A Systematic Review of Eye-Tracking Technology in Dyslexia Diagnosis

Leonie Coenen
Matthias Grünke
School of Human Sciences, University of Cologne, Germany

Sebastian Becker-Genschow
Kirsten Schlüter
School of Mathematics and Natural Sciences, University of Cologne, Germany

Matthias Schulden
Anne Barwasser
School of Human Sciences, University of Cologne, Germany

This paper presents a systematic literature review aimed at consolidating knowledge on the application of eye-tracking technology in the diagnosis of dyslexia among school-aged children (6–12 years). Through a meticulous search and selection process, 20 studies conducted over the last 10 years were identified and analyzed to evaluate the effectiveness of this technology. The findings highlight the varied methodologies, participant demographics, and outcomes of these studies, underscoring the potential of eye tracking as a non-invasive, objective tool in the early detection of and intervention for dyslexia. Despite facing limitations such as heterogeneity in study designs and the need for standardized protocols, this review illuminates the significant promise of eye-tracking technology in enhancing dyslexia diagnosis. It identifies gaps in current research, proposes avenues for future investigation, and offers evidence-based recommendations for practitioners. This endeavor not only enriches the present understanding of dyslexia diagnosis, but also establishes a foundation to ultimately improve educational outcomes for dyslexic learners.

Keywords: **dyslexia diagnosis, eye-tracking technology, school-aged children, saccades and fixations, educational assessment**

Introduction

The Critical Role of Literacy in Society

In modern, knowledge-based societies, essential literacy skills, including reading and writing, are crucial for full participation in community life (Grafwaller, 2023; Urban, 2023). The lack of proficiency in these areas

Insights into Learning Disabilities is published by Learning Disabilities Worldwide (LDW). For further information about learning disabilities, LDW's many other publications and membership, please visit our website: www.ldworldwide.org.

can adversely affect an individual's educational journey and significantly limit their access to quality apprenticeships, higher education, and employment opportunities that offer satisfactory remuneration (Bachore, 2022; Talwar et al., 2023). Beyond impacting one's professional life, this shortfall also hampers engagement in leisure pursuits, such as reading for enjoyment or navigating digital platforms like social media. Furthermore, routine written exchanges with family, friends, and colleagues through emails, messaging apps, and other platforms necessitating written language become considerably challenging (Elliott & Grigorenko, 2014; Lachmann & Weis, 2018).

Dyslexia: Implications and Identification

Most individuals successfully acquire adequate literacy skills during their schooling without significant issues. However, a considerable portion of the population experiences difficulties with reading and writing, even to the extent that their struggles align with the characteristics of dyslexia – the proportion of this group is often reported to be between 3% and 7% (Wagner et al., 2020). This learning disorder is marked by significant challenges in decoding written language, stemming from difficulties in identifying speech sounds and understanding their association with letters and words, which implicates specific language-processing regions of the brain. Individuals with dyslexia, who typically possess normal intelligence and vision, often find the following tasks to be extremely challenging: reading fluently, spelling accurately, decoding words, and (in some cases) writing coherently (Reid, 2016).

The importance of diagnosing dyslexia as early as possible cannot be overstated; preliminary detection and intervention can significantly alter the educational trajectory and self-esteem of affected individuals. Early assistance allows for harnessing the brain's adaptability during childhood, making it easier to develop effective reading strategies and mitigate many of the challenges posed by dyslexia (Colenbrander et al., 2018; Wagner & Lonigan, 2023). Although dyslexia is a lifelong condition, evidence suggests that with appropriate support and educational interventions, individuals with dyslexia can enhance their reading skills and achieve success in both academic and professional settings. Therefore, prioritizing early diagnosis and tailored interventions is crucial for empowering individuals with dyslexia to reach their full potential (Steacy et al., 2023).

Traditional Methods to Identify Dyslexia

Preliminary and precise identification of dyslexia is critical for providing the necessary support to mitigate its adverse effects (Colenbrander et al., 2018). Traditionally, dyslexia has been diagnosed through standardized testing, which involves evaluating reading, writing, spelling, phonological processing, and sometimes oral language skills for comparing an individual's

performance to normative age or grade-level expectations. These instruments are complemented by educational and psychological evaluations to assess intellectual abilities, academic achievements, and various cognitive and processing abilities. Additionally, interviews and questionnaires are utilized to collect detailed information from the individual, parents, and educators about one's developmental history, educational background, and any behavioral concerns (Christo et al., 2009; Elbeheri & Eid, 2022). While these traditional methods are invaluable, they also have several limitations: They are time-consuming, can be stressful for children, rely on the subjective interpretation of results, and may not fully account for cultural or linguistic diversity, potentially disadvantaging some individuals. Moreover, the dependency on observable academic difficulties before initiating testing can lead to a postponement in the application of critical interventions (Mather & Wendling, 2011).

Eye-tracking technology: A Novel Diagnostic Approach

An alternative to traditional diagnostic methods is the analysis of eye movements during reading, using eye-tracking technology. This approach facilitates measuring eye movements noninvasively in high temporal and spatial resolution. Eye tracking is already being used successfully as a research method in a wide range of scientific disciplines, for example, in neuroscience, psychology, and market research. However, the method is also increasingly being applied in cognitive psychology and empirical educational research (Jarodzka et al., 2017). Basically, eye movements are divided into fixations (points where the eyes stop) and saccades (jumps between fixations), the analysis of which allows conclusions to be drawn about cognitive absorption and processing of information. Eye movement data are interpreted based on the eye-mind hypothesis developed by Just and Carpenter (1980) and later confirmed by neuropsychology (Kustov & Robinson, 1996); per the hypothesis, only visually fixated information becomes cognitive, and this processing starts without delay.

