UNIVERSITY OF LATVIA

Summary of Doctoral Thesis

Evita Šerpa

ASSESSMENT OF GAZE FIXATION IN SCHOOL-AGE CHILDREN

Riga 2025

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SUMMARY OF DOCTORAL THESIS

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The thesis contains an introduction, a literature review, a methodology section, main results, a summary, and a list of references.

Form of the thesis: collection of research papers in field of physics and astronomy, subfield of medical physics.

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ABSTRACT

This work is dedicated to the assessment of gaze fixation in school-age children. Within the framework of the thesis, the influence of various factors on gaze fixation parameters was evaluated, thereby refining the methodology for gaze fixation assessment.

The results of the study provide new insights into the development of gaze fixation and the influence of eye dominance on gaze fixation stability in school-aged children, which are essential for refining the methodology for assessing monocular fixation stability in children. A relationship between binocular fixation stability and stereopsis, an important visual function, was established. It was concluded that eye movement recorders with different operating frequencies can be effectively used to assess the parameters of binocular fixation. An objective assessment of eye movements during the performance of DEM test, which approximates reading conditions, showed that the parameters of gaze fixations during this test differ from those during actual reading tasks, suggesting that the DEM test involves different information processing mechanisms and is, therefore, less correlated with overall reading performance.

Keywords: video-oculography, gaze fixation stability, reading fixations, literacy, objective

CONTENTS

1. INTRODUCTION

1.1. Relevance of the thesis

Reading is a complex acquired skill that involves the participation and coordination of many cognitive processes. It is one of the most important skills necessary for successful overall academic performance in school and studies. During the reading process, visual perception and oculomotor abilities play an essential role. Thanks to the functioning of the oculomotor system, it is possible to shift the gaze from one word to another during reading process and maintain a stable gaze position during fixation. Precise control of eye movements is essential not only in reading but also in sports, performing various daily tasks, and in social interactions (Land, 2006).

The use of eye movement recording devices provides an objective assessment of the strategies used to perform eye movements during various tasks (Land, 2006). Eye movement assessment during reading can be used to identify children with atypical reading development (Gran Ekstrand et al., 2021). Children with reading difficulties may demonstrate unstructured and disorganized strategies for performing eye movements during reading (Lefton et al., 1979). Using eye movement recording devices, it is possible to track eye movements without requiring verbal or motor responses during the task, thus conducting an objective assessment of skills.

At the moment of fixation, visual information is perceived (Rayner, 2009), and gaze fixation most accurately indicates where a person's visual attention is directed (Duchowski et al., 2017). In practice, vision specialists evaluate eye movements manually, which is often a subjective assessment. Manual methods with standardized evaluation protocols are not designed to assess fixation parameters. Moreover, manual evaluation cannot provide a quantitative assessment of eye movement parameters, which is essential, for example, in evaluating fixation stability or the duration and number of fixations in various reading-related tasks. Since the eye movement recording devices available today are becoming increasingly convenient to use outside of scientific laboratories, an objective method for evaluating visual fixation in school-aged children would be useful not only for vision specialists but also for other healthcare professionals. As approximately 90% of our viewing time is spent on fixations (Irwin, 1992), it is particularly important to evaluate how fixation parameters are related to visual functions and reading ability, as well as how various endogenous and exogenous factors can influence these parameters.

1.2. Aim and tasks of the thesis

The aim of this study is to develop a methodology for assessing gaze fixation in school-aged children, evaluating the impact of various factors on gaze fixation parameters, thereby promoting an objective approach to the evaluation of visual functions in the practice of vision specialists. To achieve the study's goal, the following objectives have been set:

1. to evaluate gaze fixation stability in the dominant and non-dominant eye of school-aged children;
2. to assess the relationship between fixation stability and stereo acuity;
3. to evaluate the impact of the eye-tracker sampling frequency on the accuracy of fixation stability assessment;
4. to determine the relationship between the execution time of the developed reading task, the duration of fixations, and the number of fixations with the child's reading performance;
5. to evaluate fixation parameters during the DEM test and the reading task.

1.3. Author's contribution

The research described in the thesis was developed at the Department of Optometry and Vision Science at the University of Latvia. The study was conducted within the project "Visual Functions in Children with Reading Disorders" with the support of the Latvian Council of Science (project no. lzp-2021/1-0219), the University of Latvia (project no. Y5-AZ77-ZF-N-100), and the University of Latvia Foundation and SIA "Mikrotīkls" (project no. 2260).

The author of the thesis developed the methodology for assessing gaze fixation stability and created age-appropriate reading stimuli, which were used for eye movement assessment during reading tasks. The eye movement measurements using the video-oculograph Tobii Pro Fusion were conducted by the author and students from the Department of Optometry and Vision Science: Līva Volberga and Viktorija Goliškina. Other data necessary for the study were collected with the help of students from the Department of Optometry and Vision Science – Madara Alecka, Elizabete Ozola, Daniela Toloka, Anete Kļavinska, Marija Koļeda, Asnate Bērziņa, Rita Miķelsone, and Sofija Vasiļjeva. Both the eye movement assessments and other measurements were carried out at the educational institutions of the participating children – Marupes State Gymnasium, Marupes Elementary School, Rigas Cultures Secondary School, Kuldigas Center Secondary School. The assessment of the reading abilities of the participating children using the Acadience™ Reading test was carried out by school speech therapists – Jolanta Hanzovska, Linda Meiersone, Madara Vorza, Ivita Petuhova, Solvita Depša, and Sigita Jirgensone.

The compilation of the data used in the study was assisted by students Madara Alecka, Elizabete Ozola, Daniela Toloka, Anete Kļavinska, and Marija Koļeda. The author of the thesis conducted the analysis of the results and the statistical processing of the data. The results have been presented by the author at both international and local conferences, participating with both oral and poster presentations. The author was the main author of five publications included in the thesis and co-author of one publication included in the thesis.

1.4. Novelty of the study

During the study, visual stimuli were created for assessing gaze fixation parameters, and an objective assessment of gaze fixation parameters was conducted in school-aged children. Additionally, the influence of various endogenous and exogenous factors on gaze fixation parameters was assessed. The study yielded new insights into the development of gaze fixation and the effect of ocular dominance on gaze fixation stability in school-aged children, which is important to consider when evaluating monocular fixation stability. Findings also revealed a connection between gaze fixation stability and stereopsis, indicating that unstable gaze fixation may indicate reduced stereoacuity in younger children. By objectively evaluating eye movements during the DEM test, which closely simulates reading conditions, new findings were obtained about the correlation between the duration of fixations in this test and during reading, as well as the overall reading ability. Additionally, the significance of reading stimulus selection was highlighted when evaluating reading fixation parameters and their correlation with reading performance.

The scientific novelty of the results of this study is supported by five published articles in international journals indexed in the SCOPUS database.

1.5. Thesis

1. It has been proven that in children under the age of eight, gaze fixation of the dominant eye is significantly more stable than gaze fixation of the non-dominant eye, while after the age of nine, the difference in fixation stability between the dominant and non-dominant eye equalizes (Serpa et al., 2023, *JEMR, 16*(3), 6).
2. In children under the age of eight, binocular fixation stability can be used to infer the quality of stereopsis (Serpa et al., 2023, *Proc SPIE*, *12624*, 126241F).
3. Fixation duration, as an objective parameter during reading, is more closely related to the assessment of reading ability than fixation duration during the DEM test (Serpa et al., 2023, *Psychological Applications and Trends 2023*, (pp. 416–418)).

1.6. Scientific publications included in the doctoral thesis

[P1] Krumina, G., Ceple, I., Goliskina, V., Kassaliete, E., Ruza, T., **Serpa, E.,** Svede, A., & Volberga, L. (2023). The Development of Objective and Quantitative Eye-Tracking-Based Method for the Diagnostics of Oculomotor Dysfunctions. In: Dekhtyar, Y., Saknite, I. (eds) *19th Nordic-Baltic Conference on Biomedical Engineering and Medical Physic, IFMBE Proceedings,* (pp. 9–17), Springer. https://doi.org/10.1007/978-3-031-37132-5_31

[P2] **Serpa, E.,** Alecka, M., Ceple, I., Krumina, G., Svede, A., Kassaliete, E., Goliskina, V., Volberga, L., Berzina, A., Mikelsone, R., Ozola, E., Toloka, D., Ruza, T., Klavinska, A., Vasiljeva, S., & Koleda, M. (2023). The impact of eye dominance on fixation stability in school-aged children. *Journal of Eye Movement Research*, *16*(3), 6. https://doi.org/10.16910/jemr.16.3.6

[P3] **Serpa, E.,** Alecka, M., Berzina, A., Goliskina, V., Kassaliete, E., Klavinska, A., Koleda, M., Mikelsone, R., Ozola, E., Ruza, T., Svede, A., Toloka, D., Vasiljeva, S., Volberga, L., Ceple, I., & Krumina, K. (2023). The effect of fixation stability on stereopsis in school-age children. *Proceedings of SPIE, 12624*, 126241F. https://doi.org/10.1117/12.2675493

[P4] **Serpa, E.,** Ceple, I., Kassaliete, E. & Krumina, G. (2024). Impact of eye tracker sampling rate on fixation stability measurement. *Proceedings of SPIE, 12998*, 129981L. https://doi.org/10.1117/12.3022364

[P5] **Serpa, E.,** Alecka, M., Berzina, A., Goliskina, V., Kassaliete, E., Klavinska, A., Koleda, M., Mikelsone, R., Ozola, E., Ruza, T., Svede, A., Toloka, D., Vasiljeva, S., Volberga, L., Ceple, I., & Krumina, K. (2023). Assessment of Children Eye Movement Performance: An Eye-Tracker Approach. In: Dekhtyar, Y., Saknite, I. (eds) *19th Nordic-Baltic Conference on Biomedical Engineering and Medical Physic, IFMBE Proceedings,* (pp. 246–250). Springer. https://doi.org/10.1007/978-3-031-37132-5_31

