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Dynamics of Visuomotor Functions in the Aging Process: Analysis of Visual Path Speed

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SUMMARY

This study investigates age-related changes in visuomotor functions by analyzing gaze path velocity (pixels per second). The research included 50 participants aged 7 to 83 years, divided into four groups: children (7–14 years), young adults (19–39 years), middle-aged adults (45–58 years), and older adults (62–83 years). Eye movements were tracked during a visual scanning task. Statistical analyses, including one-way ANOVA, post-hoc Tukey HSD tests, and effect size calculations (η^2), evaluated group differences.

Significant differences in gaze path velocity were found across groups. Children had an average velocity of 150.44 px/s, serving as a baseline. Young adults showed a substantial increase (365.97 px/s), and middle-aged adults reached the highest velocities (423.48 px/s), indicating peak visuomotor function. Older adults demonstrated a decline (256.15 px/s), reflecting age-related neuroplasticity reductions.

A nonlinear trajectory, modeled by a second-degree polynomial equation ($R^2 = 0.89$), peaked at age 46.3 years (V_{max} = 406.03 px/s). This pattern reflects rapid growth in childhood, stabilization in middle age, and decline in later life.

The findings underscore the importance of age-specific interventions, optimized user interfaces, and neurodegenerative diagnostics. Future studies should expand on sample size and consider health and lifestyle factors to enhance understanding of visuomotor variability.

Key words: age-related differences, visual perception tests, eye-tracking, oculometric parameters, aging

1. Introduction

The velocity of the gaze path has become a key indicator in studies on visual perception and eye movements (Duchowski, 2007). "Gaze path velocity" refers to the speed of eye movements along the visual path during a visual task. This parameter, expressed in pixels per second, integrates dynamic aspects of visuomotor functions. It allows for the assessment of changes in oculomotor mobility across different age groups, making it a central element of this study. Although this term is not widely used in the literature, its application in the present study highlights its innovative nature and opens new possibilities for analysis in the context of oculomotor research.

According to Holmqvist et al. (2011), analysing the dynamics of eye movements offers profound insight into cognitive processes during various visual tasks. Research into eye movements dates back to the late 19th century, when scientists began pondering how human eyes move during reading and other visual tasks. Emile Javal (1879) was a pioneer in studying eye movements during reading. He noticed that the eyes do not move smoothly along a line of text but make jumps (saccades) and brief stops (fixations) (Javal, 1879).

The renowned psychologist Titchener (1901), who also studied eye movements, focused on how people process images and text. His work was significant for the early development of experimental psychology. He first observed how people concentrate on a fixation point. His research revealed that the pattern of eye movements is closely related to the task a person performs when looking at an image (Titchener, 1901; Yarbus, 1967).

Today, eye movement research has become more advanced thanks to eye-tracking technology. Holmqvist and his team have published comprehensive manuals on eye-tracking methodology, which have become standard in the field (Rayner, 1998). Keith Rayner, one of the leading researchers in the field of reading speed and eye-tracking analysis, made invaluable contributions to the field. In the context of this work, Rayner's analysis provides tools and methodologies that can assist in understanding how people process visual information (Rayner, 2009; Rayner et al., 2006; Rayner & Pollatsek, 1989; Rayner et al., 2011; Salthouse, 2010).

As the years pass, the human body undergoes numerous changes that impact various aspects of functioning, including visual and visuomotor abilities.

Salthouse (2010) observed that aging leads to a decline in cognitive abilities, which are crucial for many aspects of visual functioning (Rayner et al., 2006). Research by Rayner et al. (2006) indicates that age affects the way people process text while reading, with younger and older readers differing in their responses to factors such as word frequency, predictability, and font readability.

Hasher and Zacks (1988) reviewed changes in working memory function and text comprehension in the context of aging, demonstrating that the ability to suppress irrelevant information (inhibition) is a key mechanism affected by the aging process. Stine-Morrow et al. (2006) further explored age differences in the self-regulation of sentence processing, noting that reading goals and intentions influence text processing differently depending on the reader's age.