The eye tracking approach to diagnosing dyslexia involves collecting objective data on reading behavior through identifying patterns, such as prolonged and frequent fixations on words, a high number of regressions (indicated by the eyes moving back to previously read text), and challenges with smooth eye movements across lines of text. These patterns suggest underlying difficulties with phonological processing and visual attention, common in dyslexia cases. Eye-tracking technology involves the use of cameras and infrared light sources to track eye movements. The technology is primarily focused on the difference in light reflection from the cornea, which covers the front of the eye, and the pupil. The pupil reflects very little to no light, appearing as a dark spot in the camera image, and the position of this dark spot is used in the software to determine the pupil's location. However, the main goal is to measure not the pupil's position in the camera image, but rather the gaze direction on a computer monitor or

digital display screen. For this, the eye tracker needs to be calibrated. During calibration, small points appear on the screen at various locations, which the participant is instructed to fixate on. This process allows the eye tracker to "learn" the relationship between the student's position in the camera image and the gaze position on the screen. Eye tracking devices can range from mounted systems for computers to wearable glasses for more natural reading scenarios. Additionally, a computer or digital display screen is necessary to present reading materials or tasks, and specialized software is required to calibrate the eye tracker, administer tasks, record eye movement data, and analyze patterns of eye movements to generate detailed metrics, such as fixation duration, saccades, and regressions (Neruŝil et al., 2021; Shalileh et al., 2023).

In diagnosing dyslexia, the eye-tracking device is first calibrated for a specific participant to tailor it to their individual gaze patterns. The individual is then exposed to reading materials of varying complexity, while the device records their eye movements, capturing details such as the duration and frequency of eye fixations, saccades, and regressions. After the reading task, the software analyzes the data to identify patterns that are characteristic of dyslexia. These results, interpreted in the context of known dyslexia-associated eye movement behaviors, provide objective insights into the individual's reading challenges, complementing traditional diagnostic assessments (Benfatto et al., 2016).

The use of eye-tracking technology in the diagnosis of dyslexia presents several advantages: It is less time-consuming than traditional methods, imposes minimal stress on participants, and reduces the fear of failure associated with testing environments. This method is a passive form of assessment requiring individuals to simply engage with text on a screen instead of responding to questions or performing difficult tasks; it thus alleviates performance pressure. Furthermore, eye-tracking technology is recognized for its potential to provide objective, quantifiable data on reading behavior, highlighting difficulties associated with dyslexia. Nevertheless, its validity as a standalone diagnostic tool requires further investigation (Rello & Ballesteros, 2015).

Objective of the Study

Through this paper, we aim to compile as comprehensive and significant a body of knowledge as possible on the application of eye-tracking technology in diagnosing dyslexia, with a special focus on school-aged children (6–12 years). We seek to offer a broad overview of existing studies on dyslexia assessment in this age group through eye-tracking technology, summarizing their findings, methodologies, and key insights. Through mapping out the research landscape of this area, this paper aims to highlight trends, discuss the diversity of approaches, and underscore any emerging patterns or conclusions that have been drawn. This effort is intended to inform both researchers and practitioners

about the current state of knowledge in the field, serving as a foundation for future research, practice, and policy development concerning the use of eye-tracking technology in the early identification and understanding of dyslexia among school-aged children.

Method

This study involves a systematic literature review focused on the use of eye-tracking technology in the diagnosis of dyslexia. We employed a rigorous and explicit set of procedures to search for, select, and critically appraise research studies. To ensure the process was carried out with the utmost professionalism, we adhered to the PRISMA 2020 guidelines as our standard (Page et al., 2021). Central to these directives is a detailed checklist comprising seven sections with 27 items, ensuring thorough and transparent reporting. Our adherence to it guarantees that the research methodology and findings are reported with clarity and integrity, covering all essential aspects from study selection to results synthesis. We used the PRISMA website (http://www.prisma-statement.org) for the checklist and flow diagram; its accessible templates and web application facilitated compliance and reporting efficiency.

To identify relevant studies, we searched five online databases expected to contain pertinent literature on the topic: APA PsycInfo, ERIC, PSYNDEX, TOC Premier, and MEDLINE. In the systematic search, conducted in August 2023, we covered publications from 2013 onward to ensure the timeliness of the studies included. Our search algorithm was "development* AND (eye tracking OR eye gaze OR eye tracker OR eye movement measurements) AND dyslex*." The terms "development*" and "dyslex*" were specifically chosen to pinpoint studies focused on developmental dyslexia and intentionally omit research on acquired dyslexia; to clarify, our emphasis on "development*" is aimed at exploring dyslexia that emerges during the educational development of individuals, typically recognized in school-aged children facing difficulties in learning to read and write. Such developmental dyslexia is in contrast to acquired dyslexia, which results from brain injury and is not the focus of our review. To be considered for inclusion in our review, each paper had to meet the criteria outlined below, in addition to being published in or after 2013:

1. The article must describe a primary study that was published in an academic journal.
2. The article must be written in English.
3. The article must have been published in a peer-reviewed journal.
4. The focus of the article must be on the use of eye-tracking technology for the diagnosis of dyslexia.
5. The participants must be school-aged children (6–12 years).

The selection process, for which we adhered to the PRISMA guidelines, unfolded as depicted in Figure 1. The primary author initiated the search, which initially resulted in 370 hits. A first inspection of the titles immediately revealed that some articles were irrelevant to our theme, because they either did not focus on the use of eye tracking technology or did not pertain to the diagnosis of dyslexia; these were excluded, leaving 186 studies. Next, 16 papers that were not in English were eliminated. Subsequently, we narrowed our focus to studies related to childhood, resulting in 75 remaining papers. A further 45 studies were excluded due to duplications. The remaining 30 articles underwent abstract screening, out of which 21 were deemed suitable for this review. In the final step of full-text screening, one additional study was found to be unsuitable and was excluded, because it was not a primary study, but a theoretical paper. Thus, through the systematic literature search, we ultimately identified 20 studies for inclusion in our literature review. The secondary author independently verified the selection process, ensuring rigor and adherence to the specified criteria, thereby affirming the final selection of studies.

