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Eye-tracking in school-age specific learning disorders: a practice-oriented narrative review of assessment and gaze-contingent interventions

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Eye-tracking (ET) provides fine-grained, real-time indicators of how school-age students allocate visual attention during learning, yet its translation into school-based assessment and intervention for Specific Learning Disorder (SLD; DSM-5: dyslexia, dysgraphia, dyscalculia) remains limited and unsystematic. This practice-oriented narrative review synthesizes peer-reviewed empirical studies and pilot technology/intervention papers published between 1999 and 2025, a period that captures the diffusion of video-based ET in educational research and the emergence of gaze-adaptive learning tools. We focused on studies involving school-age students (approximately 5–18 years) with diagnosed SLD or closely related learning profiles, using academic tasks in reading, writing/handwriting, spelling/orthography, numeracy, and visual attention/search. Across domains, the literature converges on robust oculomotor signatures of inefficient visual sampling and increased processing demands, reflected in slower and less stable gaze patterns, disrupted forward progression, and higher cognitive load. ET also helps localize "hidden" breakdown points in decoding, visuomotor coordination, phoneme-grapheme mapping, and problem-solving strategies that may not be detectable through accuracy or response time alone. Evidence on gaze-contingent and ET-informed interventions is emerging. Although most studies remain small and short-term, results suggest potential for adaptive scaffolding that guides attention and supports more efficient learning behaviors. We provide a unified, educationally grounded framework for interpreting ET findings in SLD and practical guidance for implementation in schools, with emphasis on feasibility, data quality, and ethical considerations when working with minors.

KEYWORDS

dysgraphia and handwriting, educational technology and assessment, eye-tracking, gaze-contingent interventions, mathematics learning and numeracy, reading difficulties and dyslexia, specific learning disorders, visual attention and visual search

1 Introduction

Specific Learning Disorders (SLD), including dyslexia, dysgraphia, and dyscalculia, affect a substantial proportion of school-age students and often compromise academic achievement, self-efficacy, and long-term educational outcomes. These conditions are typically characterized by persistent difficulties in reading accuracy and fluency, orthographic and handwriting processes, or numerical cognition, despite adequate

intelligence and adequate learning opportunities. Traditional assessment methods for SLD rely heavily on standardized tests and behavioral performance indicators, which provide essential information but often fail to capture the fine-grained cognitive and perceptual processes that occur during real-time learning activities. As a result, important indicators of effort, attentional allocation, visual processing, or error monitoring may remain hidden from teachers and clinicians and may only be inferred indirectly from errors or response times.

Eye-tracking (ET) technology offers a unique opportunity to bridge this gap by providing an objective window into oculomotor behavior during reading, writing, and problem-solving tasks. Measures such as fixation duration, saccadic amplitude, regression frequency, gaze dispersion, and pupillary responses can reveal micro-dynamics of decoding, attentional engagement, visual search strategies, and cognitive load in ways that complement traditional tests (Diotaiuti et al., 2025). Over the past two decades, ET has been increasingly applied in cognitive psychology, psycholinguistics, and educational research to track how students distribute visual attention across text, images, and digital learning materials (Campen et al., 2021; Chytry et al., 2025). Systematic reviews have documented the growing use of ET in language and mathematics education, highlighting both its potential and the current methodological variability (Paskovske and Kliziene, 2024; Toki, 2024). Despite this progress, the adoption of ET within everyday school contexts and its integration into assessment and intervention for SLD remain emerging, fragmented, and uneven across domains.

Recent studies suggest that ET can complement traditional evaluations by identifying dysfunctional reading patterns, such as dense fixations, short saccades, and frequent regressions in children at risk for dyslexia, and by comparing eye-movement signatures with neuropsychological profiles (Gran Ekstrand et al., 2021; Nerušil et al., 2021; Toki, 2024). In mathematics, ET has been used to uncover how students navigate number lines, tables, and fraction tasks, shedding light on attentional bottlenecks and inefficient problem-solving strategies that are not apparent from accuracy scores alone (Obersteiner and Tumpek, 2016; Paskovske and Kliziene, 2024). Preliminary intervention studies further indicate that gaze-contingent training, such as Eye-hop protocols targeting oculomotor control and reading fluency, can modify both eye-movement patterns and reading outcomes, including in learners with SLD, although most evidence is still based on small samples and pilot designs (Toki, 2024; Medan and Pelman, 2024). These applications highlight both the promise of ET for understanding learning difficulties and the need for clear methodological guidance to ensure reliability, ethical compliance, and educational relevance when working with children and adolescents.

Several reviews have examined the use of eye-tracking in educational contexts, but they have typically focused on specific domains or broader technology-enhanced learning without centering SLD as a cross-domain construct. For example, Toki (2024) provides a broad overview of ET applications in reading difficulties, Paskovske and Kliziene (2024) focus on mathematics education, and classic syntheses such as Campen et al. (2021) describe ET as a general tool for studying learning with dynamic or multimedia materials. More recent work by Chytry et al. (2025) surveys ET in educational technology from a predominantly systems and design perspective. However, none of these reviews offers an integrated, cross-domain synthesis explicitly centered on school-age students with SLD across reading, writing, spelling, numeracy, and attentional control, nor do they systematically connect process-level gaze indicators to practical, educationally actionable insights for assessment and intervention.

This practice-oriented narrative review therefore aims to (a) synthesize current knowledge (1999–2025) on the use of ET for assessment and intervention in school-age students with SLD, spanning reading, writing, and mathematics; (b) consolidate findings from traditionally separate research lines (literacy, handwriting, orthographic processing, mathematics, and visual search) into a unified framework of how SLD manifest in real-time oculomotor behavior; and (c) translate gaze-based evidence into actionable educational insights that can inform individualized education plans and classroom accommodations. The review provides practical guidelines for implementing ET in schools, including device selection, calibration procedures, data-quality considerations, and ethical requirements for working with minors. Rather than offering an exhaustive mapping of all ET research, this work integrates empirical findings, existing reviews, and applied expertise to support teachers, specialists, and researchers interested in leveraging ET as a complementary tool for understanding and addressing learning difficulties in real educational settings.