However, visual functions are not the only aspects impacted by aging. Owsley (2011) provides a comprehensive review of the overall impact of aging on visual functions, emphasizing the complexity of this process and the numerous factors influencing visual perception. Age-related changes extend beyond visual functions, as Seidler et al. (2010) highlighted significant effects of aging on motor control, demonstrating that aging is associated with changes in brain structure, function, and biochemistry, which collectively impact the ability to perform complex movements.

Analysing the relationship between age and the path of gaze requires the examination of changes occurring in both the brain and the visual system. Baltes and Lindenberger (1997) highlight that aging is a multifaceted process that affects numerous aspects of brain function, including those responsible for processing visual information. Similarly, Sailer et al. (2000) emphasize that visual functions, such as the ability to track moving objects and the speed of processing visual information, significantly decline with age.

Recent research has shown that younger age groups exhibit greater fluidity and precision in eye movements. In contrast, older groups display an increased number of saccades and longer fixation times, indicating difficulties in visual processing (Owsley, 2009). Furthermore, eye-tracking analyses reveal that older individuals require more time to focus and process visual information (Rayner et al., 2006).

A study conducted by Błasiak et al. (2019) examined differences in visual perception among individuals aged 7 to 83 years. The researchers performed two distinct visual perception tests on a sample of 44 participants. Their results demonstrated biometric stability in the subjects' eyes, particularly regarding fixation times and saccade velocities (Błasiak et al., 2019).

The differences between the youngest and oldest age groups become even more pronounced when comparing complex visuomotor tasks, such as reading text at varying speeds or recognizing rapidly changing images. In these situations, the youngest groups demonstrate greater adaptability and speed of processing, while significant delays are observed in older individuals (Stine-Morrow et al., 2006).

Czaja and Lee (2007) conducted research analyzing the impact of various factors on gaze path speed, including individual variability, lifestyle influences, and health status.

Visual processing and eye movements are significant mechanisms through which people receive and interpret visual stimuli. Understanding these processes is fundamentally important for a variety of fields – from neurology to user interface design. Research indicates that perceptual and motor abilities change as humans age, which can affect daily interactions with the visual environment (Czaja & Lee, 2007; Ball et al., 1988; Owsley, 2011; Salthouse, 1991; Scialfa et al., 1987).

In this work, the change in gaze path velocity, one of the key indicators of eye movement efficiency, was investigated with respect to age. Using eye-tracking methodology, studies were conducted on age groups ranging from children to older individuals, allowing for a comparison of visual processing dynamics at different life stages. The conducted research was based on the methodology presented by Holmqvist et al. (2011), who provided guidelines for best practices in designing and interpreting eye-tracking studies.

The observed differences in gaze path velocity between groups may be significant in the context of designing user interfaces that are age-friendly, as well as in developing intervention strategies aimed at supporting visual and cognitive perception (Park & Gutchess, 2002). Furthermore, understanding these differences can contribute to a better comprehension of the aging processes of the nervous system and provide normative data on the studied parameters for various age groups (Harper & Timney, 1999).

This paper is organized as follows: Section 2 (Experimental Procedure) describes the methodology used, including participant groups, research tools, and data collection process. Section 3 (Results and Discussion) presents the findings, analyses differences in gaze path velocity across age groups, and discusses implications of these results. Section 4 (Conclusion) summarizes the key findings and highlights potential applications, as well as directions for future research.

2. Experimental procedure

2.1. Research group

The full research group in the experiment consisted of 50 participants aged between 7 and 83 years. The age of 7 was established as the lower limit of the age group, due to the upper boundary of the formation and development of human visual capabilities and functions (Walkiewicz-Krutak, 2013). The structure of the age-dependent research groups was as follows:

Children (7–14 years): 8 participants (mean age: 10.5 years, standard deviation: 2.29 years). This group represents individuals with a physiologically formed but dynamically changing visual system.