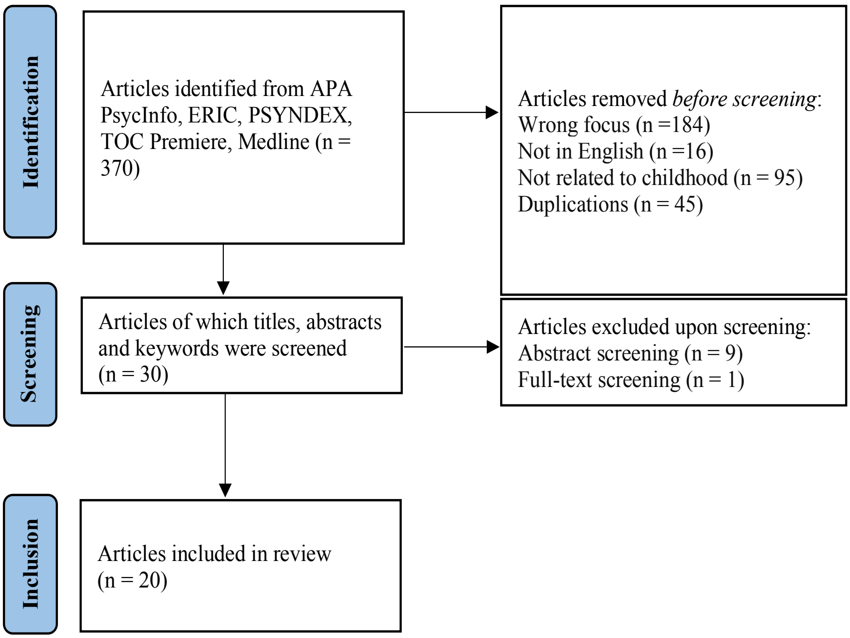

Figure 1. ***Flowchart describing the paper selection process***

Results

Table 1 summarizes the characteristics of the studies deemed eligible for our review. It includes the full titles of these studies, along with pertinent information such as the number of participants and their distribution into experimental and control groups, as well as their ages and, where applicable, their grade levels. The most comprehensive aspect covered in Table 1 includes the eye tracking metrics, specifically measured eye movements. Not all studies measured the same movements, but most recorded saccades or fixations, or both. Additionally, Table 1 mentions the type of eye tracker used, as different models were employed in the studies.

Table 1.

Authors	Title	Sample	Grade/Age	Measured Eye Movements	Eye Tracker
Åsberg Johnels, J., Hadjikhani, N., Sundqvist, M. & Galazka, M. A. (2022).	Face Processing in School Children with Dyslexia: Neuropsychological and Eye Tracking Findings	N = 43 n = 18 EG n = 25 CG	n/a, 9–13 years	Fixation duration on areas of interest (AOI)	Tobii X2-30 (Tobii Technology Inc., Danderyd, Sweden)
Bellocchi, Massendari, Grainger, Ducrot (2019)	Effects of inter-character spacing on saccade programming in beginning readers and dyslexics	N = 67 n = 24 EG n = 15 CG n = 28 CG-A	1st, 2nd, & 5th grade, 6–11 years	Initial fixation point, latency duration, initial fixation duration	Eyelink 2, (SR Research Ltd., Ottawa, Canada)
Freedman, Molholm, Gray, Belyusar, Foxe (2017)	Saccade adaptation deficits in developmental dyslexia suggest disruption of cerebellar-dependent learning	N = 25 n = 10 EG n = 15 CG	n/a, 7–15 years	Saccade length	EyeLink1000 (SR Research Ltd., Ottawa, Canada)
Ileri, Latifoğlu, Demirci (2022)	A novel approach for detection of dyslexia using convolutional neural network with EOG signals	N = 33 n = 20 EG n = 13 CG	2nd, 3rd & 4th grade, 8–11 years	Vertical and horizontal eye movements (saccades)	BIOPAC MP36 System (BIOPAC Systems, Inc.)
Jiménez, Romeo, Pérez Zapata, Puiga, Bustos-Valenzuela, Cañeteg, Varela Casal, Supèr (2020)	Eye vergence responses in children with and without reading difficulties during a word detection task	N = 116 n = 58 EG n = 58 CG	n/a, 6–10 years	Vergences	Tobii X 2–30 (Tobii Technology Inc., Danderyd, Sweden)

Table 1.

Authors	Title	Sample	Grade/Age	Measured Eye Movements	Eye Tracker
Li, Jing, Yang, Wang, Wang, Song, Fan (2013)	Eye movement study during visual search in Chinese children with developmental dyslexia	N = 71 n = 32 EG n = 39 CG	2^{nd}–5^{th} grade, 7–13 years	Fixation duration, number of fixations, fixation frequency, saccade distance, number of saccades, saccade frequency, saccade length, search time, pupil size	EyeLink II High Speed Eye Tracker (SR Research Ltd., Ottawa, Canada)
Luca, Pontillo, Primati-vo, Spinelli, Zoccolotti (2013)	The eye–voice lead during oral reading in developmental dyslexia	N = 32 n = 16 EG n = 16 CG	n/a, 11–13 years	Total fixation duration, total number of fixations, average fixation duration, saccade length in degrees, percentage of regressions	Eye Link 1000 (SR Research Ltd., Ottawa, Canada)
Lukasova, Silva, Macedo (2016)	Impaired Oculomotor Behavior of Children with Developmental Dyslexia in Antisaccades and Predictive Saccades Tasks	N = 30 n = 15 EG n = 15 CG	3^{rd}–8^{th} grade, 8–13 years	Antisaccades, predictive saccades, visually guided saccades	Tobii R 1750 (Tobii Technology Inc., Danderyd, Sweden)

Table 1.