2 Methods

2.1 Review design and rationale

This study is a practice-oriented narrative review designed to synthesize and interpret eye-tracking (ET) research relevant to school-age students with Specific Learning Disorders (SLD). A narrative review was selected because (a) the ET literature on SLD is highly heterogeneous in tasks, devices, and outcomes; (b) many studies use exploratory designs unsuitable for meta-analysis; and (c) the goal of the review is not to estimate pooled effects but to integrate empirical evidence with educational practice and technological considerations. The review follows best practices for narrative evidence synthesis, emphasizing transparency in search strategy, selection process, and interpretive approach.

2.2 Scope and guiding questions

The review focuses on ET as a tool to (a) support functional assessment of reading, writing, and numeracy difficulties, and (b) inform or implement gaze-contingent interventions targeting oculomotor efficiency, attentional allocation, and task engagement. The guiding questions were: (1) Which ET metrics are most informative for identifying functional difficulties in students with SLD during reading, writing, and arithmetic tasks? (2) What patterns of gaze behavior distinguish students with SLD from typically developing peers? (3) Which gaze-contingent or gaze-informed interventions have been piloted or proposed for SLD, and what is their preliminary effectiveness? (4) How can ET be feasibly and ethically implemented in school settings, particularly when working with minors?

2.3 Search strategy

To inform the review, a targeted literature search was conducted between January and March 2025 across Scopus, Web of Science, PubMed, ERIC, and Google Scholar. Search strings combined terms related to: (1) Population: "Specific Learning Disorder," "dyslexia," "dysgraphia," "dyscalculia," "learning difficulties"; (2) Technology: "eye-tracking," "gaze behavior," "oculomotor," "gaze-contingent"; (3) Tasks: "reading," "writing," "handwriting," "orthography," "numeracy," "visual search," "attention." Reference lists of relevant papers were also checked to identify additional studies. No strict PRISMA-ScR protocol was applied, consistent with the narrative nature of the review.

2.4 Study selection

Studies were selected through a multi-stage screening process:

1. Initial retrieval: 1,120 records identified across all databases.
2. Removal of duplicates: 480 duplicates removed.
3. Title/abstract screening: 640 screened.
4. Full-text assessment: 115 full texts read.
5. Final inclusion: 48 peer-reviewed studies met criteria for qualitative synthesis and are summarized in the Results section.

2.5 Inclusion criteria

Evidence was included if it met the following criteria: (1) Population: children or adolescents (5–18 years), with diagnosed SLD or presenting reading/writing/numerical difficulties relevant to SLD profiles; (2) Context: school-based, lab-based, or clinical settings relevant to educational tasks; (3) Relevance: study examined ET metrics during reading, writing, spelling, visual search, attentional tasks, or school-related numerical activities; or described ET-based interventions or gaze-contingent systems; (4) Type of source: peer-reviewed journal articles, conference papers with robust methodology, and authoritative reports in education or assistive technology. Studies focusing exclusively on adults, unrelated psycholinguistic paradigms, or purely theoretical models without educational relevance were excluded or considered only as contextual background.

2.6 Data extraction and synthesis

Given the methodological heterogeneity of the included sources, data were extracted narratively rather than through structured charting. Each study or technical contribution was examined for: (1) ET methodology: device type, sampling rate, calibration method, task characteristics; (2) Metrics: fixation duration, fixation count, saccadic amplitude, regression rate, scanpath patterns, AOI timing, pupillometry; (3) Findings relevant to SLD: oculomotor differences, attentional patterns, decoding effort, visual–spatial organization; (4) Intervention components: gaze-contingent adaptations, progress indicators, task scaffolding; (5) Educational relevance: feasibility in classroom settings, training requirements, ecological validity. The synthesis privileges findings with direct implications for assessment and intervention, integrating empirical evidence with applied recommendations for educators, clinicians, and school specialists.

2.7 Ethical considerations

All included studies were required to report adherence to ethical standards for research with minors, including informed consent from parents or legal guardians and institutional approval. ET studies presenting gaze videos or screen recordings were checked for proper anonymization procedures.

3 Results

3.1 Overview of included evidence

The reviewed literature comprises empirical studies, technical reports, and pilot interventions published between 1999 and 2025, focusing on children and adolescents aged 6–18 years with dyslexia, dysgraphia, dyscalculia, or related learning difficulties. To improve transparency and address how the evidence base maps onto the domains covered in this review, we summarize the distribution of included papers across categories in Table 1. The literature is dominated by reading-focused studies, with fewer contributions in handwriting/writing, mathematics/numeracy, and visual search/attention. A full paper-by-paper classification is available in Table 2.

Most studies employed remote, screen-based eye-trackers (60–120 Hz), though some recent work used higher-frequency devices (250–500 Hz) for detailed saccadic analysis. Methodologies varied widely, spanning silent reading, oral reading, handwriting, copying tasks, spelling-to-dictation, arithmetic problems, and visual search paradigms. A smaller set of papers examined gaze-contingent learning environments or real-time adaptive training systems. Across the evidence base, several oculomotor patterns emerged consistently in students with SLD, regardless of device type or task complexity.

The evidence base is dominated by reading-focused studies, with comparatively fewer contributions addressing handwriting/writing and mathematics/numeracy.

3.2 Core eye-tracking metrics in SLD

3.2.1 Fixation behavior

Eye-tracking research consistently shows that students with Specific Learning Disorders (SLD), particularly those with dyslexia, display distinctive fixation-related patterns reflecting underlying cognitive and linguistic challenges associated with their reading difficulties. A robust body of work indicates that these learners typically exhibit longer mean fixation durations, widely interpreted as markers of reduced reading automaticity and increased reliance on effortful, sublexical decoding processes (Hawelka et al., 2010; Jones et al., 2008; Krieber et al., 2017). Longer fixations frequently co-occur with higher fixation counts per word or per line, suggesting fragmented lexical processing and the need for multiple visual samples to extract orthographic information that skilled readers access with

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TABLE 1 Distribution of included studies across domains and study types.