Young adults (19–39 years): 12 participants (mean age: 29.0 years, standard deviation: 4.06 years). This group represents a physiologically stable visual system.

Middle-aged adults (45–58 years): 15 participants (mean age: 51.5 years, standard deviation: 4.03 years). This group encompasses individuals characterized by the presence of initial changes associated with the aging of the visual system, such as a decline in accommodation ability.

Older adults (62–83 years): 15 participants (mean age: 72.5 years, standard deviation: 4.34 years). This group represents individuals with a significant degree of physiological changes linked to an aging visual system.

An inclusion criterion was the absence of pathological changes in the visual system. Individuals with visual system dysfunctions were excluded at the medical interview stage and were not included in the statistics. Additionally, among the 50 individuals tested, four exhibited anomalous gaze path trajectories. After an additional interview procedure, information was obtained indicating potential visual dysfunctions. These individuals were excluded from the experiment.

The data of the participants in the experiment were anonymized, and each subject gave written informed consent to participate in the study. In the case of minors, informed consent was also signed by the parents or legal guardians of the child. The division into age groups was made arbitrarily based on practical considerations, such as the availability of participants across different age ranges. While not grounded in specific prior literature, this categorization enabled an exploratory analysis of visuomotor function changes across distinct stages of life. The broad age ranges were selected to capture key developmental and aging trends while maintaining manageable group sizes for statistical analysis.

2.2. Apparatus and research methodology

The study employed an eye-tracking device and followed the methodology outlined by Holmqvist et al. (2011). Eye movements were recorded using a simple tracking device, the Eye Tribe, and Ogama software, with a data recording frequency of 60 Hz, as described by Voskuhler et al. (2008). To maintain a stable head position during the experiment, a specially designed chin support was used. This support was adjusted for each participant to ensure comfortable observation of the screen’s central part. Measurements were conducted under controlled environmental conditions, including consistent temperature, lighting, and acoustic isolation. This setup permitted the precise recording of eye movements and related visual perception parameters.

The obtained data were analysed using the “Gaze: Path Velocity (px/s)” parameter and other related metrics. To compare age group differences, both raw data (group means) and post-hoc Tukey HSD analyses were applied. Post-hoc tests accounted for within-group variance, ensuring statistically robust evaluations of group differences. These results are presented in Table 1 and Figure 1 for clarity and consistency.

The study was non-clinical and focused on examining physiological states. It employed non-invasive methods and followed generally accepted research procedures, adhering to the ethical principles outlined in the Helsinki protocol. As the methods did not interfere with the physical or mental integrity of participants, approval from a Local Ethics Committee was not required. The research complied with the ethical guidelines of the Polish Academy of Sciences and adhered to the European GDPR regulation (2016/679), ensuring the confidentiality and privacy of participants' data.

2.3. Visual task

The visual task involved monitoring the eye movements of participants during a visual task. The test monitor was centrally positioned 70 cm away from the participants’ eyes. The task required participants to locate and read numbers from 1 to 25, which were simultaneously displayed in random positions on the computer screen. The numbers were presented in black Arial font, size 24, on a white background to ensure optimal visibility.

Before the task began, an instruction appeared on the screen: “Numbers from 1 to 25 will appear shortly. Find the numbers from 1 to 25.” Participants were instructed to read the numbers out loud in ascending order to verify task completion. The researcher monitored the participant’s gaze path on a secondary screen, allowing them to confirm task performance and completion.

The task was considered complete when the participant located and read aloud the final number (25). The task was performed only once, and participants had unlimited time to complete it. Gaze path velocity (px/s) was calculated based on an analysis of successive gaze positions recorded during the task.

The values were computed by measuring the Euclidean distance between consecutive gaze points in pixels and dividing it by the time interval between recordings.