Authors	Title	Sample	Grade/Age	Measured Eye Movements	Eye Tracker
Moiroud, Gerard, Peyre, Bucci (2017)	Developmental Eye Movement test and dyslexic children: A pilot study with eye movement recordings	N = 39 n = 13 EG n = 13 CG n = 13 CG-A	n/a, 7–12 years	Number of saccades, saccade angle, regressive saccades, duration and number of fixations	EyeBrain T2 (Mobile EBT®, SuriCog, Paris, France)
Pan, Yan, Laubrock, Shu, Kliegl (2013)	Eye–voice span during rapid automatized naming of digits and dice in Chinese normal and dyslexic children	N = 56 n = 30 EG n = 26 CG	5th grade, 10 years	Duration of gaze on numbers, duration of gaze on dice, eye–voice span for numbers and dice	EyeLink 1000 Desk-top System (SR Research Ltd., Ottawa, Canada)
Parshina, Lopukhina, Goldina, Iskra, Serebryakova, Staroverova, Zdorova, Dragoy (2022)	Global reading processes in children with high risk of dyslexia: a scanpath analysis	N = 144 n = 72 EG n = 72 CG	1st–5th grade, 9.4 years on average	First fixation duration, single fixation duration, gaze duration, skips, regressions	EyeLink 1000+or an EyeLink Portable Duo (SR Research Ltd., Ottawa, Canada)
Pina Rodrigues, Rebola, Jorge, Ribeiro, Pereira, Castelo-Branco, van Asselen (2017)	Evidence for a differential interference of noise in sub-lexical and lexical reading routes in healthy participants and dyslexics	N = 49 n = 23 EG n = 26 CG	3rd–6th grade, 9–13 years	Number of fixations, fixation duration, Number of regressions, saccade amplitude	SMI © RED remote eye tracker (SensoMotoric Instruments GmbH, Germany)

Table 1.

Authors	Title	Sample	Grade/Age	Measured Eye Movements	Eye Tracker
Raghuram, Hunter, Gowrisankaran, Waber (2019)	Self-reported visual symptoms in children with developmental dyslexia	N = 61 n = 28 EG n = 33 CG	n/a, 7–11 years	Saccades, regressive saccades	Visagraph (Taylor Associates, Huntington, NY)
Razuk, Perrin-Fievez, Gerard, Peyre, Barela, Bucci (2018)	Effect of colored filters on reading capabilities in dyslexic children	N = 36 n = 18 EG n = 18 CG	n/a, 8–11 years	Fixation duration between saccades, per saccade amplitude, number of pro- and retrosaccades	Mobile EyeBrain Tracker (Mobile EBT®, SuriCog, Paris, France)
Seassau, Gérard, Bui-Quoc, Bucci (2014)	Binocular saccade coordination in reading and visual search: A developmental study in typical-reader and dyslexic children	N = 85 n = 43 EG n = 42 CG	n/a, 8–13 years	Number of saccades, saccade amplitude, regressive saccades, fixation duration	Mobile Eyebrain Tracker (Mobile EBT®, SuriCog, Paris, France)
Tiadi, Seassau, Bui-Quoc, Gerard, Bucci (2014)	Vertical saccades in dyslexic children	N = 112 n = 56 EG n = 56 CG	n/a, 6–14 years	Saccade latency, maximum velocity, saccadic gain	Mobile Eyebrain Tracker (Mobile EBT®, SuriCog, Paris, France)

Table 1.

Authors	Title	Sample	Grade/Age	Measured Eye Movements	Eye Tracker
Tiadi, Seassau, Gerard, Bucci (2016)	Differences between dyslexic and non-dyslexic children in the performance of phonological visual-auditory recognition tasks: An eye tracking study	N = 60 n = 26 EG n = 34 CG	n/a, 8–11 years	Saccades, saccade peak velocity, saccade latency	Mobile EyeBrain Tracker (Mobile EBT®, SuriCog, Paris, France)
Vajs, Kovic, Papic, Savic, Jankovic (2022)	Spatiotemporal Eye Tracking Feature Set for Improved Recognition of Dyslexic Reading Patterns in Children	N = 30 n = 15 EG n = 15 CG	n/a, 7–13 years	Saccades, fixations, fixation intersection coefficient, fixation intersection variability, fractal dimension of fixation	SMI RED (m iMotions, Copenhagen, Denmark).
Wang, Liu, Dong, Yu (2022)	Entropy of eye movement during rapid automatized naming	N = 408	n/a, 7–11 years	Fixations, saccades, entropy	Tobii 4C (Tobii Technology Inc., Danderyd, Sweden)
Wu, Yang, Wang, Yang, Hu, Jing, Li (2018)	Eye Movement Patterns of Chinese Children with Developmental Dyslexia During the Stroop Test	N = 69 n = 32 EG n = 37 CG	2^{nd}–5^{th} grade, 7–13 years	Fixation duration, number of fixations, saccade distance, number of saccades, saccade length, fixation frequency, saccade frequency	EyeLink II (SR Research Ltd., Ottawa, Ca-nada)

General Findings

The studies analyzed were conducted in various countries: six in France, four in China, two in the United States, one in Brazil, one in Italy, one in Portugal, one in Russia, one in Serbia, one in Spain, one in Sweden, and one in Turkey. Within the relevant period of the last 10 years, 10 studies were published in the first half, from 2013 to 2018, and 10 from 2018 to 2023. The search was updated through 2023, although the most recent studies in this review are from 2022. That the selected studies vary in terms of country and publication year suggests that this literature review does not capture regional phenomena or overlook the development of newer technologies.