[P6] **Serpa, E**., Ozola, E., Alecka, M., Berzina, A., Goliskina, V., Kassaliete, E., Klavinska, A., Koleda, M., Mikelsone, R., Ruza, T., Svede, A., Toloka, S., Vasiljeva, S., Volberga, L., Ceple, I., & Krumina, G. (2023). Cognitive Demand in the DEM Test from the Perspective of Fixation Duration Analysis. Psychological Applications and Trends 2023, (pp. 416–418), p-ISSN: 2184-2205 e-ISSN: 2184-3414 ISBN: 978-989-35106-0-5. https://doi.org/10.36315/2023inpact095

1.7. Participation in conferences

1. 20th International Young Scientist Conference "Developments in Optics and Communication 2024 (Riga, Latvia, May 2–3, 2024). "Visual functions in children with reading disorders". Ceple, I., Ozola, E., Alecka, M., Berzina, A., Goliskina, V., Kassaliete, E., Klavinska, A., Koleda, M.,

Mikelsone, R., Ruza, T., **Serpa, E**., Svede, A., Toloka, D., Truksa, R., Vasiljeva, S., Volberga, L., Krumina G., – oral presentation

2. SPIE Photonics Europe 2024 (Strasbourg, France, April 7–11, 2024). "Impact of eye tracker sampling rate on fixation stability measurement", **Serpa, E**., Ceple, I., Kassaliete, E., Krumina, G., – poster presentation
3. 82th International Scientific Conference of the University of Latvia (Riga, Latvia, February 16, 2024). "Mikrosakāžu parametri un fiksācijas stabilitāte", Valujeva, L., **Šerpa, E**., Ozola, E., Alecka, M., Berziņa, A., Goliškina, V., Kassaliete, E., Kļavinska, A., Koļeda, M., Miķelsone, R., Ruža, T., Švede, A., Toloka, D., Vasiļjeva, S., Volberga, L., Ceple, I., Krumiņa G., – oral presentation
4. 82th International Scientific Conference of the University of Latvia (Riga, Latvia, February 16, 2024). "Fiksācijas parametru analīze DEM testa un lasīšanas uzdevuma izpildes laikā", Purauska, P., **Šerpa, E**., Ozola, E., Alecka, M., Berziņa, A., Goliškina, V., Kassaliete, E., Kļavinska, A., Koļeda, M., Miķelsone, R., Ruža, T., Švede, A., Toloka, D., Vasiļjeva, S., Volberga, L., Ceple, I., Krumiņa G., – oral presentation
5. European Conference on Vision perception, ECVP 2023 (Paphos, Cyprus, August 27–31, 2023). "Fixation stability in reading and non-reading task", **Serpa, E**., Ozola, E., Alecka, M., Berzina, A., Goliskina, V., Kassaliete, E., Klavinska, A., Koleda, M., Mikelsone, R., Ruza, T., Svede, A., Toloka, D., Vasiljeva, S., Volberga, L., Ceple, I., Krumina G., – poster presentation
6. SPIE Digital Optical Technologies Conference (Munich, Germany, June 26–28, 2023). "The effect of fixation stability on stereopsis in school-age children", **Serpa, E**., Ozola, E., Alecka, M., Berzina, A., Goliskina, V., Kassaliete, E., Klavinska, A., Koleda, M., Mikelsone, R., Ruza, T., Svede, A., Toloka, D., Vasiljeva, S., Volberga, L., Ceple, I., Krumina G., – poster presentation
7. 19th Nordic-Baltic Conference on Biomedical Engineering and Medical Physics, NBC 2023 (Liepaja, Latvia, June 12–14, 2023). "Assessment of children eye movement performance: An eye-tracker approach", **Serpa, E**., Ozola, E., Alecka, M., Berzina, A., Goliskina, V., Kassaliete, E., Klavinska, A., Koleda, M., Mikelsone, R., Ruza, T., Svede, A., Toloka, D., Vasiljeva, S., Volberga, L., Ceple, I., Krumina G., – poster presentation
8. 19th Nordic-Baltic Conference on Biomedical Engineering and Medical Physics, NBC 2023 (Liepaja, Latvia, June 12–14, 2023). "The development of objective and quantitative eye-tracking-based method for the diagnostics of oculomotor dysfunctions", Krumina, G., Goliskina, V., Kassaliete, E., Ruza, T., **Serpa, E.**, Svede, A., Volberga, L. – oral presentation
9. Scottish Vision Group Meeting 2023 ((Dundee, UK, April 21–23, 2023). "The effect of stimulus contrast and direction on saccadic eye movement parameters", Goliskina, V., Ceple, I., Truksa, R., Fomins, S., Ikaunieks, G., Svede, A**., Serpa, E**., Volberga, L., Krauze, L., Kassaliete, E., Vasiljeva, S., Krumina, G., – poster presentation

10. International Psychological Applications Conference and Trends, InPACT 2023 (Lisbon, Portugal, April 22–24, 2023). "Cognitive demand in the DEM test from the perspective of fixation duration analysis", **Serpa, E**., Ozola, E., Alecka, M., Berzina, A., Goliskina, V., Kassaliete, E., Klavinska, A., Koleda, M., Mikelsone, R., Ruza, T., Svede, A., Toloka, D., Vasiljeva, S., Volberga, L., Ceple, I., Krumina G., – poster presentation
11. 19th International Young Scientist Conference "Developments in Optics and Communication 2023 (Riga, Latvia, April 13–14, 2023). "Effect of eye dominance on fixation stability", Alecka, M., **Serpa, E**., Ozola, E., Berzina, A., Goliskina, V., Kassaliete, E., Klavinska, A., Koleda, M., Mikelsone, R., Ruza, T., Svede, A., Toloka, D., Vasiljeva, S., Volberga, L., Ceple, I., Krumina G. – poster presentation
12. 19th International Young Scientist Conference "Developments in Optics and Communication 2023 (Riga, Latvia, April 13–14, 2023). "Fixation stability in children with and without reading difficulties", Ozola, E., **Serpa, E**., Alecka, M., Berzina, A., Goliskina, V., Kassaliete, E., Klavinska, A., Koleda, M., Mikelsone, R., Ruza, T., Svede, A., Toloka, D., Vasiljeva, S., Volberga, L., Ceple, I., Krumina G. – poster presentation
13. 81th International Scientific Conference of the University of Latvia (Riga, Latvia, February 13, 2023). "Acs dominances ietekme uz fiksācijas stabilitāti", Alecka, M., **Šerpa, E**., Ozola, E., Berziņa, A., Goliškina, V., Kassaliete, E., Kļavinska, A., Koļeda, M., Miķelsone, R., Ruža, T., Švede, A., Toloka, D., Vasiļjeva, S., Volberga, L., Ceple, I., Krumiņa G., – oral presentation
14. 81th International Scientific Conference of the University of Latvia (Riga, Latvia, February 13, 2023). "Fiksācijas stabilitāte bērniem ar un bez lasīšanas grūtībām", Ozola, E., **Šerpa, E**., Alecka, M., Berziņa, A., Goliškina, V., Kassaliete, E., Kļavinska, A., Koļeda, M., Miķelsone, R., Ruža, T., Švede, A., Toloka, D., Vasiļjeva, S., Volberga, L., Ceple, I., Krumiņa G., – oral presentation
15. 81th International Scientific Conference of the University of Latvia (Riga, Latvia, February 13, 2023). "Fiksācijas stimula ietekme uz fiksācijas stabilitāti bērniem un pieaugušajiem", Toloka, D., **Šerpa, E**., Alecka, M., Berziņa, A., Goliškina, V., Kassaliete, E., Kļavinska, A., Koļeda, M., Miķelsone, R., Ozola, E., Ruža, T., Švede, A., Vasiļjeva, S., Volberga, L., Ceple, I., Krumiņa G., – oral presentation
16. 18th International Young Scientist Conference "Developments in Optics and Communication 2022 (Riga, Latvia, April 21–22, 2022). "The effect of object shape and location on fixation disparity", **Serpa, E.**, Kremera E. A., Ceple I., Krumina, G., – poster presentation
17. 80th International Scientific Conference of the University of Latvia (Riga, Latvia, February 11, 2022). "Acu kustības un lasītprasme", **Šerpa, E**., Ceple, I., Krūmiņa, G., – oral presentation

2. LITERATURE REVIEW

2.1. Methods for assessing eye movements

Various tests and methods are used to assess eye movements. One of the methods is direct clinical observation, where the assessment of eye movements is based on the observer's subjective judgment. One of the direct assessment tests is the NSUCO test (Northeastern State University College of Optometry oculomotor test), which is designed to evaluate smooth pursuit and saccadic eye movements by assigning a numerical value on a graded scale. A correlation has been observed between NSUCO test results and reading proficiency – more skilled readers tend to achieve better results on the test (Maples & Flickinger, 1990). Indirect assessment tests are also used to evaluate eye movements. One such test is the DEM (Developmental Eye Movement) test. It consists of A and B test cards designed for vertical reading of numbers, and C test card, which is for reading numbers aloud horizontally, similar to reading text. The time required to read the numbers, and the number of errors made in the test are compared with age- and language- appropriate norms. The test norms and the achieved result help determine whether the test taker has a problem with automatic naming, eye movements (primarily saccades), or both (Facchin, 2021). Although it has been concluded that DEM test results also correlate with reading ability in school-aged children (Serdjukova et al., 2017), this test, like the NSUCO test, does not provide a quantitative assessment of eye movement parameters

Electrophysiological methods, such as electromyography (EMG) and electrooculography (EOG), are also used to evaluate eye movements. EMG is a method where the biopotential of muscles is recorded using needle electrodes. In the analysis of eye movements, EMG is used to record the biopotential of the muscles involved in eye movements (Reuben & Gonzalez, 1964). During EOG, electrodes are used to record changes in the electric potential caused by eye movements between two electrodes placed in a horizontal or vertical direction. This method is based on the fact that the human eye is an electrical dipole consisting of a positively charged cornea and a negatively charged retina. When the eye moves, the cornea approaches one electrode while the retina moves toward the opposite electrode. Changes in the orientation of the dipole cause changes in the EOG signal. If the eyeball moves towards the electrode, the potential increases, and if it moves away, the potential decreases (Jia & Tyler, 2019). The main eye movements that can be detected using EOG are saccades and fixations, and by analyzing the recorded potential changes, it is also possible to identify moments of blinking (López et al., 2019). Although these methods provide detailed and accurate assessments of eye movements, they are invasive, and their accuracy largely depends on the experience of the examiner.