3. Results and discussion

Based on the analysis of eye mobility over time during the performance of the visual task, parameters of eye mobility were determined. The results obtained, including the average minimal and maximal eye movement speeds (Gaze: Path Velocity) for different age groups, are included in Table 1 (see Visual Summary of Findings). The results summarized in Table 1 demonstrate that gaze path velocity significantly increases from childhood to middle adulthood and declines in elderly individuals. Specifically, the average gaze tracking speed for children was 150.44 px/s, for young adults it was 365.97 px/s, for middle-aged adults it was 423.48 px/s, and for the elderly it was 256.15 px/s. These results are further illustrated in Figure 1.

It is important to note that the mean differences in gaze path velocity, as shown in Figure 1 in the Visual Summary of Findings, are derived from post-hoc Tukey HSD analysis, which adjusts for within-group variance. These adjusted differences are statistically robust and slightly differ from the raw mean differences shown in Table 1. The raw mean differences are calculated directly between group averages without considering variance adjustments. Both approaches highlight statistically significant differences between groups, but the Tukey HSD results provide a more precise estimation.

The analysis showed that in the group of children, the average gaze tracking speed was 150.44 px/s. The highest recorded speed in this group was 220.47 px/s, while the lowest was 129.82 px/s. The standard deviation for children was 31.09 px/s, indicating greater uniformity in gaze tracking among children than in other groups.

For young adults, the average speed was higher than for children, amounting to 365.97 px/s, which aligns with research suggesting an increase in visual tracking abilities during early adulthood (Peters et al., 2019). In this age group, the highest speed observed was 469.80 px/s, and the lowest was 237.09 px/s. The standard deviation for young adults was 61.24 px/s, indicating greater variability in gaze tracking compared to children.

The middle-aged group demonstrated an average gaze tracking speed of 423.48 px/s, consistent with findings that indicate high levels of visual tracking abilities are maintained through middle age before declining (Błasiak et al., 2019). In this category, the highest speed was 490.73 px/s, and the lowest was 348.50 px/s. The standard deviation was 43.75 px/s, which may indicate that middle-aged individuals have fairly uniform visual perception abilities, although with some individual differences.

The last group analysed was the elderly. Their average gaze tracking speed was 256.15 px/s. The highest speed recorded was 298.90 px/s, and the lowest was 211.61 px/s. The standard deviation for this group was 33.84 px/s. It can be noted that older individuals had a lower average speed compared to the younger groups, which may suggest a slowing down of visual perception processes with age.

The mean differences between groups, as shown in Figure 1, are based on Tukey HSD post-hoc analysis. These differences are as follows:

- Children vs. Young Adults: 197 px/s (95% CI: 138 to 256 px/s),
- Children vs. Middle-Aged Adults: 260 px/s (95% CI: 193 to 327 px/s),
- Children vs. Elderly: 93 px/s (95% CI: 28 to 158 px/s).

In contrast, the raw mean differences calculated from Table 1 are approximately 215.53 px/s, 273.04 px/s, and 105.71 px/s, respectively. These slight variations are due to the variance adjustment applied in the post-hoc analysis. Both results consistently demonstrate significant group differences.

Statistical analysis

For the presented one-way ANOVA analyses, the null hypothesis for each is: H0: $\mu 1 = \mu 2 = ... = \mu k$, where H0 is the null hypothesis and $\mu 1, \mu 2, ..., \mu k$ are the mean gaze tracking speeds in populations for each of the *k* groups (children, young adults, middle-aged individuals, and the elderly).

The analysis of sum of squares (SS Group) reflects the overall variability between groups compared to the overall mean gaze tracking speed. For the group of young adults in relation to the children's group, the SS Group value was 211103.10, for middle-aged individuals compared to children it was 261706.37, and for the elderly compared to children it was 29580.48. These values indicate that the greatest variability exists between the average gaze tracking speeds of middle-aged individuals and children, suggesting that these two groups differ the most from each other.

The results of the mean squares (MS Group) are calculated by dividing the sum of squares (SS Group) by the applied number of degrees of freedom (df Group). In all three comparisons, MS Group is equal to SS Group because the number of df is 1.