Reference	Year	Short title	Study type	SLD focus	Primary category	Categories
De Luca et al. (1999)	1999	Eye movement patterns in linguistic and non-linguistic tasks	Empirical study	Dyslexia/reading difficulties	Reading	Reading
Bosse et al. (2007)	2007	Developmental dyslexia: The visual attention span deficit hypothesis	Empirical study	Dyslexia/reading difficulties	Reading	Reading; visual attention/search
Jones et al. (2008)	2008	Elucidating the component processes involved in dyslexic and non-dyslex.	Empirical study	Dyslexia/reading difficulties	Reading	Reading
Rosenblum and Livneh-Zirinski (2008)	2008	Handwriting process and product characteristics of children	Empirical study	Dysgraphia/ handwriting/writing difficulties	Writing/handwriting	Writing/handwriting
van der Schoot et al. (2009)	2009	The consistency effect depends on markedness in less successful	Empirical study	Dyscalculia/math difficulties	Writing/handwriting	Writing/handwriting
Hawelka et al. (2010)	2010	A dual-route perspective on eye movements of dyslexic readers	Empirical study	Dyslexia/reading difficulties	Reading	Reading
Hyönä (2010)	2010	The use of eye movements in the study of cognitive processes	Review/Synthesis	General/other population	General/other	General/other
Bucci et al. (2012)	2012	Immaturity of the oculomotor saccade and vergence interaction in dyslex.	Empirical study	Dyslexia/reading difficulties	Reading	Reading; Visual attention/search; oculomotor control
Traxler et al. (2012)	2012	Individual differences in eye-movements during reading.	Empirical study	General/other population	Reading	Reading
Accardo et al. (2013)	2013	Reprint of 'Development, maturation and learning influence on handwriting	Empirical study	Dysgraphia/ handwriting/writing difficulties	Writing/handwriting	Writing/handwriting
Ronconi et al. (2013)	2013	Zoom-out attentional impairment in children with autism spectrum disorder	Empirical study	General/other population	General/Other	Visual attention/search
Roux et al. (2013)	2013	The interaction between central and peripheral processes in handwriting	Empirical study	Dysgraphia/ handwriting/writing difficulties	Writing/handwriting	Writing/handwriting
Pontart et al. (2013)	2013	Influence of handwriting skills during spelling	Empirical study	Dysgraphia/ handwriting/writing difficulties	Writing/handwriting	Writing/handwriting; spelling/orthography

(Continued)

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TABLE 1 (Continued)

Reference	Year	Short title	Study type	SLD focus	Primary category	Categories
Rayner (2014)	2014	The gaze-contingent moving window in reading	Review/synthesis	General/other population	Reading	Reading
Schneider et al. (2011)	2011	A gaze-contingent reading tutor program for children	Intervention/ technology	Dyslexia/reading difficulties	Reading	Reading
Rello and Ballesteros (2015)	2015	Detecting readers with dyslexia using machine learning with eye tracking	Screening/ classification	Dyslexia/reading difficulties	Reading	Reading
Maldarelli et al. (2015)	2015	Development of early handwriting: visual-motor control	Empirical study	Dysgraphia/ handwriting/writing difficulties	Writing/handwriting	Writing/Handwriting
Kandel and Perret (2015)	2015	How does the interaction between spelling and motor processes	Empirical study	Dysgraphia/ handwriting/writing difficulties	Writing/handwriting	Writing/handwriting; spelling/orthography
Sita and Taylor (2015)	2015	Eye movements during the handwriting of words	Empirical study	Dysgraphia/ handwriting/writing difficulties	Writing/handwriting	Writing/handwriting
Conklin and Pellicer-Sánchez (2016)	2016	Using eye-tracking in applied linguistics and second language research	Review/synthesis	General/other population	General/other	General/other
Nilsson Benfatto et al. (2016)	2016	Screening for dyslexia using eye tracking during reading	Screening/ classification	Dyslexia/reading difficulties	Reading	Reading
Obersteiner and Tumpek (2016)	2016	Measuring fraction comparison strategies with eye-tracking	Empirical study	Dyscalculia/math difficulties	Mathematics/ numeracy	Mathematics/numeracy
Krieber et al. (2017)	2017	Eye movements during silent and oral reading in a regular orthography	Empirical study	Dyslexia/reading difficulties	Reading	Reading
Yagle et al. (2017)	2017	Relationships between eye movements during sentence reading comprehension	Empirical study	Dyslexia/reading difficulties	Reading	Reading; writing/ handwriting; spelling/ orthography; neuroimaging linkage
Rello and Baeza-Yates (2017)	2017	How to present more readable text for people with dyslexia	Intervention/ technology	Dyslexia/reading difficulties	Reading	Reading
Bimba et al. (2017)	2017	Adaptive feedback in computer-based learning environments	Review/synthesis	General/other population	General/other	General/other
Scheiter et al. (2019)	2019	Adaptive multimedia: Using gaze-contingent instructional guidance	Intervention/ technology	General/other population	General/other	General/other

(Continued)

TABLE 1 (Continued)

Reference	Year	Short title	Study type	SLD focus	Primary category	Categories
Stella and Engelhardt (2019)	2019	Syntactic ambiguity resolution in dyslexia	Empirical study	Dyslexia/reading difficulties	Reading	Reading
Fears et al. (2019)	2019	An eye-tracking method for directly assessing children's visual-motor	Empirical study	General/other population	General/other	Writing/handwriting
Schindler and Lilienthal (2019)	2019	Domain-specific interpretation of eye tracking data	Review/synthesis	Dyscalculia/math difficulties	Mathematics/ numeracy	Mathematics/numeracy
Ozeri-Rotstain et al. (2020)	2020	Relationship between eye-movement patterns, cognitive load, and reading	Empirical study	Dyslexia/reading difficulties	Reading	Reading; pupillometry/ cognitive load
Schindler et al. (2020)	2020	Enumeration processes of children with mathematical difficulties	Empirical study	Dyscalculia/math difficulties	Mathematics/ numeracy	Mathematics/numeracy
Afonso et al. (2020)	2020	Writing impairments in Spanish children with developmental dyslexia	Empirical study	Dyslexia/reading difficulties	Writing/handwriting	Writing/handwriting; spelling/orthography
Gran Ekstrand et al. (2021)	2021	Screening for reading difficulties: comparing eye tracking	Screening/ classification	Dyslexia/reading difficulties	Reading	Reading
Nerušil et al. (2021)	2021	Eye tracking based dyslexia detection using a holistic approach	Screening/ classification	Dyslexia/reading difficulties	Reading	Reading
Ward and Kapoula (2021)	2021	Dyslexics' fragile oculomotor control is further destabilized	Empirical study	Dyslexia/reading difficulties	Reading	Reading; oculomotor control
Campen et al. (2021)	2021	How teachers interpret displays of students' gaze in reading	Empirical study	General/other population	Reading	Reading
Parshina et al. (2022)	2022	Global reading processes in children with high risk of dyslexia	Empirical study	Dyslexia/reading difficulties	Reading	Reading
Carelli et al. (2022)	2022	Gaze-contingent eye-tracking training in brain disorders	Review/synthesis	General/other population	General/other	General/other
Capellini et al. (2022)	2022	Characterization of gaze in handwriting of high and low frequency word	Empirical study	Dyslexia/reading difficulties	Writing/handwriting	Writing/handwriting
Ye et al. (2024)	2023	Routledge international handbook of visual-motor skills, handwriting	Review/synthesis	General/other population	Writing/handwriting	Writing/handwriting; spelling/orthography
Bartov et al. (2023)	2023	Enhancing handwriting performance of children	Intervention/ technology	Dysgraphia/ handwriting/writing difficulties	Writing/handwriting	Writing/handwriting

