped object in the reflexive saccade task and a star shaped object in the anti-saccade task (see Fig. 1). The target for saccadic eye movements was located to the right at a distance of 14.04° from the initial fixation object. A light grey background 90 cd/m2; RGB (179, 179, 179) was chosen to present the stimuli, which had been shown in previous studies to be suitable for the analysis of saccadic eye movements [14]. The luminance level of fixation stimuli and stimuli was 5 cd/m2 and RGB (0,0,0), with a corresponding contrast level of -0.94.

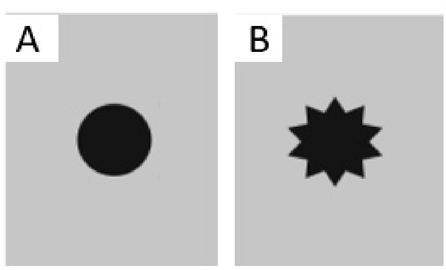

Fig. 1. Saccadic eye movement stimulus for analysis of reflexive saccades (A) and antisaccades (B).

The experiment started with assessing uncorrected or contact lens-corrected near visual acuity and eye dominance (Dolman test). Participants were positioned at a distance of 65 cm from the screen, head position was fixed using a chin and forehead rest, and the height of the chair was adjusted so that the visual stimuli were at the level of the participant's eyes. The participants were instructed to keep their heads as still as possible and to change their gaze only with their eyes. Before the experiment, all participants underwent eye movement recording device calibration, demonstrating 5 points in the calibration phase and 4 points in the validation phase. The calibration was considered accurate if the validation results did not exceed 0.5°. If the calibration results did not meet such requirements, then the calibration and validation were repeated. The calibration and validation stimulus and background color settings were identical to the experimental settings.

Participants were given two tasks: (1) reflexive and (2) anti-saccade tasks. The task consisted of horizontal saccadic eye movement stimuli presented on a computer screen in a fixed order. In the reflexive saccade task, participants were presented with a fixation stimulus in the centre of the screen for 3 s, then presented with a saccadic eye movement stimulus on the screen toward the right from the initial position of the fixation stimulus. Participants were instructed to shift their gaze (make a saccade) from to the peripheral stimulus in horizontal direction as soon as the stimulus appeared. After saccade stimulus disappeared, the participants were asked to look back at the fixation stimulus located at the centre of the screen – the arrow indicated the direction to which the saccade should be performed (see Fig. 2).

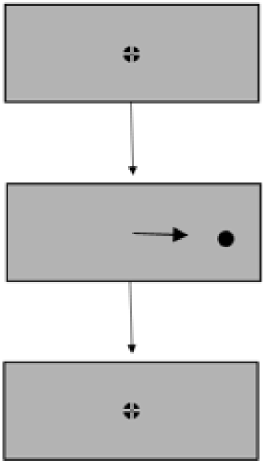

Fig. 2. Reflexive saccade task.

In the anti-saccade task, the participant was instructed to make a gaze transfer (anti-saccade) in the opposite direction, but with the same amplitude as the distance of the presented stimulus, when a saccade stimulus appeared. First, the participant was presented with a fixation stimulus (3s) followed by the anti-saccade stimulus appearing to the left from the fixation cross. The participants were instructed to make a saccade in the opposite direction (to the right) as soon as the stimulus appeared. After saccade stimulus disappeared, the participant was instructed to return their gaze at the centre of the screen where the fixation stimulus appeared - the arrow indicated the direction to which the saccade should be performed (see Fig. 3).

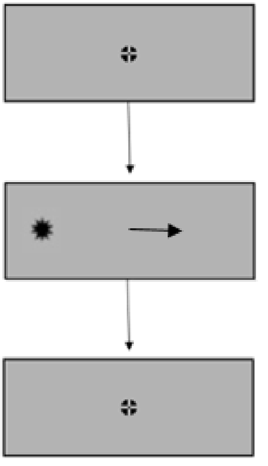

Fig. 3. Antisaccade task.

2.3. Data Analysis

Saccadic eye movements were recorded with Tobii Pro Fusion (120 Hz) eye tracking device (Tobii, Sweden). Tobii Pro Fusion determines the direction of a person's gaze on a computer screen based on the analysis of the eye image obtained with infrared light sources and the eye camera. All measurements were performed in the dark pupil illumination mode. A DELL P2419H 23.8 computer screen measuring (1920 x 1080 pixels), 51.9 x 32.5 cm was applied for stimulus presentation.