Nowadays, eye movement recording devices based on corneal reflection and pupil displacement in the video image provided by the device's camera are most commonly used for assessing eye movements. In eye movement recording devices, infrared light is often used as the light source. The corneal reflection produced by the light source is measured relative to the position of the eye pupil center (see Figure 2.1). The infrared light source is usually fixed in position relative to the eye, so the corneal reflection remains relatively stable, while pupil displacement occurs as the eye moves. Corneal reflections are also known as Purkinje reflections or Purkinje images. Eye movement recording devices based on video cameras typically localize the first Purkinje image (Duchowski, 2017). There are also devices that measure both the first and the fourth Purkinje reflections. These two reflections move equally during eye translational movements but at different distances during eye rotational movements. The first Purkinje reflection is formed by light reflecting off the anterior surface of the cornea, while the fourth Purkinje reflection is formed by light reflecting off the posterior surface of the lens (Clark, 1975).

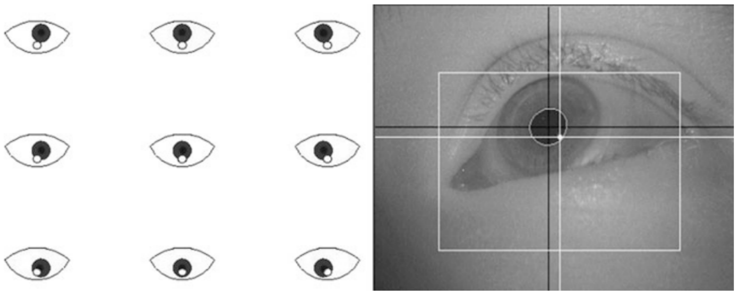

Figure 2.1. The image on the left shows the relative positions of the pupil and corneal reflection when fixating on different locations on the screen. On the right, an image captured by the eye movement recording device's camera is shown, where the white cross indicates the geometric center of the corneal reflection, and the black cross indicates the geometric center of the pupil (Majaranta & Bulling, 2014).

One of the parameters of eye movement recording devices is their sampling frequency (Hz), which indicates how many times per second the device records the eye's position. Studies suggest that the sampling frequency of eye movement recording devices plays an important role in determining the kinematic parameters of saccades, such as latency, accuracy, and peak velocity (Raynowska et al., 2018). Devices with higher sampling frequencies register more saccades and can more accurately determine their duration during reading, as well as more precisely measure fixation duration (Leube et al., 2017). The error introduced by the sampling frequency during measurements is not a practical issue when using eye movement recording devices that operate at 200 Hz or higher. When determining fixation and saccade durations, there are no significant differences observed between 250 Hz and 1250 Hz operating frequencies, but results do differ at lower frequencies. Saccade duration is more sensitive to sampling frequency than fixation duration (Andersson et al., 2010).

Using eye movement recorders, it is possible to track eye movements during reading without requiring a verbal or motor response during the task (see Figure 2.2). Eye movement assessment using eye movement recorders is an objective, efficient and accurate screening method that can be used to obtain an assessment of a child's reading skills, thereby identifying children with atypical reading development (Gran Ekstrand el al., 2021). Conducting an objective assessment of eye movements during reading can also detect early cognitive decline in older people (Fraser et al., 2017). Eye movement recorders are also used in sports science to gain insight into eye movement strategies in professional athletes (Kassem et al., 2022). The eye movement recorders available today are minimally invasive, which has made them increasingly suitable for measurement in children. Additionally, these devices are often portable, allowing for objective eye movement assessments to be conducted outside of laboratories (Sim & Bond, 2021).

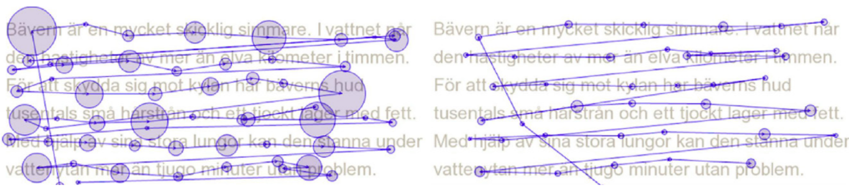

Figure 2.2. Visualization of eye movements during reading. Circles represent fixations (the larger the circle, the longer the fixation duration), and the lines between fixations represent saccades (the longer the line between two fixations, the greater the amplitude of the saccade). The reader on the left makes longer fixations and shorter saccades compared to the reader on the right (Gran Ekstrand et al., 2021).

2.2. Characteristics of gaze fixation

Approximately 90% of the time we spend looking is dedicated to fixations, during which the eyes remain in a relatively stable position (Irwin, 1992). Visual information is perceived during fixations (Rayner, 2009), and fixations most accurately indicate where a person's visual attention is directed

(Duchowski et al., 2017). Fixations naturally correspond to the desire to maintain gaze on an object of interest (Duchowski et al., 2017). One of the parameters that characterizes fixations is their duration. Typical fixations last at least 150 milliseconds (Irwin, 1992). It is believed that cognitive demand also affects fixation duration; specifically, higher demand results in longer fixations (Zegermann et al., 2016). Fixation duration is also a factor that characterizes cognitive demand in reading relates tasks (Reney et al., 2014). The duration of fixations is analyzed to evaluate decision-making speed as well (Kassem et al., 2022).

Although the eyes are relatively stable during fixations, very small, involuntary eye movements occur: drift, tremor, and microsaccades (see Figure 2.3). The main function of these fixation eye movements is to prevent neural adaptation of retinal cells, ensuring that the relatively unchanging image during fixation does not fade and remains clearly visible throughout the fixation period (Martinez-Conde et al., 2004).

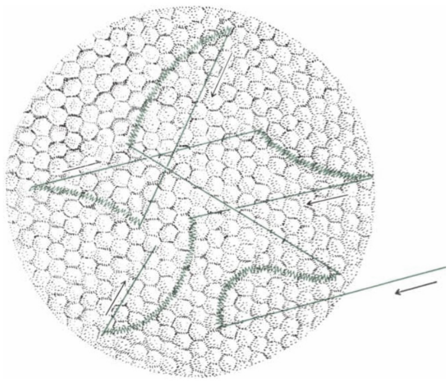

Figure 2.3. Fixational eye movements shift the image across the retinal photoreceptors. Tremor occurs simultaneously with drift (curved lines). Microsaccades (straight lines) typically move the image to the central part of the fovea. The size of these fixation eye movements is very small; the diameter of the depicted foveal area is 0.05 mm (Pritchard, 1961).

Tremor is the smallest of the fixational eye movements, occurring simultaneously with drift. Tremors is high-frequency (up to 100 Hz) eye movement with an amplitude typically around 0.008 degrees, and usually do not exceed the diameter of a retinal receptor cell. One reason for the incomplete understanding of tremor's role during fixation is its simultaneous occurrence with drift, as well as the difficulty in registering it due to tremor's amplitude and frequency often falling within the error range of eye movement recording devices (Martinez-Conde et al., 2004; Alexander & Martinez-Conde, 2019).

Drift is a slow eye movement with a velocity typically below 0.5 degrees per second (°/s) and an amplitude under 0.13 degrees (Rolfs, 2009). During drift, the fixation object may be moved over a distance of several photoreceptors. Although drift is believed to be caused by instability in the oculomotor system, it also plays a compensatory role in maintaining stable fixation when the microsaccade system is disrupted (Martinez-Conde et al., 2004).

Microsaccades are small saccadic eye movements that occur during fixation, with amplitudes typically under 0.5 degrees but sometimes reaching up to 1 degree. During fixation, microsaccades occur 1–2 times per second, and their primary function is to prevent neural adaptation of the retina and correct the fixation inaccuracies caused by drift. Microsaccades last about 25 milliseconds, during which the fixation object can be moved up to several hundred retinal photoreceptors (Martinez-Conde et al., 2004; Rolfs, 2009). Although drift is also believed to play a role in maintaining a stable image during fixation, only microsaccades can restore a clear image after it has faded, which is linked to the speed and amplitude of microsaccades (Alexander & Martinez-Conde, 2019).

2.2.1. Fixation stability

Fixation stability refers to the ability to maintain a stable gaze at fixation target. At birth, an infant's fixation is not fully developed. This visual function begins to be observable at around one month of age, when the infant can briefly fixate on large, bright, nearby objects. Thanks to the process of myelination of the optic nerve and the development of other central nervous system (CNS) structures, the ability to fixate stabilizes over the subsequent months of life (Zimmermann et al., 2019). As the child grows older, fixation becomes increasingly stable (Aring et al., 2007; Pueyo et al., 2022), but it changes throughout life, becoming less stable after the age of 50 (Altemir et al., 2021).