Participants

In total, data collected from 1,566 children across the 20 studies were analyzed. Of these children, 549 were assigned to experimental groups and 618 to control groups. The study by Wang et al. (2022) included 408 children, the largest group within this literature review. However, the sample descriptions do not clearly indicate how the children were classified. The age structure of the participants in the studies shows a core age bracket of 7–11 years (17 out of 20 studies covered this range); 11 studies included children older than 11, and two studies involved children younger than 7 (aged 6 and over). One study (Parshina et al., 2022) provides no age range, but only the average age of the participants. Precise information on the children's grade levels was much less common (mentioned in eight instances).

Setting

The tests were always conducted in a one-on-one setting. All children were taken to a separate room with the experimenter, which was sometimes darkened, sometimes bright, but always quiet. The participant's head was often supported by a chin and/or forehead rest to stabilize it, which was important for the most accurate measurement of eye movements. It should be noted at this point that such head supports are no longer needed with current technology. Regardless, it is, of course, the case that these devices were often still utilized in the studies analyzed here.

Eye Trackers

As shown in Table 1, researchers applied various eye trackers. Eye Link, in different models, was used seven times, and Tobii Ltd. was used four times. A model from Mobile EyeBrain was also used four times, and a tracker from SMI RED twice. The remaining three trackers were each used once. All researchers used the software provided with their equipment for analyzing eye movements. The most frequently measured eye tracking metrics were saccades and fixations, with the measurements focused especially on the number of these metrics' movements, the length of saccades, and the duration of fixations.

Study Summaries

Åsberg Johnels et al. (2022) studied eye movement patterns in schoolchildren recognizing faces; to explore a potential link with dyslexia, they conducted tests that included reading and memory exercises. Their findings did not reveal significant differences in eye movement patterns between groups, but the authors note that students with dyslexia took longer to complete tasks with more variation among them.

Bellocchi et al. (2019) explored how altering letter and hash mark distances affected saccadic activity in children with dyslexia. Their experiments revealed that increased spacing had a negative impact on eye movement behavior. The researchers conclude that the benefits of increased letter spacing on reading might not stem from improved saccadic activity.

Freedman et al. (2017) investigated saccade adaptation in children with dyslexia and found that the latter exhibited no adjustment in saccade amplitudes in response to visual errors, suggesting underlying cerebellar dysfunction. Their results indicate that saccadic adaptation, or the lack thereof, might serve as a noninvasive indicator for identifying dyslexia, reflecting potential issues with cerebellar functionality.

Ileri et al. (2022) introduced an approach using an electrooculogram (EOG) for early dyslexia identification, achieving high accuracy in detecting expected eye movements in dyslexic students. This method features a technique to measure the electrical activity linked with eye movements, enabling early and accurate identification of patterns indicative of dyslexia in children.

Jiménez et al. (2020) examined convergence reflex in children, where both eyes move inward toward the nose to focus on a close object. They found age-related improvements in students from the control group, but observed delayed responses in those with reading difficulties, indicating a potential link between convergence reflex efficiency and reading capabilities.

Li et al. (2013) examined visual search skills in children with dyslexia, finding deficits across tasks including letter, digit, single-character, phrase, and facial-expression identification, but not with geometric shapes (tangram figures). Dyslexic students showed lower fixation frequencies and shorter saccade amplitudes and distances compared to controls. The researchers found consistent underperformance in the dyslexic group across tasks without variation by task type, indicating a broad visual processing challenge rather than task-specific difficulties.

Luca et al. (2013) discovered that dyslexic children demonstrated slower reading with shorter eye–voice spans compared to controls, indicating difficulties in word decoding. Their findings suggest that the decoding issues could be related to either visual or phonological deficits, highlighting significant disparities in the reading process between dyslexic and typical readers.

Lukasova et al. (2016) identified that dyslexic students exhibited impaired eye movement patterns in antisaccade and predictive-saccade tasks, pointing to difficulties in implicit learning and oculomotor control. However, no significant difference was found in visually guided saccades, suggesting that dyslexia affects specific aspects of eye movement and cognitive processing.

Moiroud et al. (2018) found using the Developmental Eye Movement (DEM) test with an eye tracker that longer fixation durations and reading times correlated with lower reading abilities. Their study shows that dyslexic children and their reading-age-matched non-dyslexic counterparts had significantly longer fixation times and were slower on Test C of the DEM test than chronological-age-matched non-dyslexics, highlighting the critical role of cortical maturation in reading proficiency.

Pan et al. (2013) explored the eye–voice span (EVS) in children with dyslexia by examining their performance in rapid automatized naming (RAN) tasks involving digits (numbers 1–5) and die surfaces (dots 1–5). They found that the discrepancy in the EVS between the control group and the group of students with dyslexia was more pronounced in the digit-RAN task. This observation suggests that digit-RAN serves as a more effective indicator of dyslexia compared to dice-RAN.

Parshina et al. (2022) employed scanpath analysis to compare global reading processes between children with dyslexia and their typically developing peers, across grades 1–5. They discovered that while both groups exhibited qualitative similarities in reading patterns, students with dyslexia experienced a three-year developmental delay in reaching adult-like fluency with reading processes, achieving this advanced stage by the fifth grade, matching the control group's second-graders.

Pina Ridriguez et al. (2017) investigated white noise's effect on reading in dyslexic and typical children using a lexical-decision task. Dyslexics were mainly affected in accuracy, whereas controls were affected in response time and eye movements. Noise notably impaired pseudoword reading in typical readers, hinting at sub-lexical route disruption. These findings stress the importance of reading strategies and stimulus types in dyslexia research.

Raghuram et al. (2019) validated self-reported vision-related symptoms more common in dyslexic children, including tired eyes, double vision, and blurred words when reading. Their findings correlated these symptoms with oculomotor outcomes: a lower reading speed (words per minute), an increased number of fixations, and more regressive saccades (per 100 words).

Razuk et al. (2018) found that the use of a green filter significantly enhanced reading speed and reduced fixation times for students with dyslexia. They suggest that the filter improves reading ability through facilitating cortical

activity and reducing visual distortions. Their study highlights the potential of green filters in supporting reading performance in dyslexic children.