The F-value statistic is the ratio of MS Group to the mean squares within groups. For children and young adults, the F-value is 59.82 ($p<0.001$, $\eta^2=0.42$), for children and middle-aged individuals it is 44.17 ($p<0.001$, $\eta^2=0.36$), and for children and elderly individuals, it is 5.53 ($p=0.05$, $\eta^2=0.12$). All of these values are higher than the critical values of the F-test (4.28, 4.54, 4.49, respectively), indicating the statistical significance of differences between groups.

Eta-squared (η^2) is a measure of effect size used in ANOVA analyses to quantify the proportion of variance in the dependent variable that is attributed to the independent variable. It provides insight into the magnitude of the differences between groups.

In this study, η^2 was calculated using the formula:

$$\eta^2 = \frac{SS_{Between}}{SS_{Total}}$$

where $SS_{Between}$ represents the sum of squares between groups, and SS_{Total} is the total sum of squares.

The η^2 values obtained in this study (e.g., $\eta^2=0.42$ for children vs. young adults) indicate a large effect size, as values above 0.14 are generally considered substantial in behavioural research. The η^2 values reported for comparisons involving middle-aged individuals ($\eta^2=0.36$) and elderly individuals ($\eta^2=0.12$) suggest a decreasing effect size with age.

The effect size, represented by η^2, indicates a large effect size for comparisons involving young adults and middle-aged individuals ($\eta^2>0.14$) and a medium effect size for comparisons involving elderly individuals ($\eta^2=0.12$).

The analysis of the p-value coefficient provides detailed information about the statistical significance of the results. All observed values are lower than the standard significance threshold (0.05), with values for children and young adults ($p<0.001$), children and middle-aged individuals ($p<0.001$), and children and elderly individuals ($p=0.05$). These values suggest that the null hypothesis of no differences between age groups is rejected.

The Tukey HSD post-hoc test further confirmed statistically significant differences between means for children compared with young adults and middle-aged individuals. The most significant difference occurs between children and middle-aged individuals, suggesting significant biometric or behavioural changes in these age groups. Differences between children and elderly individuals, although smaller, are still statistically significant.

Visual summary of findings

Figure 1 displays the results of the Tukey HSD test for all comparative age groups. The graph illustrates the differences in mean gaze path velocity (in pixels per second) among the three age groups: children vs. young adults, middle-aged individuals, and elderly individuals. Each point on the plot represents the estimated difference in means between groups, with horizontal lines indicating 95% confidence intervals. The effect sizes (η^2) calculated for these comparisons highlight large differences between children and both young adults ($\eta^2=0.42$) and middle-aged individuals ($\eta^2=0.36$), as well as moderate differences between children and elderly individuals ($\eta^2=0.12$).

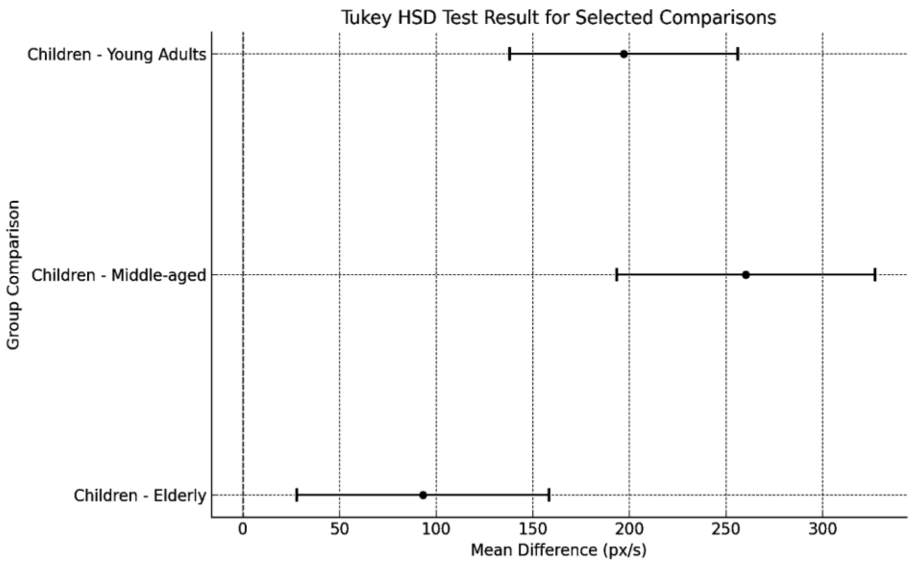

Figure 1. Tukey's HSD Test – comparing differences in average gaze path velocity (in pixels per second) between three age groups. Each point represents the estimated mean difference between groups, with horizontal error bars indicating 95% confidence intervals