Data analysis was performed by Tobii Pro Eye Tracker Manager and Tobii Pro Lab, working in accordance with the eye movement recording device. Event detection was performed by applying Tobii I-VT and ClearView filters [14]. The I-VT filter identifies fixations and saccades based on the distance and velocity between two succeeding coordinates in the raw gaze data. If the gaze direction coordinates of two adjacent data records are relatively close, this indicates that the velocity of the eye movements is small, which in turn indicates that the small eye movement is part of the fixation. Otherwise (if the peak velocity of eye movements exceeds the specified threshold), a saccade is detected. A single-parameter I-VT filter with a peak velocity threshold of 30°/s was applied to distinguish between saccades and fixations.

To obtain information on the first saccade conducted towards the target object, the Tobii Pro Lab function for AOI (Area of Interest) analysis was applied. The shape and size of the AOI was a 1.48° square. The region of interest (an area invisible to the observer for data analysis) was placed in the centre of the screen, where the fixation stimulus was located before demonstrating the saccadic eye movement stimulus. In order to obtain the necessary parameters of saccadic eye movements towards the target object, two main indicators were determined: time to exit saccade – a saccade conducted away from the area of interest (right after the appearance of the saccadic eye movement stimulus) and peak velocity of the exit saccade. Only monocular data for the dominant eye were used in the data analysis (see Fig. 4).

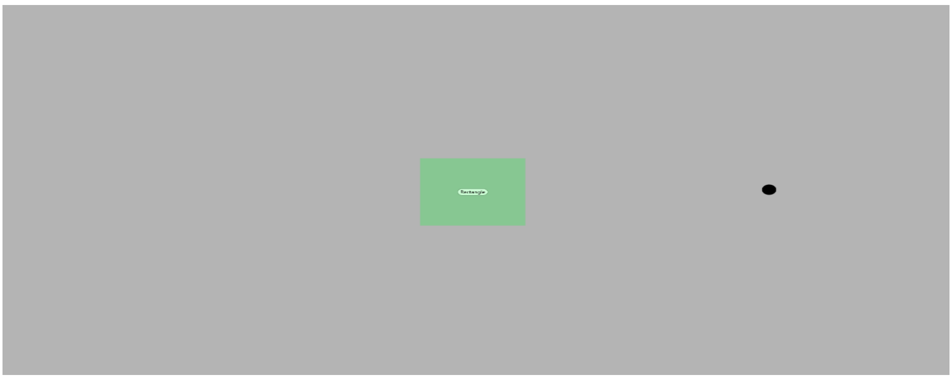

Fig. 4. AOI (Area of interest) applied to determine the exit saccade towards the stimulus.

Saccade latency and peak velocity were obtained from Tobii Pro Lab metric data, and the amplitude of saccadic eye movements was calculated based on the raw gaze direction data. In this case, the data export function was applied, which contained data on the gaze direction of the right and left eyes on the computer screen in x and y coordinates (gaze point left/right x and y) every 8.3 ms [14].

The final data analysis included 295 children between the ages of 7 and 12 – antisaccades were recorded for 227 children, and reflexive saccades were recorded for 229 children with the Tobii Pro Fusion device. The Microsoft Excel software program was applied in data processing.

To determine saccadic eye movement accuracy, only the first saccade towards the target was selected. The accuracy was calculated based on the actual distance of the target and the amplitude of the performed saccadic eye movement. The amplitude of saccadic eye movements was determined in Microsoft Excel using Eq. (1):

$$\text{Amplitude} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}\,, \tag{1}$$

where $x1, x2$ – horizontal coordinates of eye fixation before (x_1) and after (x_2) the saccade (px); $y1, y2$ – vertical coordinates of eye fixation before (y_1) and after (y_2) the saccade (px).

The accuracy was calculated by Eq. (2):

$$\text{Accuracy} = 1 - \frac{S_e}{T_e}\,, \tag{2}$$

where S_e – landing error (cm);
T_e – distance between fixation position and target position (cm).