Typically, binocular fixation, or fixation with both eyes simultaneously, is more stable than monocular fixation (González et al., 2012; Raveendran et al., 2019). Unless there is some pathology, the fixation stability of the right and left eyes is nearly identical (González et al., 2012; Subramanian et al., 2013). However, in pathological cases, fixation stability may be better in one eye. For example, in maculopathy, fixation is more stable in the healthier eye (Samet et al., 2018), while in amblyopia, fixation is less stable in the amblyopic eye (González et al., 2012; Aizenman & Levi, 2021). Although fixation is less stable in the amblyopic eye, it is the stability of fixation in the non-amblyopic eye that correlates with reading speed – slower reading speeds are observed with less stable fixation (Kelly et al., 2017). Unstable gaze fixation can also negatively affect other visual functions, such as visual acuity (Aizenman & Levi, 2021) and the quality of stereopsis (Birch et al., 2013; Aizenman & Levi, 2021).

Fixation stability can be quantitatively assessed using various methods. One such method is the Center of Gravity method, where the average distance of fixation from the center is calculated. A greater distance indicates less stable fixation (Aring et al., 2007). Fixation stability is also characterized by the proportion of gaze positions within a specific area during fixation. According to Fujii et al. (2002), fixation is considered stable if 75% of gaze positions during fixation are within 2 degrees of the fixation center; it is relatively unstable if less than 75% of gaze positions are within 2 degrees, but more than 75% are within 4 degrees; and fixation is considered unstable if more than 75% of gaze positions are beyond 4 degrees from the fixation center. Thaler et al. (2013) assessed fixation stability by analyzing the dispersion of fixation and the number of microsaccades observed during fixation. A higher number of microsaccades is associated with less stable fixation. However, the most commonly used method for quantitatively assessing fixation stability is the calculation of the bivariate contour ellipse area (BCEA), which takes into account the standard deviation of gaze fixation along both the horizontal and vertical meridians (Crossland & Rubin, 2002; Subramanian et al., 2013; Altemir et al., 2021). A smaller ellipse area indicates more stable fixation (Crossland & Rubin, 2002). To perform a quantitative assessment of fixation stability, objective eye movement recording is necessary, as manual evaluation cannot detect small changes in gaze position during fixation.

In studies describing fixation stability, the methodology varies. Fixation stability can be analyzed binocularly, where the gaze position is calculated as the average of the right and left eye gaze positions (Kim et al., 2022), or monocularly, where the stability of gaze fixation is analyzed based on the position of one eye. When selecting which eye's fixation stability to analyze, attention may be given to the dominant eye, focusing on its fixation stability (Jones et al., 2016), or the analysis may be performed on an eye without considering the dominant eye principle (Crossland & Rubin, 2002; Thaler et al., 2013).

Gaze fixation stability can also be affected by the chosen fixation stimulus (Thaler et al., 2013). Although smaller fixation stimuli provide more stable fixation (Hirasawa et al., 2016), various stimuli are used in fixation stability analysis in children. These stimuli can range from a simple small circle (Aring et al., 2007; Kim et al., 2022) to different types of animations (see Figure 2.4). The animations used may involve changing shapes and colors (Vinuela-Navarro et al., 2017) or include additional motion elements, such as a static bee with vibrating wings (Altemir et al., 2021).

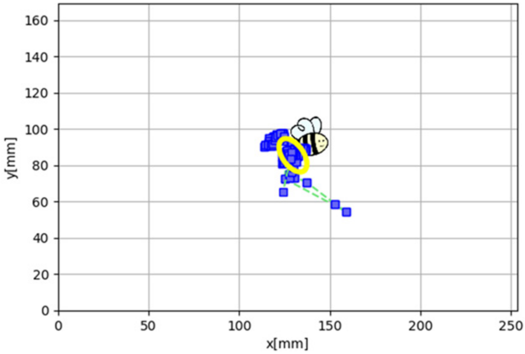

Figure 2.4. Fixation on a stimulus consisting of a stylized bee and a bivariate contour ellipse area (yellow ellipse) representing fixation stability (Altemir et al., 2021).

2.3. Eye movement control

Saccades are rapid eye movements that enable the gaze to move from one object of interest to another. These movements are ballistic and conjugate (Richardson et al., 2007; Purves et al., 2004). The initiation and precise direction of saccadic eye movements are controlled by the midbrain structure called the superior colliculus and the frontal eye field (FEF) located in Brodmann area 8. The upper neurons in these structures, each containing a topographic motor map, activate just before a saccade is made. As a specific area in the superior colliculus or the frontal eye field activates, it triggers a saccadic eye movement in a specific direction and distance, independent of the eyes' initial position in the orbit (Purves et al., 2004).

Each saccade is followed by a fixation during which visual information is processed (Rayner, 2009). Although the eyes appear stationary during fixation, the process is dynamic and involves several brain structures that also play roles in eye movement control. The position of the eyes during fixation is regulated and depends on the bilateral activation of the superior colliculus and the medioposterior cerebellum (MPC). Disruptions in activity within these structures can cause systematic deviations in eye position during both fixation and smooth pursuit movements. The superior colliculi and MPC determine where the eyes should remain during fixation and when to initiate the next saccade. The omnipause neurons in the raphe interpositus nucleus of the reticular formation are involved in fixation. During fixation, these neurons exhibit increased activity, which decreases during saccadic movements (Krauzlis et al., 2017).

2.3.1. Characteristics of eye movements during reading

During reading, saccades move the gaze from word to word (see Figure 2.5). The length and duration of saccades during reading are influenced by whether the text is read aloud or silently. When reading silently, the average saccade amplitude is approximately 2 degrees, or 7–9 letters, whereas when reading aloud, the amplitude is about 1.5 degrees. Fixations made while reading aloud are longer because the reader must verbally articulate each word. The average duration of a fixation while reading aloud is approximately 275–325 milliseconds, whereas it is about 225–250 milliseconds when reading silently. During a single fixation, a reader can perceive information about 3–4 characters to the left of the fixation point and 14–15 characters to the right of the fixation (Rayner, 2009). These saccade amplitudes, perceptual span, and average fixation durations are characteristic of skilled readers.

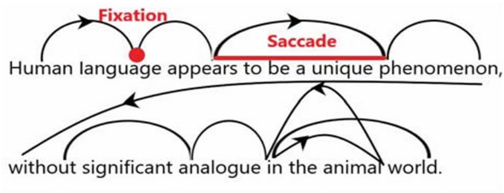

Figure 2.5. Graphical representation of saccadic eye movements and fixations during reading (Gündüz & Najjar, 2018).

When children begin to learn reading, their eye movement and text scanning habits are not deeply integrated, resulting in a symmetric perceptual span during fixation, meaning the number of symbols perceived to the right and left of the fixation point is equal. Approximately one year after the initiation of reading, the perceptual span becomes asymmetric, shifting in the direction of reading. While proficient readers can perceive information about 14–15 symbols to the right of the fixation point, emerging readers can perceive information about 11 symbols. The size of the perceptual span is influenced by text complexity. However, the size of the perceptual span does not affect the slow reading rate of beginner readers (Rayner, 1986).

As reading proficiency develops, the number of saccades made during reading decreases (Wertli et al., 2023), the amplitude of saccades in the reading direction increases, and the number of regressive saccades decreases (Strandberg et al., 2022). Additionally, the number of fixations per word decreases (Wertli et al., 2023; Spichtig et al., 2017), as does the total number of fixations made during reading (Spichtig et al., 2017). The duration of fixations during reading becomes shorter (Strandberg et al., 2022; Spichtig et al., 2017), and the overall reading speed increases with the development of reading skills (Wertli et al., 2023;

Spichtig et al., 2017). In elementary school children, a higher number of saccades and fixations may be observed if their native language differs from the language in which they are learning to read and receiving education, compared to peers who are learning to read in their native language. However, by ages 11–12, differences in eye movements during reading are no longer observed (Wertli et al., 2023). Eye movement parameters during reading are influenced not only by reading proficiency but also by text complexity. As text complexity increases, the amplitude of saccades decreases, the number of regressive saccades and fixation duration increases (Rayner, 1998).

Changes in eye movements during reading occur not only with the development of reading proficiency. Children with reading difficulties exhibit less structured and disorganized eye movement strategies during reading compared to children without reading difficulties (Lefton et al., 1979). Children with reading difficulties read more slowly (Spichtig et al., 2017), make more regressive saccades during reading (Lefton et al., 1979), and perform more fixations with longer durations compared to children without reading difficulties (Lefton et al., 1979; Spichtig et al., 2017). Among younger students, eye movement assessments not only correlate with existing reading proficiency but also predict reading proficiency outcomes for the following year based on the amplitude of saccades in the reading direction and average fixation duration (Strandberg et al., 2023). The study by Spichtig et al. (2017) concluded that longer fixations, a greater number of fixations, and more regressive saccades during reading are observed not only in younger students with reading difficulties but also in high school students.

3. METHOD

3.1. Development of the method

The method for assessing gaze fixation in school-aged children is based on evaluating eye movements during various visual tasks using eye-tracking equipment, with different processing algorithms applied for result analysis. Visual stimuli were developed based on scientific literature and an assessment of previously used methodologies for eye movement evaluation [P1].

The study involved 378 school-aged children from Marupes State Gymnasium, Marupes Elementary School, Rigas Cultures Secondary School, Kuldigas Center Secondary School. The study involved children from grades 1 to 6, aged 6 to 13 years. The total number of children in each grade group is shown in Table 3.1.

Table 3.1

The total number of children in each grade.

Grade	Boys	Girls	Total
1	33	26	59
2	34	29	63
3	31	36	67
4	39	38	77
5	26	28	64
6	20	28	48

Participation in the study was voluntary, and only those children whose parents or legal guardians provided written consent were included. Before granting consent, parents and legal guardians were briefed on the study protocol. The study was approved by the Ethics Committee of the University of Latvia and was conducted in accordance with the Helsinki Declaration.