Seassau et al. (2014) investigated binocular eye movement behavior during reading and visual search tasks and discovered distinct differences in dyslexic children compared to age-matched typical readers. Using video-oculography, they found that dyslexic students displayed impaired ocular motor characteristics in reading tasks and exhibited deficiencies in visual attentional processing, as well as in the interaction between ocular motor saccade and vergence systems.

Tiadi et al. (2014) studied vertical saccades in dyslexic children, comparing them with age-matched non-dyslexic peers, and uncovered significant delays in saccade latency, reduced saccade velocity, and abnormalities in saccade execution among the dyslexic group. These findings suggest impairments not only in the cortical areas responsible for vertical saccade performance, but also in the peripheral mechanisms of the extra-ocular muscles, alongside a visuo-attentional bias causing up-down asymmetry in saccade triggering.

Extending their prior work, Tiadi et al. (2016) investigated phonological visual-auditory recognition tasks and found that dyslexic children spent uniform durations on targets across different phonological conditions and displayed consistent latency, unlike their non-dyslexic counterparts. These results indicate a distinct challenge with phonological processing in the dyslexic group, highlighted through eye movement patterns.

Vajs et al. (2022) investigated the impact of different-colored backgrounds on eye movement patterns in children, focusing on identifying dyslexic tendencies through advanced eye tracking metrics and machine learning analysis. They evaluated the children's reading of text segments across 13 color configurations. Despite finding no consistent preference for a specific background color among the dyslexic participants, the researchers achieved a notable dyslexia detection accuracy of 94% using a combination of conventional and newly proposed eye tracking features.

Wang et al. (2022) investigated cognitive processes in RAN tests through eye movement entropy, noting that task complexity affects entropy. This approach involves examining the diversity and unpredictability of eye movements in specific cognitive tasks and observing how the complexity of these tasks impacts the underlying cognitive processes.

Finally, Wu et al. (2018) explored how the Stroop Color and Word Test affects eye movements in dyslexic students and found that the latter experienced more difficulties with task completion and interference suppression than non-dyslexic children. The study shows that the dyslexic children had abnormal eye-movement patterns, including shorter saccade distances and a higher number of

fixations and saccades, highlighting significant challenges in visual processing and attention management.

Discussion

Main Findings

The above systematic review of 20 studies on the application of eye tracking technology in diagnosing dyslexia among school-aged children reveals significant insights into the efficacy and applicability of this approach. Through their measurement of specific metrics, such as saccades and fixations, the reviewed studies collectively highlight eye tracking technology's capability to reveal distinct visual-cognitive discrepancies associated with dyslexia. A key finding from our review is the variability in eye movement patterns observed in dyslexic children compared to their non-dyslexic counterparts. These patterns, particularly the longer fixation durations and altered saccadic movements, suggest that eye tracking metrics can reliably indicate reading difficulties, shedding light on the underlying visual-cognitive challenges of dyslexia. Moreover, the impact of task complexity on eye movement underscores the necessity of considering cognitive demand in diagnostic assessments, since more complex tasks reportedly tend to elicit greater variability in eye movement among dyslexic individuals.

The controlled environments in which these studies were conducted point to the sensitivity of eye tracking measurements to external factors, emphasizing the importance of standardized testing conditions for accurate dyslexia diagnosis. Additionally, the diverse methodologies and technologies employed across the 20 studies reflect the field's growth, yet also underline the need for standardization or comparative research to identify the most effective eye tracking tools for dyslexia assessment.

The link between eye movement metrics and reading skills highlights the need for targeted dyslexia interventions, such as designing customized reading materials with optimized letter spacing, developing tools for early detection of dyslexia through specific eye movement patterns, creating cognitive-load-adjusted learning tasks, implementing visual and linguistic processing skill enhancements, and introducing environmental or assistive technologies such as color filters to support reading efficiency. Future research efforts should be focused on method standardization and the educational use of eye tracking to fully leverage its benefits in dyslexia care.

Limitations

Despite the comprehensive nature of this review, several limitations warrant attention. First, the heterogeneity in study designs, eye tracking methodologies, and participant demographics across the included studies complicates the direct comparison and synthesis of findings. The variability in eye-tracker models and the specific eye movements measured introduces another

layer of complexity, potentially affecting the generalizability of the results. Additionally, the concentration of studies within certain geographical regions may limit the applicability of findings across diverse linguistic and cultural contexts. Lastly, the lack of detailed information on the diagnostic criteria for dyslexia and the classification of participants into experimental or control groups in some studies raises questions about the consistency and specificity of the findings. These limitations highlight the need for more standardized research protocols and broader inclusion criteria in future studies to enhance the reliability and applicability of eye tracking technology in diagnosing dyslexia among school-aged children.

Practical Implications and Conclusion

Implications of our findings are multifaceted, extending beyond the immediate realm of dyslexia diagnosis into broader educational and clinical practices. The evidence underscores the potential of eye tracking technology to aid noninvasive, objective, and detailed assessments of reading-related eye movements, which can significantly contribute to early detection of dyslexia and suitable intervention strategies. Specifically, the nuanced understanding of saccades and fixations possible through eye tracking can inform tailored reading interventions and educational supports that accommodate the unique needs of dyslexic learners. Furthermore, this technology holds promise for enhancing existing diagnostic frameworks, potentially leading to more precise and personalized educational planning. The cross-cultural and age-specific insights gleaned also suggest the importance of considering demographic and linguistic diversity in applying eye tracking diagnostics and developing more inclusive and effective educational practices.