Group analysis of age correlation is presented in Figure 2 and was conducted using linear group Pearson correlation between age and eye-tracking path velocity (Figure 2a) and polynomial fitting of eye-tracking path velocity as a function of age (Figure 2b).

Based on the linear fitting shown in Figure 2a, a strong positive correlation (r=0.72) with a p-value of 0.044 was observed in the group of children (7–14 years), indicating a statistically significant increase in eye-tracking path velocity with age in this cohort. The equation $y=-0.3607x+1.0202$, displayed in Figure 2a, represents the linear regression model fitting the data for group-wise correlation between age and eye-tracking path velocity. Here, y_y

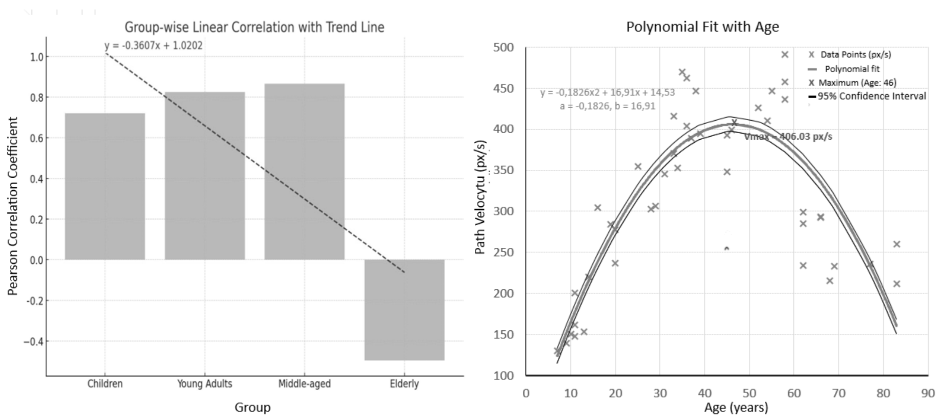

Figure 2. (a) Pearson correlation coefficients for different age groups, illustrating the strength and direction of linear relationships between age and gaze path velocity. (b) Polynomial fitting of eye-tracking path velocity as a function of age, with a second-degree polynomial equation $y=-0.1826x^2+16.91x+14.53$. The maximum velocity ($V_{max}$=406.03 px/s) is marked at age 46.3 years, and data points represent individual measurement. The shaded area around the polynomial fit represents the 95% confidence interval

denotes the normalized path velocity, and x_x represents the age group (Children, Young Adults, Middle-aged, Elderly). The negative slope indicates a decline in velocity with increasing age. In the young adults group (16–39 years), the observed correlation was even stronger (r=0.83), with a p-value below 0.001.

In Figure 2b, a nonlinear relationship between eye-tracking path velocity and age is presented with a second-degree polynomial fitting. The equation of the fitted polynomial was $y=-0.1826x^2+16.91x+14.53$, indicating an increase in eye-tracking path velocity up to a maximum point at age 46.3 years (V_{max}=406.03), after which a decline was observed. The polynomial fit shown in Figure 2b has an R^2 value of 0.89, indicating a very good fit to the data. This high coefficient of determination confirms that the model accurately describes the nonlinear relationship between age and eye-tracking path velocity. Additionally, the alignment of the polynomial curve with the data points further supports the validity of the model. These values are particularly interesting as they show that eye-tracking path velocity not only increases with age during childhood and early adulthood but reaches a peak in middle adulthood, followed by a decline, suggesting a potential degradation of visuomotor abilities in later life. These changes correlate well with physiological aging processes occurring in the eye, specifically in its muscular system (Maruta et al., 2017; Garzorz et al., 2015).