Landing error, or Se, is described as the vector size between the coordinates of the gaze direction after the saccade ($\vec{b}$ – amplitude of saccadic eye movements) and the actual target of eye movements ($\vec{a}$ – real target distance of saccadic eye movements). This means that the magnitude of the landing error depends on the location of the saccade target, including its direction and distance. Equation (3) was based on the Euclidean distance and was applied to calculate the landing error:

$$S_e = \sqrt{(a-b)^2}, \tag{3}$$

where a – the actual target distance of the saccades (px);
b – amplitude of saccadic eye movements (px).

To compare the parameters of saccadic eye movements in children, statistical analysis was performed with the SPSS program. For the data analysis, linear regression was used, with the age being the independent factor, and peak velocity and latency were referred as the dependent factors.

3. RESULTS

3.1. Reflexive Saccades Depending on Age

Latency of Reflexive Saccades

To determine changes in the latency of saccadic eye movements with age, a linear regression analysis was performed for rightward saccades. The results of linear regression did not indicate a significant age effect on the saccadic latency measurements (F(1;227) = 0.719, p = 0.397). A relatively large data dispersion of R = 0.056 was also observed (see Fig. 5).

Fig. 5. Simple linear regression analysis on the changes in saccadic eye movement latency measurements with age (n=229).

Peak Velocity of Reflexive Saccades

The results of linear regression did not indicate a significant age effect on the saccadic peak velocity measurements (F(1;227) = 1.028, p = 0.312). A relatively large data dispersion of R = 0.067 was observed (see Fig. 6).

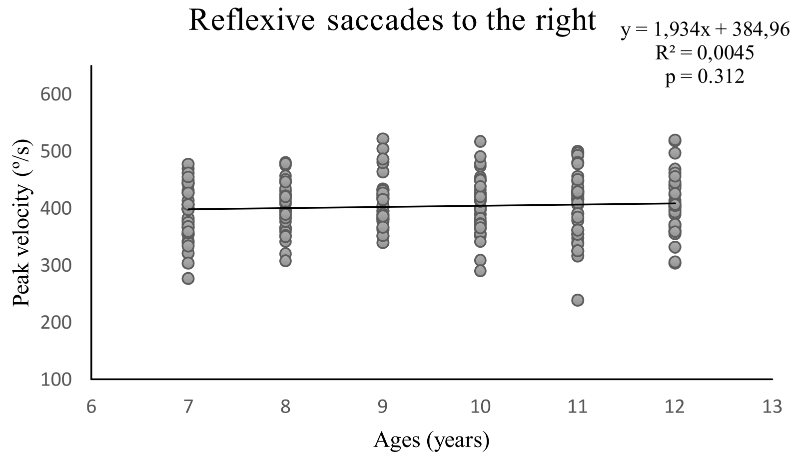

Fig. 6. Simple linear regression analysis on the changes in saccadic eye movement peak velocity measurements with age (n=229).

Accuracy of Reflexive Saccades

To determine changes in the accuracy of saccadic eye movements with age, a linear regression analysis was performed for rightward saccades. The results of linear regression did not indicate a significant age effect on the saccadic accuracy measurements (F(1;227) = 0.025, p = 0.875). A relatively large data dispersion of R = 0.010 was observed (see Fig. 7).

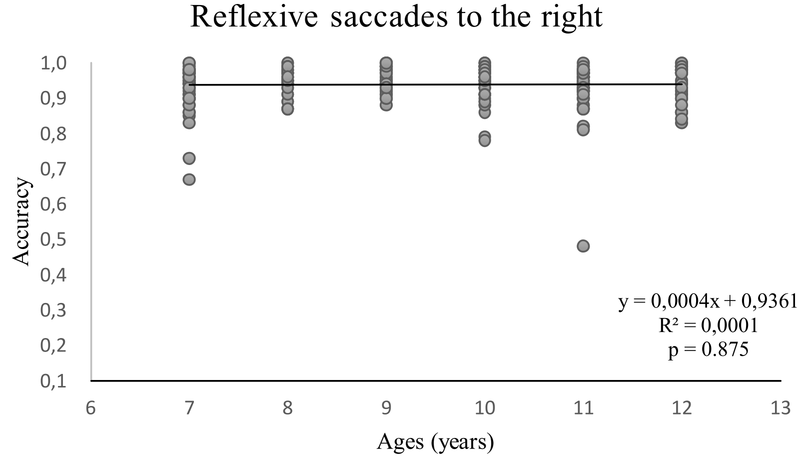

Fig. 7. Simple linear regression analysis on the changes in saccadic eye movement accuracy measurements with age (n=229).