In light of the identified limitations and the evolving landscape of dyslexia research, several suggestions for future research emerge. First, there is a critical need for standardized protocols in the use of eye tracking technology, including uniformity in eye movement metrics and diagnostic criteria for dyslexia. Future studies should aim to include larger, more diverse samples, encompassing a wider range of languages and cultural contexts to enhance the generalizability of our findings. Investigations of the longitudinal impact of eye-tracking-based interventions on reading outcomes would also be valuable in offering insights into the long-term efficacy of such approaches. Additionally, the integration of eye tracking with other diagnostic tools could result in a more holistic understanding of dyslexia, potentially unveiling novel biomarkers for early identification. Finally, researchers should also focus on the cost-effectiveness and accessibility of eye tracking technology, ensuring that its benefits can be broadly realized across different educational settings and socioeconomic backgrounds.

References

Åsberg Johnels, J., Hadjikhani, N., Sundqvist, M., & Galazka, M. A. (2022). Face processing in school children with dyslexia: Neuropsychological and eye tracking findings. *Developmental Neuropsychology*, *47*(2), 78–92. https://doi.org/10.1080/87565641.2022.2034828

Bachore, M. M. (2022). English language literacy skills and academic achievement of urban and rural secondary schools: The case of high and low achievers. *Education Research International*, Article 2315426. https://doi.org/10.1155/2022/2315426

Bellocchi, S., Massendari, D., Grainger, J., & Ducrot, S. (2019). Effects of inter-character spacing on saccade programming in beginning readers and dyslexics. *Child Neuropsychology*, *25*(4), 482–506. https://doi.org/ 10.1080/09297049.2018.1504907

Benfatto, M. N., Seimyr, G. Ö, Ygge, J., Pansell, T., Rydberg, A., & Jacobson, C. (2016). Screening for dyslexia using eye tracking during reading. *PLoS ONE*, *11*(12), Article e0165508. https://doi.org/10.1371/journal.pone.0165508

Colenbrander, D., Ricketts, J., & Breadmore, H. L. (2018). Early identification of dyslexia: Understanding the issues. *Language, Speech, and Hearing Services in Schools*, *49*(4), 817–828. https://doi.org/10.1044/2018_LSHSS-DYSLC-18-0007

Elbeheri, G., & Tridas, E. Q. (2022). *Assessing dyslexia: A teacher's guide to understanding and evaluating their pupils' needs*. Routledge. https://doi.org/10.4324/9781003212058

Elliott, J. G., & Grigorenko, E. L. (2014). *The dyslexia debate*. Cambridge University Press. https://doi.org/10.1017/CBO9781139017824

Freedman, E. G., Molholm, S., Gray, M. J., Belyusar, D., & Foxe, J. J. (2017). Saccade adaptation deficits in developmental dyslexia suggest disruption of cerebellar-dependent learning. *Journal of Neurodevelopmental Disorders*, *9*(1), Article 36. https://doi.org/10.1186/s11689-017-9218-5

Grafwallner, P. (2023). *Clearing the path for developing learners: Essential literacy skills to support achievement in every content area*. Solution Tree.

Ileri, R., Latifoğlu, F., & Demirci, E. (2022). A novel approach for detection of dyslexia using convolutional neural network with EOG signals. *Medical & Biological Engineering & Computing*, *60*(11), 3041–3055. https://doi.org/10.1007/s11517-022-02656-3

Jiménez, E. C., Romeo, A., Pérez Zapata, L., Solé Puig, M., Bustos-Valenzuela, P., Cañete, J., Varela Casal, P., & Supèr, H. (2020). Eye vergence responses in children with and without reading difficulties during a word detection task. *Vision Research*, *169*(1), 6–11. https://doi.org/10.1016/j.visres.2020.02.001

Jarodzka, H., Holmqvist, K., & Gruber, H. (2017). Eye tracking in educational science: Theoretical frameworks and research agendas. *Journal of Eye Movement Research*, *10*(1), 1–18. https://doi.org/10.16910/jemr.10.1.3

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review*, *87*(4), 329–354. https://doi.org/10.1037/0033-295X.87.4.329

Kustov, A. A., & Robinson, D. L. (1996). Shared neural control of attentional shifts and eye movements. *Nature*, *384*, 74–77. https://doi.org/10.1038/384074a0

Lachmann, T., & Weis, T. (2018). *Reading and dyslexia: From basic functions to higher order cognition*. Springer. https://doi.org/10.1007/978-3-319-90805-2

Li, X.-h., Jing, J., Yang, D.-s., Wang, H., Wang, Q.-x., Song, S.-s., & Fan, F. (2013). Eye-movement study during visual search in Chinese children with developmental dyslexia. *Chinese Medical Journal*, *126*(22), 4306–4311. https://doi.org/10.3760/cma.j.issn.0366-6999.20123067

Luca, M. de, Pontillo, M., Primativo, S., Spinelli, D., & Zoccolotti, P. (2013). The eye-voice lead during oral reading in developmental dyslexia. *Frontiers in Human Neuroscience*, *7*, Article 696. https://doi.org/10.3389/fnhum.2013.00696

Lukasova, K., Silva, I. P., & Macedo, E. C. (2016). Impaired oculomotor behavior of children with developmental dyslexia in antisaccades and predictive saccades tasks. *Frontiers in Psychology*, *7*, Article 987. https://doi.org/10.3389/fpsyg.2016.00987

Mather, N., & Wendling, B. J. (2011). *Essentials of dyslexia assessment and intervention*. Wiley.