Table 1 presents the mean gaze path velocity (in pixels per second) across different age groups, including children, young adults, middle-aged adults, and the elderly. It provides the standard deviation, standard deviation of the mean, maximum, and minimum speeds for each group, as well as the median (50th percentile), first quartile (Q1), and third quartile (Q3) values. Additionally, the post-hoc difference in gaze velocity between children and the other groups is included. Significant differences in gaze path velocity were observed across all age groups.

Table 1. Analysis of eye movement speed (Gaze: Path Velocity) across different age groups

Research group	Mean speed (px/s)	Standard deviation (px/s)	Standard deviation of the mean (px/s)	Maximum speed (px/s)	Minimum speed (px/s)	Post-hoc difference vs. children (px/s)	Median (px/s)	First quartile (Q1)	Third quartile (Q3)
Children	150.44	31.09	11.00	220.47	129.82	-	153.24	139.57	161.63
Young adults	365.97	61.24	14.86	469.80	237.09	197	354.55	284.23	403.90
Middle-aged adults	423.48	43.75	14.58	490.73	348.50	260	436.49	410.32	457.92
Elderly	256.15	33.84	10.70	298.90	211.61	93	236.33	211.61	260.51

Table 2 summarizes the results of the ANOVA test comparing gaze path velocity between individual age groups. It includes values for the sum of squares (SS), degrees of freedom (df), mean squares (MS), F-values, p-values, and F-tests for comparisons between children and young adults, children and middle-aged adults, and children and elderly individuals. The significant differences in gaze path velocity between children and the other age groups are highlighted, with all p-values being well below 0.05.

Table 2. ANOVA test results for individual groups

Research group	SS Group	df Group	MS Group	F-value	p-value	F-test
Children vs young Adults	211103.10	1	211103.10	59.82	7.61E-08	4.28
Children vs middle-aged adults	261706.37	1	261706.37	44.17	7.79E-06	4.54
Children vs elderly	29580.48	1	29580.48	5.53	0.032	4.49

4. Conclusion

This study provides a detailed analysis of gaze path velocity across various age groups, using c.hildren as a baseline reference. The results demonstrate significant changes in gaze path velocity throughout different life stages.

In children, gaze path velocity served as a baseline for comparisons with older groups, being characterized by relatively low variability (SD = 31.09 px/s). Pearson correlation analysis revealed a strong positive relationship between age and gaze path velocity in this group ($r = 0.72$, $p = 0.044$), indicating rapid perceptual development. In young adults, velocity continued to increase, with an even stronger correlation ($r = 0.83$, $p < 0.001$), peaking in middle age. Middle-aged participants showed the highest average velocity (423.48 px/s, V_{max} = 406.03 px/s at age 46.3 years), reflecting optimal visuomotor efficiency during this stage of life.

Statistical analyses, including ANOVA and post-hoc Tukey HSD tests, confirmed significant differences between groups, with large effect sizes (η^2 = 0.42 for children vs. young adults, η^2 = 0.36 for children vs. middle-aged individuals). However, a decline in velocity was observed in the elderly group, reflecting age-related reductions in neuroplasticity ($\eta^2 = 0.12$).

Polynomial modeling captured the nonlinear trajectory of gaze path velocity across the lifespan, highlighting an increase during childhood and early adulthood, stabilization in middle age, and a subsequent decline in later life. This trajectory aligns with physiological aging processes affecting visual and muscular systems.

The study emphasizes the importance of children as a reference point for understanding developmental turning points in visuomotor functions. The findings have implications for educational and therapeutic interventions, diagnostics, and the design of age-specific user interfaces. Future research should explore larger, more diverse samples and consider lifestyle and health factors to provide a broader perspective on the variability of gaze path velocity across the population.

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