The selection of children for the study was conducted by school speech therapists based on random sampling. Before testing the developed method, the school speech therapists assessed the reading skills of the selected children using the Acadience™ Reading test. This reading assessment test includes several subtests designed to evaluate various skills necessary for successful reading. The sets of subtests and assessment criteria are developed according to the children's age and the academic period during which the test is administered.

The composite score, which combines the results of each subtest, provides the most accurate assessment of a child's reading proficiency level (Kaminski et al., 2008).

3.1.1. Created visual stimuli

Gaze fixation stability assessment

Two stimuli were designed for evaluating fixation stability (see Figure 3.1). One stimulus consisted of a combination of a black circles (RGB: 0; 0; 0) and a white cross (RGB: 255; 255; 255). This stimulus was selected based on the study by Thaler et al. (2013), which identified it as effective in ensuring stable fixation. The use of attention grabbing stimuli promotes engagement of younger children in eye movement measurements (Irving et al., 2011), so a second stimulus was created as a stationary animation of a bee. The fixation stimuli were presented at the center of the screen. Prior to displaying the fixation stimuli, a black dot (RGB: 0; 0; 0) on a gray background (RGB: 180; 180; 180) was shown at the center of the screen for 3 seconds. Before starting the fixation task, children were instructed to focus only on the central part of the fixation stimulus as soon as it appeared on the screen. The duration of the fixation stimulus presentation was 10 seconds, but the fixation analysis includes the middle 9 seconds, excluding the first and last 0.5 seconds.

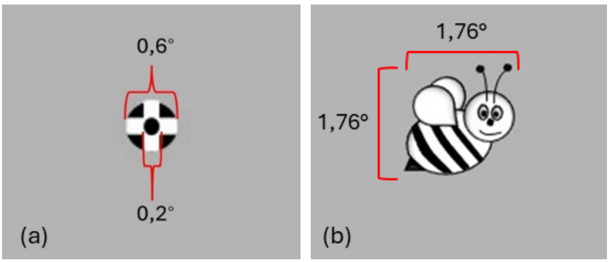

Figure 3.1. Fixation stimuli: (a) combination of a circle and cross, (b) a bee.

Assessment of fixation during reading

To assess eye movements during reading, age-appropriate reading stimuli were created for each age group to read during the reading task. These stimuli consisted of short texts that were both age-appropriate in terms of content and text technical characteristics (see Table 3.2). The texts were adapted from the teacher's guide "Lasītprasmes pārbaudes darbi 1.–4. klasei" (Logina, 2002). The text was displayed in black letters (RGB: 0, 0, 0) on a white background (RGB: 255, 255, 255).

Table 3.2

Grade 1	Angular size of one letter: ~ 0.71 degrees Line spacing: ~ 1.17 degrees Text width: 14.9 degrees Number of words: 24 Number of letters:123
Reiz kādā mājiņā uz maza zemes stūrīša dzīvoja māte ar dēlu. Katru dienu viņus apmeklēja zaķis. Tas nopostīja viņu dārziņu un noēda visus kāpostus.	
Grade 2	Angular size of one letter: ~ 0.66 degrees Line spacing: ~ 1.17 degrees Text width: 14.9 degrees Number of words: 24 Number of letters: 137
Pāri mežam vēlās lietus mākonis un lejup birdināja aukstas lāses. Tās pakšķēja lācītim uz pleciem, un bija gaužām nepatīkami. Viņš meklēja vietu, kur patverties.	
Grade 3	Angular size of one letter: ~ 0.60 degrees Line spacing: ~ 0.88 degrees Text width: 14.9 degrees Number of words: 31 Number of letters: 147
Te sniega un zaru mājoklī janvārī un februārī piedzimst mazie lācēni, parasti viens, divi vai trīs. Dažus mēnešus tie pavada kopā ar māti ik minūti, jo tā no migas nemaz neiziet.	
Grade 4–6	Angular size of one letter: ~ 0.60 degrees Line spacing: ~ 0.88 degrees Text width: 14.9 degrees Number of words: 24 Number of letters: 150
Pārbijušās peles uzrāpās Pelēkā kalna virsotnē. Ar šausmām viņas skatījās uz trakojošo upi. Bet ūdens cēlās arvien augstāk un augstāk, apdraudēdams Pelēkā kalna iedzīvotājus.	

The DEM test C card, designed for horizontal number naming similar to reading text, was also used as a reading stimulus. The original test card contains 80 numbers (Facchin, 2021), but to maintain the children's interest and to assess eye movements within a relatively short period, a modified shorter version with 40 numbers was used. The smallest space between two numbers was 1.4 degrees, while the largest was 6.7 degrees. The distance from the first to the last number on a line was 14.9 degrees, similar to the created reading stimuli. The size of the numbers was 0.55 degrees, and the line spacing was 0.33 degrees (see Figure 3.2). During the DEM test C card reading task, the children were instructed to name the numbers aloud as quickly and accurately as possible.

3	5			2			7		6
2		7			4	9			8
1			6	3		5			2
7	9		4					2	1
4				7		3	1		9
5		6				9		1	3
7	4			2		3			2
9			7		4		8		6

Figure 3.2. DEM Test C card.

3.1.2. Eye movement recording device

All eye movement measurements were conducted using the Tobii Pro Fusion eye tracker (Tobii AB, Sweden), (see Figure 3.3).

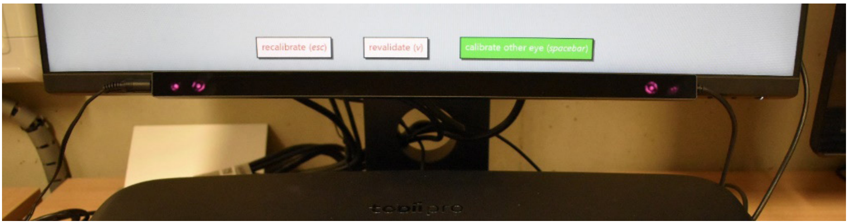

Figure 3.3. Tobii Pro Fusion eye tracker (Tobii AB, Sweden).

The operating principle of the device is based on detecting corneal reflection and pupil displacement. The device is equipped with two cameras, allowing it to capture images from both eyes, providing stable and accurate assessments of gaze direction and eye position in three-dimensional space. An infrared light source is used to create the corneal reflection. The device operates in both dark and bright pupil illumination modes. The Tobii Pro Fusion eye tracker can record eye movements at frequencies of 30 Hz, 60 Hz, 120 Hz, and 250 Hz. The device has an accuracy of 0.3 degrees and a precision of 0.2 degrees. Accuracy refers to how close the eye tracker's estimated point of gaze is to the actual point, while precision indicates the reliability of repeated measurements. Eye movement recording with the Tobii Pro Fusion is conducted binocularly, meaning both eyes are tracked simultaneously.

3.1.3. Measurement procedure

Before conducting measurements with the eye-tracking device, the visual acuity and binocularity of the selected children were assessed. Measurements with the eye-tracking device were only performed on children with binocular single vision (evaluated using the TNO test[1]) and whose uncorrected monocular visual acuity was at least Visus = 0.4 (in decimal units). This means that each eye separately had to be capable of recognizing optotypes corresponding to the specified visual acuity on a near vision acuity chart. At a distance of 65 cm, with this level of visual acuity, the smallest object that can be clearly seen is approximately 0.24 cm or 0.21 degrees in size. This visual acuity threshold was chosen to ensure that the child could clearly see both the text and other visual stimuli on the computer screen without glasses, even if they were normally worn. The use of glasses was not permitted during the measurements because reflections from the surfaces of the lenses could affect measurement accuracy (Gwon et al., 2014).

Before conducting the measurements with the eye-tracking device, the children's other visual functions, including stereopsis, were also assessed to analyze the relationship between visual function impairments and the evaluated eye movement parameters. Additionally, before starting the measurements, the dominant eye of each child was determined at a distance of 40 cm, as the dominant eye processes sensory information faster and more strongly (Shneor & Hochstein, 2005).

The visual stimuli were displayed on a computer monitor 65 cm away from the participant. The physical size of the monitor was 53.4 cm × 35.6 cm, and its display area was 52.70 cm × 29.64 cm. Before starting measurements for each participant, a calibration procedure was conducted, followed by a calibration validation procedure. During calibration, fixation points are displayed at various locations on the screen, and participants are instructed to look at them as accurately as possible. In this study, a five-point calibration was performed, meaning the fixation stimulus was presented at five points on the screen. The calibration procedure was performed monocularly, meaning it was done separately for each eye. During both the calibration and the actual measurement, the child's head was supported by a chin and forehead rest to prevent unnecessary head movements that could affect the measurement results and to ensure the head was aligned with the central part of the monitor (see Figure 3.4).

[1] A test based on the random dot stereogram principle, designed for the quantitative evaluation of stereopsis and also including a suppression test (*Walraven,* 1975).

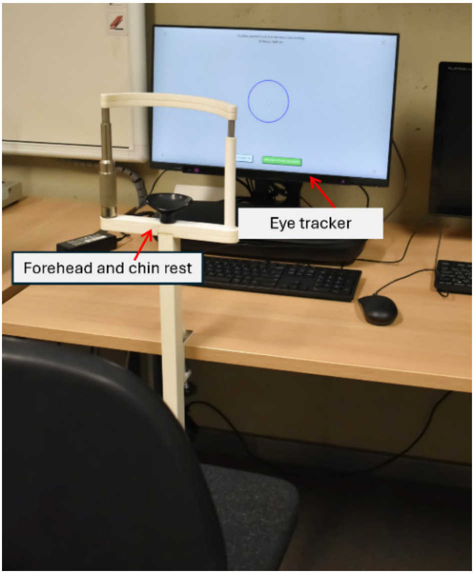

Figure 3.4. Measurement setup layout.