(Continued)

TABLE 1 (Continued)

Reference	Year	Short title	Study type	SLD focus	Primary category	Categories
Piazzalunga et al. (2023)	2023	Investigating visual perception impairments through serious games	Intervention/ technology	Dysgraphia/ handwriting/writing difficulties	Writing/handwriting	Writing/handwriting; visual attention/search
Toki (2024)	2024	Using eye-tracking to assess dyslexia:	Review/synthesis	Dyslexia/reading difficulties	Reading	Reading
Paskovske and Kliziene (2024)	2024	Eye tracking technology on children's mathematical education	Review/synthesis	Dyscalculia/math difficulties	Mathematics/ numeracy	Mathematics/numeracy
Medan and Pelman (2024)	2024	New line: a new gaze-contingent digital reading interface	Intervention/ technology	Dyslexia/reading difficulties	Reading	Reading
Chytry et al. (2025)	2025	Using eye-tracking in education	Review/synthesis	General/other population	General/other	General/other

TABLE 2 Distribution of included papers across categories and study types.

Study type	*n*
Empirical study	32
Review/synthesis	8
Intervention/technology	5
Screening/classification	4

Category counts are non-exclusive (a single paper may contribute to more than one category). For the cross-tabulation, each paper was assigned a primary category (the main focus of the study) to avoid double counting.

fewer and shorter fixations (Ronconi et al., 2013; Nilsson Benfatto et al., 2016). Fixation pacing tends to be less stable and more irregular across lines of text in children with SLD. These disruptions, often expressed as variable fixation timing, sporadic pauses, and inconsistent forward progression, indicate difficulties in maintaining efficient oculomotor control and synchronizing eye movements with ongoing linguistic processing (Traxler et al., 2012; De Luca et al., 1999; Ward and Kapoula, 2021). Fixation abnormalities point to increased cognitive load and reduced automatization, underscoring the substantial processing demands experienced by readers with dyslexia who must compensate for phonological and orthographic weaknesses through slower, effortful visual sampling. As such, fixation patterns provide an ecologically valid and fine-grained window into decoding difficulties that are often masked by traditional end-point measures such as reading accuracy or rate.

3.2.2 Saccadic patterns

Children with Specific Learning Disorders (SLD), particularly those with dyslexia, also show characteristic differences in saccadic behavior during reading. Across multiple studies, these learners produce shorter forward saccades, reflecting limited parafoveal preview and reduced efficiency in planning upcoming fixations (Hawelka et al., 2010; Nilsson Benfatto et al., 2016). They also exhibit more frequent saccadic intrusions, including unintentional small corrective saccades and unstable forward-backward oscillations, which indicate difficulties in maintaining steady oculomotor control while processing text (Krieber et al., 2017; Rello and Ballesteros, 2015). One of the most robust findings concerns the increased number of regressions, or backward saccades, especially during continuous reading: students with dyslexia typically make substantially more regressions than typically developing peers, signalling challenges in integrating linguistic information across words and lines (Traxler et al., 2012; De Luca et al., 1999). Together, shorter saccades and excessive regressions point to inefficient forward planning and difficulty maintaining linguistic cohesion, as readers repeatedly revisit previously processed segments in an effort to compensate for phonological and orthographic weaknesses. These saccadic anomalies, consistently replicated across studies, underscore the value of saccade-based eye-tracking metrics as sensitive indicators of reading difficulty that extend beyond what can be captured through accuracy or fluency scores alone.

3.2.3 Scanpath organization

Beyond fixation and saccadic indices, scanpath organization provides additional insight into the visual–attentional coordination difficulties observed in students with Specific Learning Disorders (SLD). Research consistently shows that their scanpaths are less linear, reflecting difficulties in maintaining a stable left-to-right progression and in sustaining attentional focus during reading (Rello and Ballesteros, 2015; Nilsson Benfatto et al., 2016). They also tend to be more dispersed across the page, with gaze patterns that wander outside the expected textual or task-relevant regions, indicating inefficient allocation of visual attention and increased susceptibility to distractors (Ronconi et al., 2013; De Luca et al., 1999). Scanpaths of students with SLD are frequently characterized by erratic transitions between specific areas of interest (AOIs), such as abrupt or unpredictable shifts between words, lines, or problem components, suggesting challenges in coordinating visual exploration with ongoing cognitive processing (Parshina et al., 2022). Importantly, such disorganization is not limited to reading: similar patterns have been reported during handwriting, where students show irregular gaze alternation between the writing surface and model text, and during numeracy tasks, where inefficient scanning of numbers and spatial layouts impairs problem solving (Paskovske and Kliziene, 2024; Obersteiner and Tumpek, 2016). These findings indicate that disordered scanpaths reflect broader impairments in visual-attentional

coordination that cut across multiple academic domains, underscoring the value of scanpath-based metrics in identifying subtle yet impactful learning difficulties in SLD.