Moiroud, L., Gerard, C. L., Peyre, H., & Bucci, M. P. (2018). Developmental eye movement test and dyslexic children: A pilot study with eye movement recordings. *PLoS ONE*, *13*(9), Article e0200907. https://doi.org/10.1371/journal.pone.0200907

Nerušil, B., Polec, J., Škunda, J., & Kačur, J. (2021). Eye tracking based dyslexia detection using a holistic approach. *Scientific Reports*, *11*, Article 15687. https://doi.org/10.1038/s41598-021-95275-1

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *International Journal of Surgery*, *88*(1), 1–11. https://doi.org/10.1016/j.ijsu.2021.105906

Pan, J., Yan, M., Laubrock, J., Shu, H., & Kliegl, R. (2013). Eye-voice span during rapid automatized naming of digits and dice in Chinese normal and dyslexic children. *Developmental Science*, *16*(6), 967–979. https://doi.org/10.1111/desc.12075

Parshina, O., Lopukhina, A., Goldina, S., Iskra, E., Serebryakova, M., Staroverova, V., Zdorova, N., & Dragoy, O. (2022). Global reading processes in children with high risk of dyslexia: A scanpath analysis. *Annals of Dyslexia*, *72*(3), 403–425. https://doi.org/10.1007/s11881-021-00251-z

Pina Rodrigues, A., Rebola, J., Jorge, H., Ribeiro, M. J., Pereira, M., Castelo-Branco, M., & van Asselen, M. (2017). Evidence for a differential interference of noise in sub-lexical and lexical reading routes in healthy participants and dyslexics. *Cognitive Neuropsychology*, *34*(1-2), 42–51. https://doi.org/10.1080/02643294.2017.1299001

Raghuram, A., Hunter, D. G., Gowrisankaran, S., & Waber, D. P. (2019). Self-reported visual symptoms in children with developmental dyslexia. *Vision Research*, *155*(1), 11–16. https://doi.org/10.1016/j.visres.2018.11.007

Razuk, M., Perrin-Fievez, F., Gerard, C. L., Peyre, H., Barela, J. A., & Bucci, M. P. (2018). Effect of colored filters on reading capabilities in dyslexic children. *Research in Developmental Disabilities*, *83*(1), 1–7. https://doi.org/10.1016/j.ridd.2018.07.006

Rello, L., & Ballesteros, M. (2015). Detecting readers with dyslexia using machine learning with eye tracking measures. *Proceedings of the 12th International Web for All* Conference, 1–8. https://doi.org/10.1145/2745555.2746644

Seassau, M., Gérard, C. L., Bui-Quoc, E., & Bucci, M. P. (2014). Binocular saccade coordination in reading and visual search: A developmental study in typical reader and dyslexic children. *Frontiers in Integrative Neuroscience*, *8*, Article 85. https://doi.org/10.3389/fnint.2014.00085

Shalileh, S., Ignatov, D., Lopukhina, A., & Dragoy, O. (2023). Identifying dyslexia in school pupils from eye movement and demographic data using artificial intelligence. *PLoS ONE*, *18*(11), Article e0292047. https://doi.org/10.1371/journal.pone.0292047

Steacy, L. M., Edwards, A. A., Rigobon, V. M., Gutierrez, N., Marencin, N. C., Siegelman, N., Himelhoch, A., Himelhoch, C., Rueckl, J., & Compton, D. L. (2022). Set for variability as a critical predictor of word reading: Potential implications for early identification and treatment of dyslexia. *Reading Research Quarterly*, *58*(2), 254–267. https://doi.org/10.1002/rrq.475

Talwar, A., Magliano, J. P., Higgs, K., Santuzzi, A., Tonks, S., O'Reilly, T., & Sabatini, J. (2023). Early academic success in college: Examining the contributions of reading literacy skills, metacognitive reading strategies, and reading motivation. *Journal of College Reading and Learning*, *53*(1), 58–87. https://doi.org/10.1080/10790195.2022.2137069

Tiadi, A., Seassau, M., Bui-Quoc, E., Gerard, C.-L., & Bucci, M. P. (2014). Vertical saccades in dyslexic children. *Research in Developmental Disabilities*, *35*(11), 3175–3181. https://doi.org/10.1016/j.ridd.2014.07.057

Tiadi, A., Seassau, M., Gerard, C.-L., & Bucci, M. P. (2016). Differences between dyslexic and non-dyslexic children in the performance of phonological visual-auditory recognition tasks: An eye tracking study. *PLoS ONE*, *11*(7), Article e0159190. https://doi.org/10.1371/journal.pone.0159190

Urban, K. (2023). *Development of key literacy skills in early childhood education*. Peter Lang. https://doi.org/10.3726/b20261

Vajs, I., Ković, V., Papić, T., Savić, A. M., & Janković, M. M. (2022). Spatiotemporal eye tracking feature set for improved recognition of dyslexic reading patterns in children. *Sensors*, *22*(13), Article 4900. https://doi.org/10.3390/s22134900

Wagner, R. K., & Lonigan, C. J. (2023). Early identification of children with dyslexia: Variables differentially predict poor reading versus unexpected poor reading. *Reading Research Quarterly*, *58*(2), 188–202. https://doi.org/10.1002/rrq.480

Wagner, R. K., Zirps, F. A., Edwards, A. A., Wood, S. G., Joyner, R. E., Becker, B. J., Liu, G., & Beal, B. (2020). The prevalence of dyslexia: A new approach to its estimation. *Journal of Learning Disabilities*, *53*(5), 354–365. https://doi.org/10.1177/0022219420920377

Wang, H., Liu, F., Dong, Y., & Yu, D. (2022). Entropy of eye movement during rapid automatized naming. *Frontiers in Human Neuroscience*, *16*, Article 945406. https://doi.org/10.3389/fnhum.2022.945406

Wu, Y. J., Yang, W. H., Wang, Q. X., Yang, D. S., Hu, X. Y., Jing, J., & Li, X. H. (2018). Eye-movement patterns of Chinese children with developmental dyslexia during the Stroop test. *Biomedical and Environmental Sciences: BES*, *31*(9), 677–685. https://doi.org/10.3967/bes2018.092

Author's Note

Correspondence concerning this article should be addressed to Leonie Coenen, Department of Special Education & Rehabilitation, University of Cologne, Klosterstr. 79b, Cologne, Northrhine-Westfalia, 50931, Germany, Email: leonie.coenen@outlook.de.