Eye movements were recorded simultaneously for both eyes using the Tobii Pro Fusion device operating at a 250 Hz frequency. The experimental design for the visual tasks was created in the Titta Master toolbox (Niehorster et al., 2020), and its operation was synchronized with the eye-tracking device during the recording of eye movements. Titta Master toolbox also offers monocular calibration options, and it can be synchronized not only with the Tobii Pro Fusion eye tracker but also with other devices.

During the visual task performance, a RAW data file was recorded for each child. The eye-tracking RAW data file includes information on gaze coordinates on the screen for both the right and left eyes, pupil size, missing data, time of eye movement recording and other data. To extract fixations and obtain information on their duration, number, location on the screen and the stability of each fixation, the I2MC (Identification by Two-Means Clustering) algorithm was used. Compared to other similar algorithms, such as the Binocular-Individual Threshold (BIT) algorithm (Lans et al., 2011) or the C-DT algorithm (Veneri et al., 2011), which are designed for detecting fixation moments in RAW eye movement data, the I2MC algorithm is recognized as the most appropriate for analyzing data with high noise levels and missing data, making it especially suitable for analyzing children's data (Hessels et al., 2017). The algorithm's flowchart is shown in Figure 3.5.

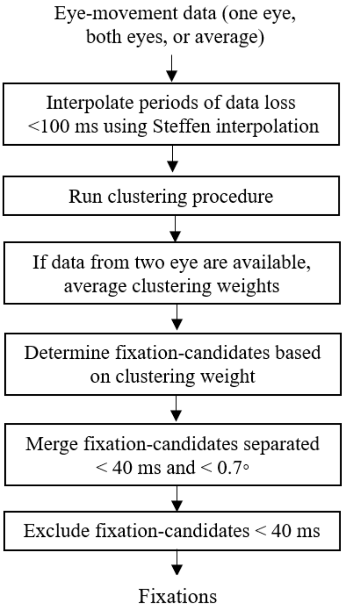

Figure 3.5. Flow-chart of the I2MC algorithm (Hessels et al., 2017).

The I2MC algorithm enables the analysis of each eye's fixation separately and allows for the evaluation of binocular fixation by incorporating data from both eyes into the analysis. This capability is particularly useful for assessing gaze fixation stability, as it allows for the analysis of both monocular fixation stability and binocular fixation stability. Gaze fixation stability was expressed as the bivariate contour ellipse area (BCEA), which was calculated using the following formula:

$$BCEA = 2k\pi\sigma_H\sigma_V(1 - \rho^2)^{\frac{1}{2}}$$

σ_H – the fixation standard deviation in the horizontal meridian;

σ_V – the fixation standard deviation in the horizontal meridian;

ρ – the Pearson product-moment correlation coefficient between the two meridians;

k is 1.14, as the chosen probability area is 68% (Crossland & Rubin, 2002).

The BCEA value is expressed in degrees^2. A smaller BCEA value indicates more stable fixation.

4. RESULTS

4.1. The impact of eye dominance on fixation stability

Eye dominance can influence various eye movement parameters, such as saccadic velocity (Oishi et al., 2005) and the accuracy of smooth pursuit eye movements (Elbaum et al., 2017). Since it is unclear if there is a difference in fixation stability between the dominant and non-dominant eye in children, and whether eye dominance should be considered in studies analyzing gaze fixation stability when selecting one eye, the effect of eye dominance on fixation stability in school-aged children was assessed using the developed methodology [P1].

Children whose fixation stability and dominant eye were assessed were divided into six age groups (see Table 4.1). The results obtained from the fixation stability assessment using the fixation stimulus (a) were used.

Table 4.1

The total number of children and the distribution of dominant eyes in each age group.

Age (years)	**Number of children (*n*)**	**Dominant eye**	
		Right	**left**
7	44	31	13
8	49	34	15
9	47	33	14
10	54	37	17
11	55	41	14
12	31	19	12

Since the Shapiro-Wilk test results indicate that the fixation stability measurement values of the study participants do not follow a normal distribution ($p < .05$), the non-parametric Wilcoxon signed-rank test was used to compare if there is a significant difference in fixation stability between the dominant and non-dominant eyes in each age group. The results show that fixation in the dominant eye is significantly more stable than in the non-dominant eye for 7-year-old children ($Z = -2.101$, $p = .036$) and 8-year-old children ($Z = -2.601$, $p = .009$), while no significant difference between the dominant and non-dominant eyes was found among children of other ages (see Table 4.2).

Table 4.2

Fixation stability (mean ± standard deviation) in the dominant and non-dominant eye in each age group. Highlighted are the age groups where a significant difference in fixation stability between the dominant and non-dominant eye was observed [P2].

Age (years)	Dominant eye, BCEA (degrees²) ± SD	Non-dominant eye, BCEA (degrees²) ± SD	*p*
7	***0.52 ± 0.26***	***0.59 ± 0.32***	***0.036***
8	***0.44 ± 0.27***	***0.49 ± 0.29***	***0.009***
9	0.42 ± 0.23	0.44 ± 0.25	0.634
10	0.44 ± 0.24	0.42 ± 0.22	0.651
11	0.41 ± 0.24	0.42 ± 0.26	0.880
12	0.40 ± 0.29	0.40 ± 0.34	0.601

The Spearman's rank correlation coefficient r_s indicates a correlation between the children's age and fixation stability in the dominant eye ($r_S = 0.181$, $n = 280$, $p = .02$) and the non-dominant eye ($r_S = 0.272$, $n = 280$, $p < .001$). Additionally, it is observed that as age increases, fixation becomes more stable in both the dominant and non-dominant eyes (see Figure 4.1)

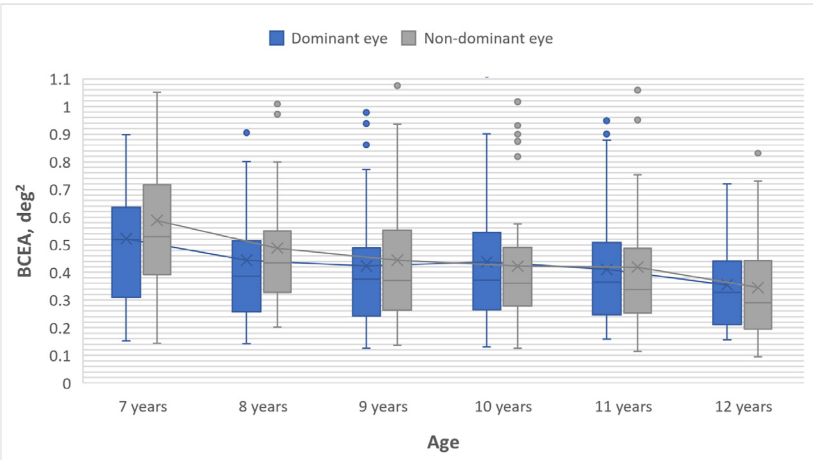

Figure 4.1. Comparison of gaze fixation stability between the dominant and non-dominant eyes across children's age groups. Box plots present interquartile range, upper on lower whisker, median value marked with a line and mean value marked with a cross. Box plots are connected with trend line at their mean values [P2].

It was compared whether there is a difference in fixation stability between the right and left eyes, without considering eye dominance. Using the Wilcoxon signed-rank test, it was found that there are no statistically significant differences in fixation stability between the right and left eyes in any of the age groups (see Table 4.3).

Table 4.3

Fixation stability (mean ± standard deviation) in the right and left eyes in each age group [P2].

Age (years)	Right eye, BCEA (degrees^2) ± SD	Left eye, BCEA (degrees^2) ± SD	*p*
7	0.55 ± 0.27	0.56 ± 0.31	0.852
8	0.45 ± 0.26	0.48 ± 0.29	0.441
9	0.44 ± 0.24	0.43 ± 0.25	0.751
10	0.42 ± 0.23	0.44 ± 0.23	0.265
11	0.41 ± 0.24	0.42 ± 0.26	0.675
12	0.32 ± 0.14	0.38 ± 0.20	0.078

The Spearman's rank correlation coefficient indicates a correlation between children's age and fixation stability in the right eye ($r_S = 0.245$, $n = 280$, $p < .001$) and the left eye ($r_S = 0.213$, $n = 280$, $p < .001$). It is observed that as age increases, fixation becomes more stable in both eyes (see Figure 4.2)

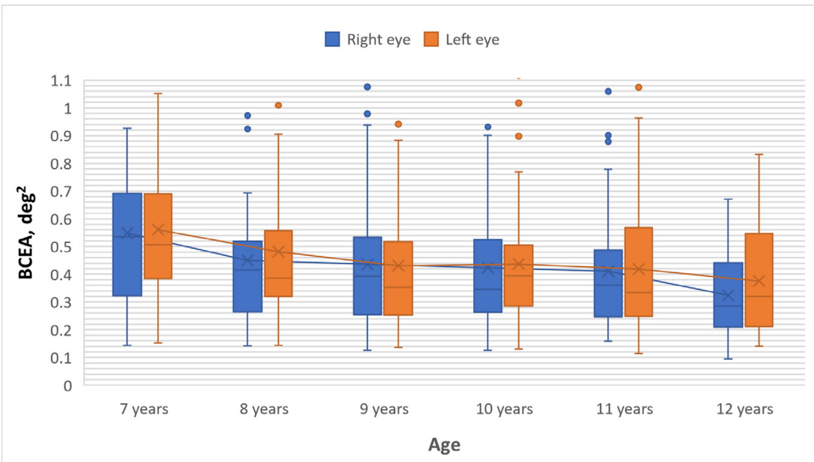

Figure 4.2. Comparison of gaze fixation stability between the right and left eyes across children's age groups. Box plots present interquartile range, upper on lower whisker, median value marked with a line and mean value marked with a cross. Box plots are connected with trend line at their mean values [P2].