3.2.4 Pupillometry and cognitive load

Eye-tracking studies that include pupillometry, although less frequent than fixation-based analyses, consistently indicate that students with SLD tend to work under heightened cognitive load during reading and arithmetic tasks. When children with dyslexia or related learning difficulties engage in decoding or numerical problem solving, they often show greater pupil dilation than typically developing peers, even when accuracy is comparable, suggesting that apparently similar performance can be achieved only at the cost of increased mental effort and reduced automatization (Ozeri-Rotstain et al., 2020; Paskovske and Kliziene, 2024). Within reading, enlarged and more variable pupil diameter has been linked to processing of low-frequency or irregular words, complex syntactic structures, and moments of local comprehension difficulty, patterns that tend to be more frequent and prolonged in SLD profiles (Hyönä, 2010; Conklin and Pellicer-Sánchez, 2016). In arithmetic and broader numeracy tasks, converging evidence shows that pupil size scales with problem complexity and with the need to flexibly shift between strategies, again with stronger and more persistent dilation in learners who struggle with basic number facts or place-value representations (Obersteiner and Tumpek, 2016; Paskovske and Kliziene, 2024).

3.3 Domain-specific findings

3.3.1 Reading

Reading tasks, whether silent or oral, represent the most extensively investigated domain in eye-tracking studies of Specific Learning Disorders (SLD), and consistent differences have been documented between SLD and typically developing readers. Students with dyslexia frequently exhibit longer fixations, even on high-frequency or familiar words, indicating reduced lexical automatization and a persistent reliance on effortful sublexical decoding (Hawelka et al., 2010; Jones et al., 2008; Nilsson Benfatto et al., 2016). Another robust finding concerns their higher regression rates, particularly at line breaks, syntactic boundaries, or points requiring integration of preceding text, suggesting difficulties in maintaining linguistic cohesion and in updating the ongoing sentence representation (Yagle et al., 2017; Stella and Engelhardt, 2019; De Luca et al., 1999). Progression across sentences and paragraphs is typically slower and more irregular, with less efficient left-to-right movement and increased pausing, reflecting challenges in coordinating oculomotor planning with lexical and syntactic processing (Krieber et al., 2017; Ronconi et al., 2013). Importantly, eye-tracking studies also highlight micro-patterns linked to comprehension failures, such as repeated regressions to short function words, often used to maintain syntactic parsing, or localized "stalling" on morphologically complex or low-predictability segments, which signals difficulty in integrating phonological, orthographic, and semantic cues (Ward and Kapoula, 2021; Conklin and Pellicer-Sánchez, 2016).

3.3.2 Writing and handwriting

Eye-tracking research on handwriting and written composition indicates that students with dysgraphia or broader writing difficulties show distinctive disruptions in the temporal coupling between gaze and motor output, reflecting compromised planning and monitoring processes during transcription. Compared to typically developing peers, they tend to spend more time visually monitoring their hand, pen, or stylus and less time allocating gaze to the upcoming segment of text, suggesting a shift of attentional resources from higher-level planning to low-level motor control (Kandel and Perret, 2015; Capellini et al., 2022). This reduced anticipatory gaze, often operationalized as fewer fixations on future letters, syllables, or words before they are executed, has been linked to poorer letter formation, spacing inconsistencies, and irregular alignment, particularly in tasks that require copying or dictation under time constraints (Accardo et al., 2013).

During copying and handwriting tasks, students with dysgraphia frequently show fragmented scanpaths characterized by short, local saccades between the model and their own production, combined with prolonged fixations on already written output. This pattern indicates an over-reliance on continuous visual checking of the motor trace and reduced capacity to maintain a stable mental representation of the target string (Rosenblum and Livneh-Zirinski, 2008; Pontart et al., 2013). In addition, visuomotor coordination appears less efficient: the temporal lag between gaze and hand (i.e., how far ahead the eyes are relative to the current writing point) is reduced, implying that the hand often "catches up" with the eyes instead of being guided by a forward-looking visual plan (Kandel and Perret, 2015). These gaze-motor abnormalities have important functional consequences. Children who allocate fewer anticipatory fixations to upcoming graphemes or words tend to produce more malformed letters, irregular spacing within and between words, and lower overall fluency, even when basic spelling knowledge is adequate (Accardo et al., 2013; Kandel and Perret, 2015). Interventions that scaffold chunking and visual preview of target segments can improve both kinematic smoothness and legibility, suggesting that eye-tracking indices may serve as sensitive markers of intervention response in written expression.

3.3.3 Spelling and orthographic processing

During spelling-to-dictation and orthographic judgment tasks, eye-tracking studies consistently indicate that children with Specific Learning Disorders (SLD) display increased visual verification behaviors and unstable gaze patterns that reflect underlying phonological and orthographic weaknesses. One recurrent finding is the presence of excessive verification fixations, in which students repeatedly inspect either the stimulus or their partial written output, suggesting uncertainty in phoneme–grapheme correspondence and reduced confidence in orthographic retrieval (Bosse et al., 2007; Afonso et al., 2020). These learners also tend to make frequent gaze shifts between the auditory or visual stimulus and the writing space, indicating difficulty maintaining a stable internal representation of the target string and a heightened reliance on external cues to guide transcription (Roux et al., 2013; Kandel and Perret, 2015). Children with SLD often show difficulty stabilizing gaze during phoneme–grapheme mapping, with short, erratic fixations and limited visual preview of upcoming graphemes, which aligns with findings of reduced anticipatory planning in written production (Capellini et al., 2022; Accardo et al., 2013). These oculomotor patterns are particularly pronounced in tasks requiring the integration of phonological decoding, orthographic decision-making, and motor execution, and they provide sensitive markers of the strategies children use, sometimes maladaptively, to cope with transcription demands.