3.2. Antisaccades Depending on Age

Antisaccade Latency

The results of linear regression did not indicate a significant age effect on the saccadic latency measurements ($F(1;225) = 2.294$, $p = 0.131$). A relatively large data dispersion of $R = 0.100$ was observed (see Fig. 8).

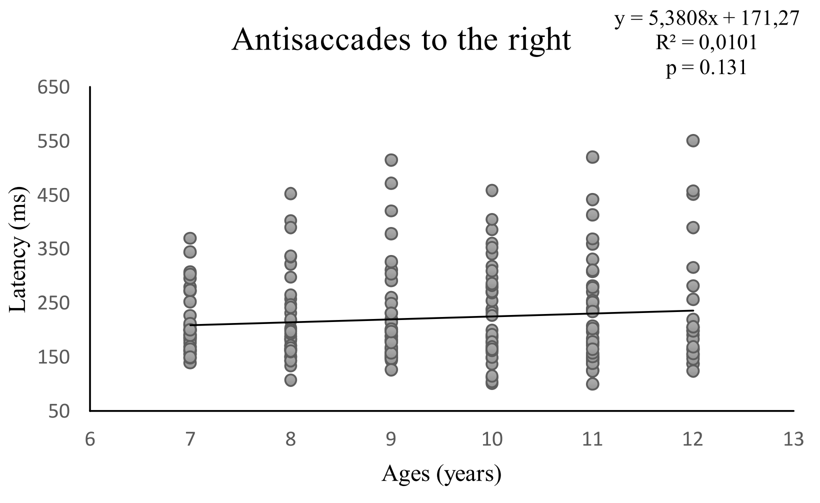

Fig. 8. Simple linear regression analysis on the changes in saccadic eye movement latency measurements with age (n=227).

Peak Velocity of Antisaccades

The results of linear regression indicated a significant age effect on the saccadic peak velocity measurements ($F(1;225) = 5.151$, $p = 0.024$). A relatively large data dispersion of $R = 0.150$ was observed (see Fig. 9).

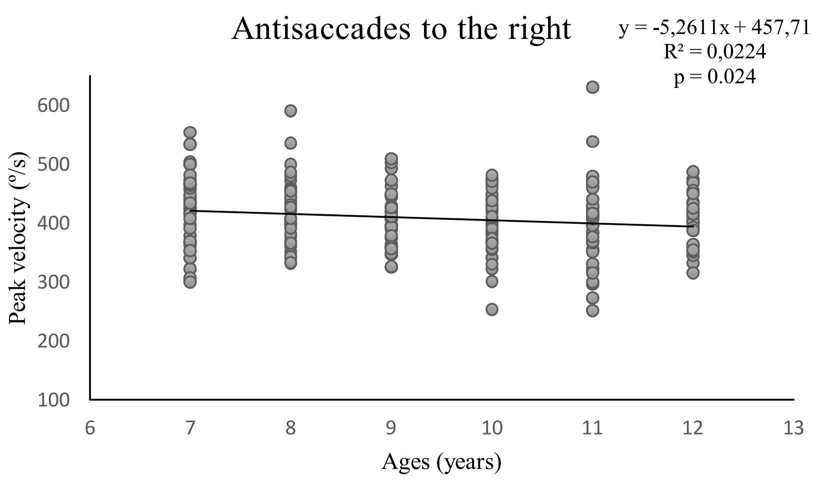

Fig. 9. Simple linear regression analysis on the changes in saccadic eye movement peak velocity measurements with age (n=227).

Antisaccade Accuracy

Finally, the results of linear regression did not indicate a significant age effect on the saccadic accuracy measurements (F(1;225) = 3.464, p = 0.064). A relatively large data dispersion of $R = 0.123$ was observed (see Fig. 10).