4.2. The relationship between gaze fixation stability and stereoacuity assessment

Since studies indicate that the use of various three-dimensional visualizations in the educational process can enhance learning outcomes, and that effective use of these visualizations requires good stereopsis or depth perception (Wainman et al., 2020; Bogomolova et al., 2021), this study examined whether there is a relationship between binocular gaze fixation stability and stereoacuity [P3].

Children who were assessed for fixation stability and stereoacuity were grouped according to the age and the results of the stereoacuity assessment (see Table 4.4). In the TNO test, reduced stereoacuity is defined as 120 arcseconds or worse, while normal stereoacuity corresponds to at least 60 arcseconds (Williams et al., 1988). The results obtained from the fixation stability assessment using the fixation stimulus (a) were used to evaluate binocular fixation stability.

Table 4.4

Distribution of participants by age and stereoacuity [P3].

	Group 1 (7–8 year)	**Group 2 (9–10 year)**	**Group 3 (11–12 year)**
Normal stereoacuity (≤ 60 arcsec)	n = 49	n = 37	n = 38
Reduced stereoacuity (≥ 120 arcsec)	n = 36	n = 32	n = 27

The Mann-Whitney U test results show that binocular fixation stability significantly differed between children with reduced and normal stereoacuity only in the first group (U = 507, p = .001), meaning that children with less stable fixation also had reduced stereoacuity. In the second group, children with normal stereoacuity had more stable fixation compared to children with reduced stereoacuity, but the difference was not significant (U = 580, p = .09). In the third group, there was a tendency for children with normal stereoacuity to have more stable fixation than children with reduced stereoacuity, but the difference was not significant (U = 455, p = .44), (see Figure 4.3).

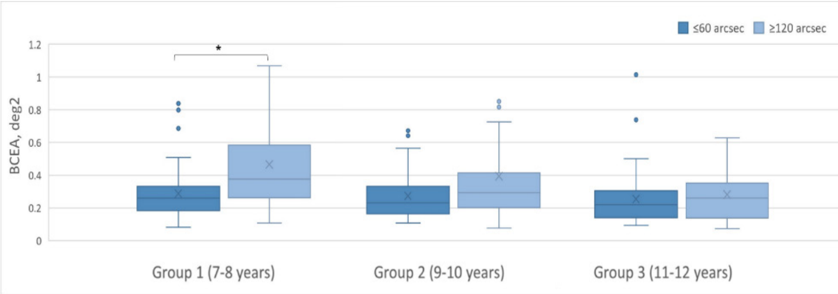

Figure 4.3. Fixation stability in children with normal and reduced stereoacuity in each age group [P3].

The Kruskal-Wallis test results also revealed that fixation stability significantly differed between age groups in children with reduced stereoacuity ($\chi^2(2) = 7.785$, $p = .02$). Fixation stability also varied among age groups in children with normal stereoacuity, but this difference was not significant ($\chi^2(2) = 3.589$, $p = .15$), (see Table 4.5).

Table 4.5

Age-related changes in fixation stability in children with normal and reduced stereoacuity [P3].

	Group 1 (7–8 year)	**Group 2 (9–10 year)**	**Group 3 (11–12 year)**	***p***
BCEA (children with normal stereoacuity)	0.29 ± 0.16 deg^2	0.27 ± 0.14 deg^2	0.25 ± 0.18 deg^2	0.15
BCEA (children with reduced stereoacuity)	0.47 ± 0.32 deg^2	0.39 ± 0.36 deg^2	0.28 ± 0.16 deg^2	0.02

4.3. The impact of eye tracker sampling rate on fixation stability measurement

Although studies analyzing gaze fixation stability expressed as the bivariate contour ellipse area (BCEA) use different eye-tracking device sampling frequencies, there have been limited studies on whether the device sampling frequency affects the assessment of this fixation parameter. Therefore, gaze fixation stability was evaluated and compared at various frequencies in 11 adults aged 20 to 30 years (mean age 24 years). Fixation stability measurements were performed using three operating frequencies of the Tobii Pro Fusion eye tracker: 60 Hz, 120 Hz, and 250 Hz. Stimulus (a) was used for the fixation task [P4].

The mean values of binocular fixation stability (BCEA) determined using measurements with different eye-tracking device sampling frequencies are shown in Table 4.6.

Table 4.6

BCEA values measured with three different eye tracker sampling rates [P4].

	Eye tracker sampling rate		
	60 Hz	120 Hz	250 Hz
BCEA, deg^2 (mean ± SD)	0.114 ± 0.044	0.134 ± 0.045	0.135 ± 0.04

The results of the repeated measures ANOVA test indicate that no significant difference in fixation stability assessment was observed when measurements were taken using different eye-tracker sampling frequencies ($F(2, 20) = 2.955$, $p = .075$), (see Figure 4.4)

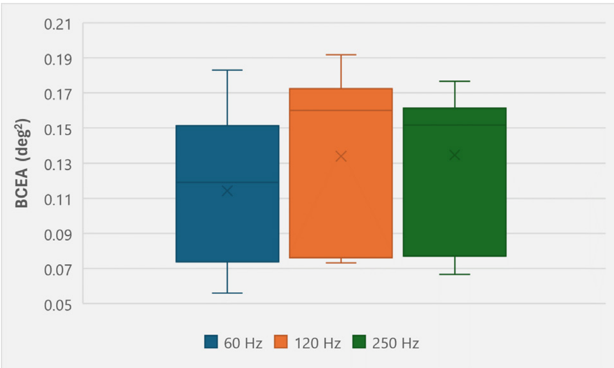

Figure 4.4. The measurement of fixation stability using different eye tracker sampling rates [P4].

The results show that there is a strong correlation between each participant's fixation stability measurements at different eye-tracker sampling frequencies (see Table 4.7).

Table 4.7

Correlation between the BCEA value across all eye-tracker sampling rates [P4].

Frequence	60 Hz	120 Hz	250 Hz
60 Hz		$r = 0.706$, $p = 0.015$	$r = 0.766$, $p = 0.006$
120 Hz	$r = 0.706$, $p = 0.015$		$r = 0.725$, $p = 0.012$
250 Hz	$r = 0.766$, $p = 0.006$	$r = 0.725$, $p = 0.012$	

4.4. The relationship between parameters analyzed in the reading task and reading assessment

Using the developed methodology, eye movements during the reading task were assessed. To determine the relationship between eye movement parameters and reading performance, correlations were analyzed between parameters such as the total reading task execution time, mean fixation duration, and the number of fixations with the child's individual composite score on the Acadience™ Reading test [P5].

Analyzing the results of 53 second-grade children, it was found that there is a moderately strong correlation between the composite score and the mean fixation duration during reading ($r = -0.604$, $n = 53$, $p < .001$), (see Figure 4.5). The Acadience™ Reading test indicated that 28% of children in this group exhibited reading difficulties. Dividing the children into two subgroups based on their reading assessment, it was determined that children with reading difficulties had significantly longer fixations ($M = 701$ ms, $SD = 286$) compared to those without reading difficulties ($M = 462$ ms, $SD = 132$), ($t(16) = 3.106$, $p < .007$).

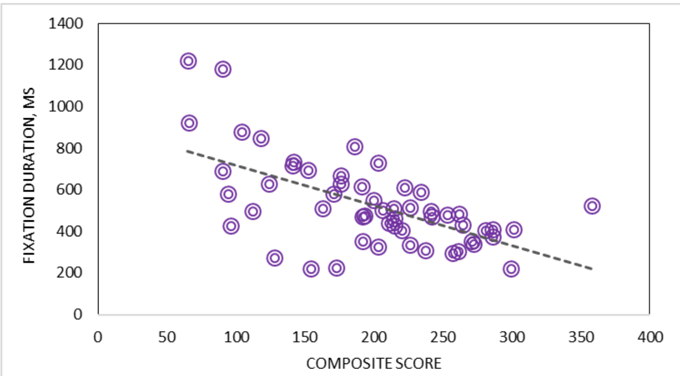

Figure 4.5. A correlation between the fixation duration and the composite score [P5].

Analyzing the relationship between the total performance time of the reading task and the composite score, a moderately strong correlation is observed ($r = -0.619$, $n = 53$, $p < .001$), (see Figure 4.6).

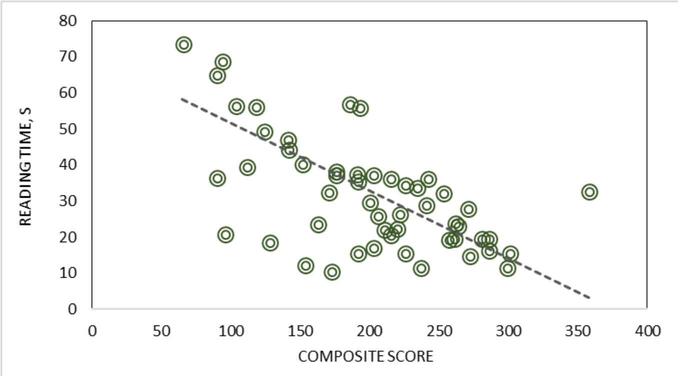

Figure 4.6. A correlation between the reading time and the composite score [P5].

Although the correlation coefficient is lower than for the two previously mentioned parameters, there is still a moderate relationship between the composite score and the total number of fixations observed (r = −0.400, n = 53, p = .003), (see Figure 4.7).

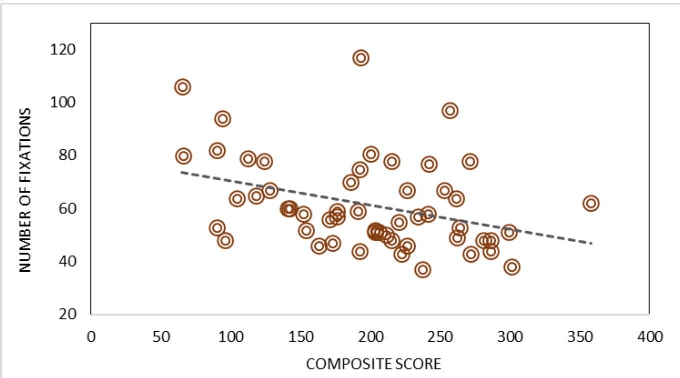

Figure 4.7. A correlation between the number of eye fixations and the composite score [P5].