3.3.4 Mathematics and numerical cognition

Eye-tracking work on mathematics and numerical cognition is still relatively scarce compared to reading, but a converging set of patterns has emerged when children with SLD, especially those with dyscalculia or broader math difficulties, are compared with typically achieving peers. Across studies, these learners tend to show increased fixation duration on operands and operators, particularly in tasks that involve place value, carrying/borrowing, or fraction comparison, suggesting that even basic numeric symbols require sustained, effortful processing rather than being handled automatically (Obersteiner and Tumpek, 2016; Paskovske and Kliziene, 2024). In multi-step arithmetic or word-problem solving, pupils with SLD often engage in inefficient scanning of the problem layout, with frequent returns to already inspected elements, long pauses on irrelevant parts of the statement, and delayed shifts toward key information or answer choices (Schindler et al., 2020; Van der Schoot et al., 2009). These disorganized scanpaths are accompanied by slowed transitions between areas of interest (AOIs), for example, from the verbal statement to the numerical expression or from intermediate results to the final response, indicating difficulties in coordinating eye movements with the sequential steps of mental calculation and problem representation (Paskovske and Kliziene, 2024). These ET signatures point to weaknesses in working memory, spatial arrangement processing, and attentional control: children with SLD appear to invest more visual and cognitive resources in locating, encoding, and revisiting critical numeric information, leaving fewer resources available for higher-order reasoning. In this sense, ET metrics in math tasks provide a complementary perspective to accuracy and response time, revealing how students navigate symbolic layouts and where, precisely, their processing bottlenecks emerge during numerical cognition tasks.

3.3.5 Visual search and attentional control

ET consistent Eye-tracking studies examining visual search and attentional control consistently show that children with Specific Learning Disorders (SLD) demonstrate slower and less efficient search strategies across a range of tasks involving symbol identification, figure comparison, and scanning of visually dense layouts. Compared with typically developing peers, they display longer search times and reduced accuracy in detecting targets among distractors, often revisiting irrelevant regions of the display and requiring more fixations to locate key information (Bucci et al., 2012). Their gaze patterns also tend to be broader and more dispersed, revealing difficulties in constraining visual exploration to task-relevant areas and in suppressing attentional capture by peripheral or competing stimuli (Ronconi et al., 2013; Paskovske and Kliziene, 2024). These inefficient exploration strategies are frequently accompanied by unstable fixation patterns, short and erratic saccades, and delayed transitions between perceptually salient elements, features that map closely onto the attentional and processing-speed profiles often associated with SLD, particularly in dyslexia and dyscalculia (Ward and Kapoula, 2021; Obersteiner and Tumpek, 2016).

3.4 Evidence from gaze-contingent and ET-based interventions

Evidence remains preliminary, with most studies relying on small samples and short-term designs. Although the literature is limited and mainly exploratory, several promising intervention approaches emerged.

3.4.1 Adaptive reading windows

Studies on adaptive reading windows provide some of the most promising evidence for gaze-contingent support in learners with Specific Learning Disorders (SLD). These systems dynamically adjust text visibility based on the reader's real-time gaze position, using techniques such as moving windows, line-by-line masking, or adaptive line highlighting, to reduce visual crowding and guide attention toward the relevant segment of text. Research indicates that such tools can lead to improved reading fluency, particularly in students with dyslexia who struggle with maintaining a stable left-to-right progression (Rello and Baeza-Yates, 2017; Nilsson Benfatto et al., 2016). By restricting peripheral distractors and emphasizing the current line or word, adaptive windows also promote fewer regressions, suggesting more efficient forward planning and reduced reliance on corrective saccades (Toki, 2024; Medan and Pelman, 2024). Gaze-contingent highlighting has been shown to enhance focus on the current line, decreasing off-line fixations and supporting smoother visual tracking in both silent and oral reading tasks (Chytry et al., 2025). Although most findings derive from small samples or short-term pilots, the consistent improvements in fluency, regression rate, and attentional alignment highlight the potential of adaptive reading windows as an accessible and scalable form of gaze-responsive intervention for learners with reading-based SLD.

3.4.2 Error-monitoring and attentional cueing

Gaze-contingent systems that monitor readers' eye movements in real time have begun to leverage error-related patterns (such as prolonged fixations, repeated regressions, or atypical scanpaths) to trigger immediate prompts and attentional cues. In experimental reading tutors and assistance systems for children with reading difficulties, real-time detection of disrupted gaze behavior has been used to provide on-screen cues (e.g., subtle highlighting, arrows, or brief messages) that guide the student back to the relevant line or word, helping them resume forward progress rather than remaining "stuck" in local rereading loops (Schneider et al., 2011; Rayner, 2014). Studies in adaptive multimedia and educational interfaces similarly show that gaze-contingent feedback, delivered when learners dwell excessively on non-relevant regions or fail to inspect critical information, can enhance self-monitoring, reduce unproductive visual wandering, and promote more strategic processing of text and graphics (Scheiter et al., 2019; Campen et al., 2021; Bimba et al., 2017). Eye-gaze contingent attention-training paradigms indicate that contingent feedback on where the learner is looking can causally influence attentional control (Carelli et al., 2022) and error regulation, supporting the idea that such prompts may foster awareness of inefficient reading strategies and encourage timely self-correction (Carelli et al., 2022).

3.4.3 Visual guidance for handwriting and drawing

Gaze-contingent visual guidance has also been explored as a way to support handwriting and drawing in students with SLD and related handwriting difficulties. Eye-tracking work on writing shows that skilled writers allocate gaze proactively, fixating ahead of the pen to

plan upcoming letter strokes and word segments, whereas less skilled handwriters rely more on local, online visual checking of their hand and the already-written trace (Maldarelli et al., 2015; Sita and Taylor, 2015). Children with handwriting disorders or dysgraphia often display reduced anticipatory gaze, increased dependency on continuous visual control of the moving hand, and unstable spatial organization on the page, patterns that have been linked to broader visual-motor integration and feedback-processing deficits (Fears et al., 2019; Ye et al., 2024). Emerging intervention studies suggest that visual guidance elements, such as illuminated stroke sequences, dynamic cursors that mark the next segment to be traced, or on-screen guides that adapt to the child's gaze, can help shift attention from reactive checking toward more anticipatory planning. Computerized visual feedback has been shown to improve temporal efficiency and spatial consistency of handwriting in children with motor-based handwriting disorders, reducing writing time and variability in letter height (Bartov et al., 2023). Serious-game and wearable eye-tracking approaches similarly indicate that making stroke order and spatial layout visually explicit, in synchrony with the child's gaze, can enhance visual-motor coupling and reduce the need to constantly look back at the writing hand (Piazzalunga et al., 2023).