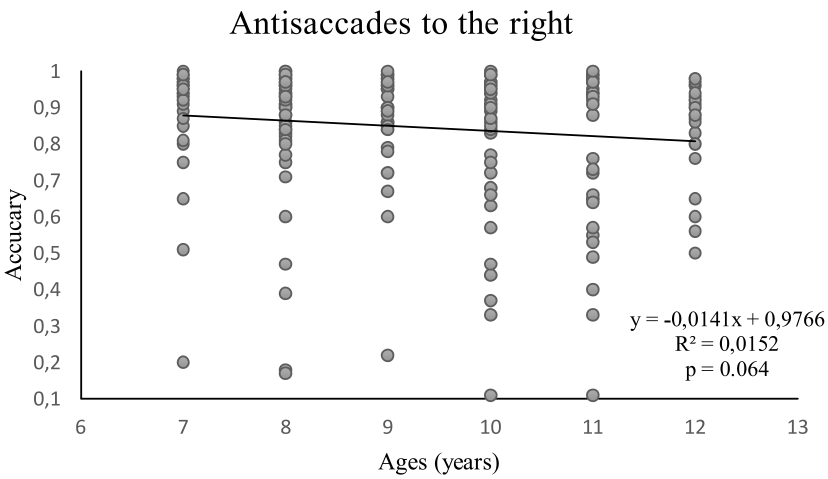

Fig. 10. Simple linear regression analysis on the changes in saccadic eye movement accuracy measurements with age (n=227).

The summary for age effect on different reflexive and anti-saccade parameters are presented in Table 1. The summary includes the p-value and the coefficient of determination of the linear regression analysis (see Table 1).

Table 1. Linear Regression Analysis on the Age Effect on the Saccadic Eye Movement Parameters

	Reflexive saccades		Anti-saccades	
	p	R^2	*p*	R^2
Latency	0.397	0.0032	0.131	0.0101
Peak Velocity	0.312	0.0045	0.024	0.0224
Accuracy	0.875	0.0001	0.064	0.0152

4. DISCUSSION

The current study has explored the age effect on the reflexive and anti-saccade latency, peak velocity, and accuracy parameters. The results have indicated that none of the reflexive saccade parameters (latency, peak velocity, or accuracy) significantly change from ages 7 to 12. Only a significant decrease in the peak velocity of the antisaccades has been observed from ages 7–12 years.

Bucci & Seassau (2012) evaluated the relationship between reflexive saccade performance and spatial working memory in children aged 6 to 15 years, thus analysing the development of eye movement control and its relationship with other cognitive functions. The results indicated that as the child's age increased, a decrease in saccade latency could be observed in all types of saccade tasks. Latency of horizontally directed saccades stabilises around the age of 12 when reaching the adult levels. Bucci & Seassau (2012) argued that up to the age of 12 years an active maturation processes of neural pathways could be observed, leading to an improvement in the coordination of visual and motor signals and the improvement of cognitive functions, such as attention and working memory [15]. Irving et al. (2006) investigated the age effect on saccadic eye movement parameters. The results indicated that during the lifespan three main latency related changes could be observed: rapid development was observed in childhood and early adolescence, then relatively stable indicators between the ages of 10 and 50 years, after which an increase in latency was observed, which might be related to biological changes in the cerebral cortex [4]. The results by [16] indicated that the stabilisation of saccadic eye movements was observed around the age of 14–15 years after which the saccadic eye movement parameters remained relatively stable until adulthood.

While the results by [17] also indicated a significant age effect on the saccadic latency indicators, the reported changes were only about 1.83 milliseconds per year, which, as pointed out, were not clinically significant. The results of the current study only partially align with the results by [18] and are opposite to the results demonstrated by [15] and [16], indicating that there are no significant changes either in the reflexive, or the anti-saccade latencies with age.

Irving et al. (2006) evaluated the age effect on the dynamics of horizontally directed reflexive saccades. The results demonstrated that peak saccade velocity rates changed with age – peak saccade velocity increased during childhood, reaching a peak around 10–15 years of age, and then a gradual decrease in peak velocity was observed [4]. The current study demonstrates a discrepancy with the results by [4]; however, the results are, to a certain extent, similar to the results obtained by [17] indicating that no changes in the reflexive saccades peak velocity are found as the child's age increases, and the stabilisation of the peak velocity of saccadic eye movements can be observed already at primary school age. The current study demonstrates similarities with the results obtained by [18] indicating that the peak velocity of the horizontally directed saccades is not related to age. Changes in peak velocity with age reflect a complex interplay between brain development and aging that affects saccade speed as brain structures develop and age, particularly the frontal lobe, which controls volitional oculomotor functions.