4.5. The relationship between fixation duration in the DEM test and reading assessment

Although the DEM test is designed to assess eye movements under conditions similar to reading, it does not provide a quantitative assessment of eye movements during its clinical administration. By using eye-tracking devices, it is possible to conduct an in-depth analysis of eye movements during this test and determine how significantly parameters such as fixation duration are related to reading performance and fixation duration during reading [P6].

Comparing the mean fixation duration of 57 fourth-grade children (ages 9–11, mean age 10 years) in the DEM test (M = 353 ms, SD = 53) and during the reading task (M = 472 ms, SD = 163), it was found that fixations were significantly shorter during the DEM test ($t(56) = -6.01$, $p < .001$). The results of the correlation analysis indicate that, although weak, there is a relationship between fixation duration in the DEM test and during the reading task (r = 0.349, n = 57, p = .008), (see Figure 4.8).

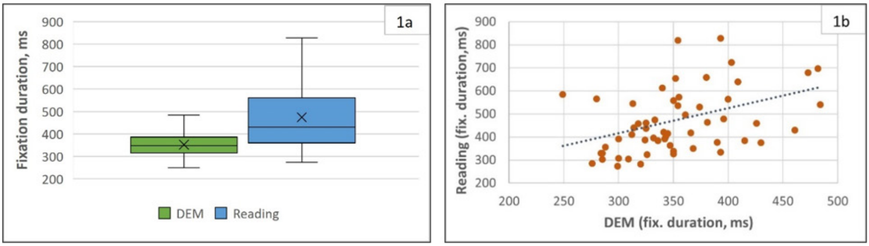

Figure 4.8. The fixation duration in the DEM test and during reading (1a) and a correlation between the fixation duration in the DEM test and during reading (1b) [P6].

Correlation analysis revealed a moderately strong relationship between fixation duration during reading and the composite score on the Acadience™ Reading test (r = 0.698, n = 57, $p < .001$). However, the relationship between the composite score, which characterizes reading performance, and the mean fixation duration in the DEM test was weak (r = 0.141, n = 57, p = .295).

DISCUSSION

Manual eye movement assessment methods do not provide a detailed and accurate assessment of the oculomotor system, including gaze fixation and its parameters. These limitations of manual eye movement assessment methods highlight the need for an objective eye movement assessment approach.

In this study, objective assessment of gaze fixation was performed in 378 school-aged children. The method for assessing gaze fixation in school-aged children was based on the assessment of eye movements during various visual tasks using an eye tracking technology. The visual stimuli were developed based on scientific literature and an evaluation of the previously used methodology for eye movement assessment [P1]. To improve the methodology for assessing gaze fixation, the study also evaluated the influence of various endogenous and exogenous factors on gaze fixation parameters.

Various eye-tracking devices, which may have different characteristic parameters, can be used for the objective assessment of gaze fixation parameters. When evaluating the impact of the eye-tracking device's sampling frequency on fixation stability measurement results, expressed as the bivariate contour ellipse area (BCEA), it was concluded that this characteristic parameter of the device does not significantly affect the fixation measurement results. This indicates that devices with lower sampling frequencies can also be used for accurate fixation stability assessment [P4]. Similar results were obtained when comparing fixation stability measurements performed using microperimeters with integrated eye-tracking technology (Liu et al., 2015). However, the sampling frequencies of these microperimeters were 25 Hz and 8 Hz, which are considered very low for eye movement assessment (Andersson et al., 2010). It was also observed that the sampling frequency of eye-tracking devices does not affect fixation stability assessment in the study by Maniarasu et al. (2023). Unlike the study conducted in this work, the study by Maniarasu et al. (2023) involved a single eye-tracking recording using a 500 Hz device frequency and reduced the initial dataset to match the volume characteristic of lower frequencies. In this study, a separate recording was performed for each eye-tracking device frequency. Overall, the findings that accurate gaze fixation assessment can be achieved even with lower frequency devices suggest that eye-tracking equipment does not need to be expensive and restricted to scientific laboratories. This encourages vision specialists to use eye-tracking devices in their practices for objective and quantitative eye movement assessment, which cannot be achieved with existing manual tests.

Previous studies on the adult population suggest that either eye dominance has no significant effect on gaze fixation stability (Raveendran et al., 2019), or that fixation in the dominant eye is slightly more stable (Vikesdal & Langaas, 2016). Since the impact of eye dominance on fixation stability in school-aged children has not been analyzed so far, there are no unified guidelines on which eye's measurement results should be selected when analyzing monocular fixation stability. The results obtained in this study make a significant contribution to improving the methodology for assessing monocular fixation stability in children [P2]. Given the results of this study, eye dominance can significantly affect the results, so in studies analyzing data from one eye, attention should be paid to which eye is chosen. This is especially important in studies involving younger children, as fixation in the dominant eye is significantly more stable than in the non-dominant eye for children under the age of 8.

Evaluating the relationship between age and gaze fixation stability revealed that both binocular [P3] and monocular [P2] fixation become more stable as children grow older. Given that this study provides a quantitative assessment of both binocular and monocular gaze fixation stability, the fixation stability values described in the study can serve as reference values to make conclusions about a child's fixation stability development relative to their age. The assessment of fixation stability is important not only for evaluating its development but also because binocular gaze fixation stability can be an indicator of the quality of stereovision, particularly in children under the age of 8 [P3]. Reduced stereoacuity may also be linked to reading difficulties (Christian et al., 2018).

When analyzing both monocular and binocular fixation stability, it should be noted that the children in the study were assessed for fixation stability without their refractive correction if the visual acuity criterion was met without it. The literature suggests that minor refractive errors do not significantly affect fixation stability (Ukwade & Bedell, 1993), while the presence of amblyopia can influence both fixation stability (Aizenman & Levi, 2021; González et al., 2012) and the quality of stereovision (Aizenman & Levi, 2021). The visual acuity criterion chosen in this study, determined prior to performing measurements with the eye-tracking device, does not completely rule out the possibility of amblyopia among the children. This factor must be considered, as it may affect the individual child's fixation stability assessment. However, since the prevalence of amblyopia in European countries is approximately 2.66% (Hu et al., 2022), its occurrence among children should not significantly impact the overall fixation stability assessment for each group. Nonetheless, a limitation of the study is that gaze fixation was not assessed in children whose vision problems require constant use of glasses.

To assess fixation of gaze during reading, specific reading tasks were created, consisting of a short, age-appropriate text. Several studies (Lefton et al., 1979; Spichtig et al., 2017; Strandberg et al., 2022) suggest that longer fixations during reading characterize children with poorer reading skills, and that children with poorer reading skills perform more fixations during reading

(Lefton et al., 1979; Spichtig et al., 2017). It was found that the duration of fixations during the reading task correlates with children's reading skills, as assessed by the Acadience™ Reading test [P5, P6], and this correlation is stronger than the correlation between the number of fixations and reading performance [P5]. Despite the reading tasks being only 24 words long, a positive correlation was observed between the total time taken to complete the reading task and reading performance [P5]. By using the developed reading stimuli, not only the assessment of gaze fixation but also the overall evaluation of eye movement parameters during reading can be completed in a relatively short time.

Since the DEM test's C card is designed to simulate the eye movements performed during reading, C card was also used as a reading stimulus. The fixation parameter assessed during this stimulus was fixation duration. It was found that the fixation duration in the DEM test was significantly shorter than during actual reading. As previous studies have not directly compared fixation durations between these two tasks, this finding provides an important contribution to the understanding of eye movement parameters during DEM test performance [P6]. The shorter fixations observed during the DEM test, compared to those during reading, might be explained by the different cognitive demand, which may be lower during the DEM test (Reney et al., 2014; Zegermann et al., 2016). Although the DEM test is designed to assess eye movements under conditions similar to reading, the fixation durations during this test show only a weak correlation with reading performance [P6], whereas fixation durations during reading tasks are more indicative of reading performance (Lefton et al., 1979; Spichtig et al., 2017; Strandberg et al., 2022). Given that the fixation parameters evaluated in the text-based reading stimuli [P5, P6] show a stronger correlation with reading performance than reading stimulus consisting of the DEM test's C card [P6], it can be concluded that the DEM test is not suitable for evaluating reading-related fixation parameters.

SUMMARY

As part of the thesis, an objective assessment of gaze fixation in school-age children was conducted. The work provides a detailed description of the stimuli used for assessing gaze fixation, with their selection and development based on scientific literature and previously established insights into eye movement assessment methodology. The process of evaluating gaze fixation parameters and obtaining the results is also explained.

The results provide new methodological insights for accurately assessing monocular fixation stability. It was found that binocular fixation stability evaluation can be used to infer the quality of stereopsis, one of the most crucial visual functions. Additionally, it was concluded that the eye movement parameters in the widely used DEM test differ from those during reading, making text-based stimuli more suitable for evaluating reading-related fixation parameters. Overall, reading ability significantly impacts the parameters of fixations during reading.

The work provides quantitative values for both binocular and monocular gaze fixation stability, which can be used as reference values to draw conclusions about a child's fixation stability development. Since it has been determined that the operating frequency of eye-tracker does not significantly affect the gaze fixation assessment results, expressed as bivariate contour ellipse area (BCEA), objective and accurate assessment of fixation stability can be performed using various eye-trackers.

The work also provides quantitative values for individual eye fixation parameters during reading. However, further analysis is needed to draw conclusions about how these eye movement parameters change with age.

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