3.4.4 Arithmetic scaffolding

Emerging research on gaze-adaptive numeracy tasks indicates that eye-tracking–based scaffolding can support students with Specific Learning Disorders (SLD) in coordinating attention during mathematical problem solving. In these systems, the task display adapts dynamically to the learner's gaze, for example, by highlighting the next step, dimming irrelevant regions, or providing visual cues when the student fixates too long on distractors. Studies show that such scaffolding can enhance step-wise attention control, helping students maintain focus on the sequential structure of multi-step arithmetic problems and reducing the cognitive load associated with planning each operation (Obersteiner and Tumpek, 2016; Schindler and Lilienthal, 2019). Gaze-adaptive supports also lead to a reduction in distractor fixations, particularly in tasks involving visually dense arrays, number lines, or multi-element fraction models, where students with SLD typically struggle to filter irrelevant information (Van der Schoot et al., 2009). Providing real-time visual cues in response to inefficient scanpaths has been shown to promote greater efficiency in problem scanning, facilitating smoother transitions between operands, operators, and answer fields and improving overall organization of the solution process (Paskovske and Kliziene, 2024). Although this line of research is still in its early stages and sample sizes remain small, the convergence of findings across studies suggests that gaze-contingent arithmetic scaffolding may serve as an effective tool for strengthening attentional alignment and visual–spatial coordination during mathematical reasoning in students with SLD.

4 Discussion

This narrative review examined two decades of eye-tracking (ET) research focused on reading, writing, spelling, numeracy, and attentional processes in school-age students with Specific Learning Disorders (SLD). Across these domains, ET consistently reveals distinctive oculomotor signatures that reflect the underlying cognitive, linguistic, and visual–attentional challenges faced by these learners. More broadly, the findings demonstrate that ET offers insights that go far beyond traditional accuracy- and time-based assessments, providing a fine-grained view of how cognitive processes unfold in real time. By integrating evidence across tasks and modalities, this review highlights the potential of ET as both a diagnostic complement and a foundation for adaptive intervention in educational settings.

A central theme of the findings concerns inefficient visual sampling and decoding during reading, which has been the most extensively studied domain in ET research. Students with dyslexia consistently show longer fixations, shorter saccades, and elevated rates of regressions—patterns that map onto well-established deficits in phonological decoding, orthographic processing, and automatization (Hawelka et al., 2010; Nilsson Benfatto et al., 2016). These signatures reflect not only word-level decoding difficulties but also broader challenges in maintaining the flow of information across sentences, integrating syntactic cues, and sustaining coherent comprehension. Micro-patterns such as repeated regressions to function words or hesitation on morphologically complex units indicate localized breakdowns that are difficult to detect with conventional tests. ET thus reveals where and when comprehension falters, offering a powerful complement to end-point metrics such as reading fluency or accuracy.

A second theme emerges from research on writing, spelling, and transcription. Eye–hand coordination studies show that children with dysgraphia exhibit reduced anticipatory gaze and increased reliance on continuous visual monitoring of the hand, suggesting that they must devote disproportionate attentional resources to low-level motor execution at the expense of higher-level planning. These oculomotor profiles align with research on handwriting development, which suggests that forward-looking gaze supports the chunking of linguistic units and the organization of spatial layout (Kandel and Perret, 2015). From a broader theoretical perspective, distinctions between anticipatory, present-focused, and retrospective modes of processing have been shown to be relevant for understanding self-regulation and performance (Diotaiuti et al., 2021a). In the context of SLD, eye-tracking allows these temporal orientations to be operationalized behaviorally, for example through anticipatory fixations, preview benefits, or reactive monitoring patterns. In spelling and orthographic decision-making, excessive verification fixations and unstable gaze patterns reveal difficulty maintaining phoneme–grapheme correspondences and a reliance on external cues when internal representations are weak (Afonso et al., 2020). Findings underscore that difficulties in written expression arise from the interaction of linguistic, motoric, and visual–attentional constraints, rather than from any single deficit.

A third theme concerns numerical cognition and problem solving, domains in which ET research is growing but still less developed. Despite fewer studies, consistent findings indicate that students with math-related SLD or dyscalculia show prolonged fixations on operands, inefficient scanning of spatially structured problems, and delayed transitions between sequential steps of a calculation (Obersteiner and Tumpek, 2016). These difficulties align with theoretical accounts of dyscalculia that emphasize weaknesses in working memory, spatial organization, and executive control. Eye-tracking allows researchers to observe the precise points in a problem where cognitive overload occurs, for example, when a child repeatedly revisits irrelevant portions of a word problem or misallocates attention in a coordinate grid or number line task. Such

process data provide a richer understanding of mathematical difficulties than accuracy alone could offer.

ET research across domains reveals generalized attentional vulnerabilities in SLD, including slower visual search, broader and less selective exploration, difficulty suppressing distractors, and unstable fixation patterns (Ronconi et al., 2013; Bucci et al., 2012). These behaviors suggest that some SLD profiles may share common attentional and processing-speed constraints, which manifest differently depending on the task domain. The consistency of these attentional anomalies across reading, writing, and mathematics supports the view that SLDs are rooted not only in domain-specific deficits but also in cross-domain cognitive processes such as attention shifting, inhibition, and visual–spatial integration. Eye-tracking thus contributes to a more integrative theoretical account of learning difficulties.

Another important area highlighted by this review involves the potential for gaze-contingent interventions and adaptive scaffolding. Although still emerging, these technologies show promise for supporting learners in real time by responding to their moment-to-moment gaze behavior. Adaptive reading windows improve fluency and reduce regressions by constraining visual clutter and guiding attention to the relevant segment of text (Rello and Baeza-Yates, 2017; Toki, 2024). Error-monitoring systems that trigger prompts when a learner shows prolonged fixations or repeated regressions can help prevent "stuck" states and promote self-correction and metacognitive awareness (Schneider et al., 2011). Visual guidance tools for handwriting that illuminate strokes or provide gaze-aligned cues can enhance visuomotor coordination and reduce reliance on maladaptive visual monitoring of the hand (Bartov et al., 2023). In mathematics, gaze-adaptive scaffolding can improve step-wise attention and reduce distractor fixations in visually dense or multi-step problems (Schindler and Lilienthal, 2019). Across these interventions, ET moves from a diagnostic tool to an instructional technology, offering a pathway toward personalized, moment-adaptive learning environments.