The results by [7] indicated an age effect on the horizontally directed saccade accuracy, meaning that as age and saccade size increased, participants between the ages of 3 and 86 years made increasingly hypometric saccades during their lifetime. The results of the current study indicate that reflexive saccadic eye movement accuracy does not change significantly within the ages of 7–12 years, which is inconsistent with the results by [15] demonstrating an increase in accuracy in precisely the same study groups as in the current study. However, the results of the current study are similar to the ones demonstrated by [19], indicating that age does not affect the accuracy of saccades. Fioravanti et al. (1995) evaluated binocular saccades in children aged 5–13 years to investigate changes in coordination and growth. The results showed that in young adults, hypometria was found to be 10 %, but in children from 5 to 15 years of age, the accuracy depended on the size of the step, i.e., in cases of irrelevant deviations, children more often performed overshooting saccades, which was more pronounced in younger children [20].

The observed differences with other studies could be related to different methodologies adapted in this and other studies – eye movement recording device and its parameters, number of participants, tasks, stimuli, etc. Leube & Rifai (2017) demonstrated that eye tracking devices with an operating frequency of 60 Hz showed a reduced saccade detection accuracy, while devices with an operating frequency of at least 120 Hz revealed a more accurate detection of saccades and fixations, based on the saccade speed detection algorithm [21]. The current study applied Tobii Pro Fusion (120 Hz) eye movement recorder similar to [4] applying a similar binocular video-based eye tracker with the sampling frequency of 120 Hz. The study by [17] used an infrared video-oculography device (220 Hz). Therefore, the difference in the sampling frequency could not be the reason why different results were obtained. Therefore, it can be concluded that the different results obtained in different studies are probably related to other methodological issues.

Possible differences with the results obtained in other studies may also be related to the number of participants and the selected range of different age groups. In the study by [4], 195 children (aged from 3 to 86 years) were engaged as a whole, [20] evaluated binocular saccades in 12 children aged 5–13 years, [15] had 72 children (aged from 6 to 15 years) participating in the study, and the study by [17] involved 100 children (aged from 6 to 76 years). The current study evaluated binocular saccades in 295 children between the ages of 7 and 12. This means that age groups may influence statistical results due to cognitive and developmental changes: younger participants show greater developmental variability, while older participants show declines due to age-related changes. This may lead to a shift in mean scores and a decrease in variance. In addition, an age range that is too narrow or too wide may distort the overall conclusions of the study.

Although the task was to perform saccades in the horizontal direction, the stimulus size, stimulus colour, and stimulus distance could influence the statistical results. The study [4] used a white dot on a black background that appeared randomly without pauses or overlaps between stimuli, which induced saccades of varying sizes from 1° to 60° in the horizontal direction at two different distances of 1 and 2 metres. While [17] applied a target which appeared in four directions with variable target offsets (5°, 15°, 30° horizontally). The current study had a fixed stimulus size, a fixed stimulus distance, and the stimulus colour was black, but the difference was in the shape of the stimulus, since a star was used for antisaccades and a circle for reflexive saccades. This means that colour affects contrast and visibility, changing the velocity and accuracy of the response. The shape of the stimulus can speed up or slow down identification depending on the complexity. Distance affects the amplitude and accuracy of movements, increasing the number of errors as it increases.

5. CONCLUSION

The results of the study do not demonstrate changes in saccadic eye movements as the child's age increases, but raise various methodological issues that should be taken into account when developing a study on the parameters of saccadic eye movements. The results obtained in the present study indicate that an age-related decrease in the peak velocity of the antisaccades is observed only when the saccadic eye movement stimulus is demonstrated in the rightward spatial position. The rest of reflexive and antisaccades parameters demonstrated no significant age-related changes. There is also an asymmetry in peak velocity and accuracy scores comparing reflexive saccades and antisaccades to the right. Consequently, future studies should take into account that if the stimuli are presented in a horizontal direction, the performance of saccadic eye movements may differ, depending on the tested saccade parameter.

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