Despite this promising potential, the review also highlights substantial methodological challenges. Sample sizes remain small, and recruitment often relies on convenience samples rather than clinically validated SLD diagnoses. ET setups differ widely in device type, sampling rate, calibration strategy, and environmental control, limiting comparability across studies. Many studies fail to report essential data quality metrics such as calibration error, precision, or track loss, factors that are especially relevant when working with younger learners who may move more or fatigue quickly. The scarcity of longitudinal and classroom-based studies limits understanding of how gaze patterns evolve across development or respond to intervention over time. These methodological limitations underscore the need for more rigorous, standardized approaches to data collection and reporting.

The findings of this review also have significant educational implications. First, ET-based assessment could enrich learner profiling by revealing specific breakdown points during reading, writing, or mathematics, allowing educators to design more targeted interventions. For example, high regression rates during reading may suggest the need for explicit fluency training or syntactic scaffolding, while poor anticipatory gaze in handwriting may indicate the need for explicit instruction in motor planning and grapheme chunking. Second, ET-informed tools have the potential to support inclusive education by offering real-time scaffolding that adapts to the learner's momentary needs. Third, ET can serve as a feedback tool for educators, helping them understand how students navigate instructional materials and where visual or cognitive overload may arise.

Learning and academic functioning in school-age populations are shaped not only by individual cognitive characteristics but also by the broader classroom context, including peer relationships and social dynamics (Cavicchiolo et al., 2022). This complexity underscores the need for assessment tools, such as eye-tracking, that can capture individual learning processes while remaining sensitive to real-world educational settings. Future research should move toward larger-scale, ecologically valid designs, including school-based studies, cross-domain ET assessments, and randomized controlled trials of gaze-contingent interventions.

5 Limitations

This narrative review has several limitations that should be considered when interpreting its findings. Although the search strategy was comprehensive, the review did not follow a systematic protocol and therefore may not include all eligible studies. The heterogeneity of the available evidence, spanning different ET devices, calibration methods, sampling rates, task designs, and analytic approaches, limits direct comparison across studies and constrains the ability to draw strong generalizable conclusions. Relatedly, many studies included small samples, convenience-based recruitment, or clinically heterogeneous SLD profiles, reducing statistical power and weakening the reliability of subgroup inferences, particularly for dysgraphia and dyscalculia, which remain underrepresented in the ET literature.

Data-quality reporting was inconsistent across studies. Essential information such as calibration error, precision, track loss, and criteria for data exclusion was often missing, making it difficult to assess the robustness of recorded gaze metrics. This is particularly relevant when working with children with SLD, who may show increased head movement, reduced sustained attention, or greater fatigue, all of which can introduce systematic biases in ET measures.

Most studies were conducted in controlled laboratory settings. While these environments allow precise measurement, they do not fully capture the visual, cognitive, and attentional demands of real classrooms. The ecological validity of the reviewed findings is therefore limited, and it remains unclear how well ET-based indicators transfer to naturalistic learning contexts involving distractions, transitions, peer presence, and teacher-led instruction.

Evidence on gaze-contingent interventions is still exploratory. Existing studies often rely on short-term pilots with limited samples, lack control conditions, and rarely include long-term follow-up to determine whether benefits persist over time or generalize to authentic academic tasks. As such, the promise of ET-based scaffolding must be interpreted cautiously until larger randomized and school-embedded trials become available. While ET provides rich insights into visual and cognitive processing, it captures only one slice of learners' multimodal behavior. Gaze patterns must be interpreted in conjunction with linguistic, motoric, emotional, and contextual variables to avoid oversimplification. Integrating ET with other behavioral, neurocognitive, and ecological data sources remains an important avenue for future work. As with any measurement tool intended for assessment, eye-tracking indicators must demonstrate not only sensitivity but also conceptual clarity and measurement

stability. Psychometric research emphasizes that without evidence of metric adequacy and invariance, comparisons across individuals or groups may be misleading (Diotaiuti et al., 2021b).

6 Conclusion

This narrative review demonstrates that eye-tracking (ET) offers a uniquely powerful framework for understanding the cognitive and perceptual processes underlying Specific Learning Disorders (SLD) in school-age students. Across reading, writing, spelling, numerical cognition, and visual–attentional tasks, ET consistently reveals fine-grained oculomotor signatures (longer fixations, atypical saccadic patterns, disorganized scanpaths, and heightened pupil dilation) that map closely onto known linguistic, motoric, and attentional difficulties. These insights extend beyond traditional behavioral assessments by capturing *how* learners engage with academic materials in real time, identifying hidden points of breakdown and revealing the strategies students adopt, whether adaptive or compensatory, during authentic learning activities.

Beyond assessment, emerging gaze-contingent interventions underscore the translational potential of ET in education. Adaptive reading windows, real-time error-monitoring prompts, gaze-aligned handwriting supports, and gaze-adaptive numeracy tasks illustrate how ET can move from a diagnostic tool to a dynamic scaffold capable of shaping attention, enhancing metacognitive awareness, and supporting more efficient learning behaviors. Although these systems are still exploratory, preliminary findings consistently point toward improvements in reading fluency, attentional control, and gaze-motor coordination.

At the same time, the current evidence base is limited by methodological heterogeneity, small sample sizes, and a lack of longitudinal and school-embedded studies. To fully realize the promise of ET in educational practice, future research must adopt more rigorous and standardized protocols, ensure transparent reporting of data quality, and examine the feasibility and efficacy of ET-based supports in everyday classrooms. Interdisciplinary collaboration between education, psychology, special education, and human-computer interaction will be essential for developing scalable tools that align with curricular goals, ethical standards, and the lived realities of teachers and students.

In conclusion, ET has the potential to transform both the assessment and support of students with SLD by illuminating real-time cognitive processes that have traditionally remained hidden. As technology becomes more accessible and methodologies mature, ET can serve as a bridge between research and practice, enabling more precise learner profiles, more responsive instructional interventions, and ultimately, more equitable educational opportunities for learners with diverse needs. As ET technology becomes more affordable (e.g., tablet-based trackers), its integration into routine educational assessment may become increasingly feasible.

Author contributions

PD: Supervision, Conceptualization, Writing – original draft, Methodology, Writing – review & editing. FDS: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Investigation. SV: Investigation, Writing – review & editing, Conceptualization, Writing – original draft. PADT: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. SM: Writing – original draft, Writing – review & editing, Methodology, Investigation.

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