

Developmental Dyslexia: From Cognitive and Neural Mechanisms to Diagnosis, Intervention, and Artificial Intelligence: A Narrative Review

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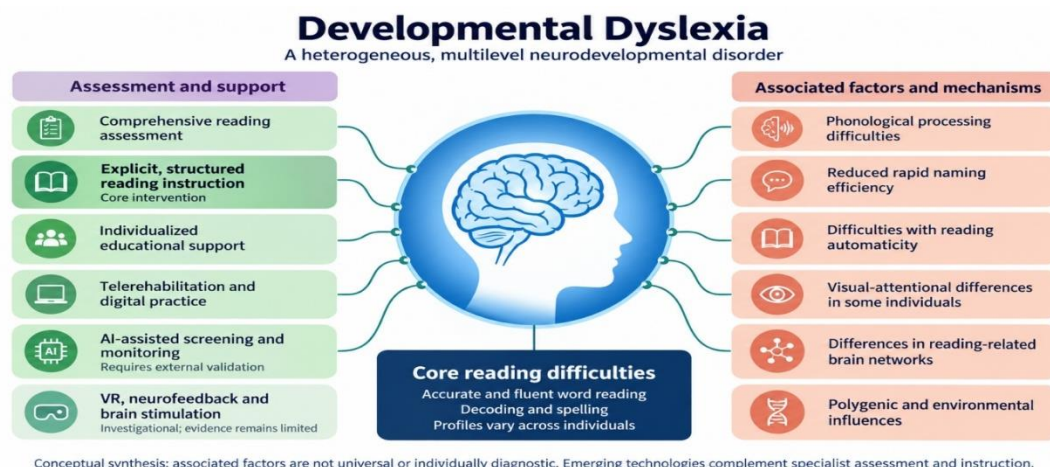
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ABSTRACT

Developmental dyslexia (DD) is a complex and heterogeneous neurodevelopmental disorder characterized by persistent difficulties in accurate and fluent reading, decoding, and spelling; the wide individual variation in the severity and manifestation of these problems indicates that it cannot be explained by a single cause. The aim of this narrative review was to synthesize existing evidence regarding cognitive mechanisms, genetic factors, brain networks, diagnostic methods, educational and rehabilitative interventions, and artificial intelligence applications in the context of DD. A literature search was conducted across PubMed, Web of Science Core Collection, and Google Scholar; following the removal of duplicates and the screening of titles, abstracts, and full texts by three authors, 56 articles were included in the final analysis. Findings indicate that phonological processing continues to play a significant role in DD, although factors such as rapid naming, attention, working memory, skill automatization, and visual processing also contribute to individual differences. Genetic evidence supports the polygenic nature of the disorder, and neuroimaging studies have revealed differences in the organization and connectivity of networks involved in reading, language, attention, and visual processing. Regarding diagnosis, the direct assessment of reading skills—combined with a review of developmental and educational history and the evaluation of linguistic and cognitive abilities—remains critically important, whereas methods such as electroencephalography (EEG), eye-tracking, and machine learning primarily serve as complementary tools. Direct and structured reading instruction remains the most vital intervention, while digital technologies and innovative methods have yielded promising yet heterogeneous results. Overall, DD can best be examined within a multilevel framework that considers the interaction among cognitive, genetic, neurological, and environmental factors.

Keywords: Dyslexia; Neurodevelopmental Disorder; Brain Networks; Genetics; Diagnosis; Intervention; Artificial Intelligence; Neuroimaging



INTRODUCTION

Developmental dyslexia (DD) or Reading disorder, is one of the most common neurodevelopmental learning disorders, characterized by persistent difficulties in acquiring reading skills—specifically in the accurate and fluent recognition of words, decoding, and spelling. Despite the individual possessing normal intelligence, adequate educational opportunities, and intact sensory function, this disorder can lead to significantly reduced academic performance and limitations in the learning trajectory [2, 5]. Contemporary definitions of DD emphasize that the core of the disorder lies in difficulties with accurate and fluent word recognition, decoding, and spelling, whereas reading comprehension issues are generally viewed as secondary consequences of reduced reading experience and limited language skill development [2]. The global prevalence of DD among primary school children is approximately 7.1%, although reported rates vary depending on diagnostic methods, the characteristics of the studied population, and the nature of the writing system. The significant prevalence of this disorder and its long-term impact on academic success underscore the importance of precisely understanding underlying mechanisms and developing effective diagnostic and intervention methods. Historically, DD research focused primarily on a central cognitive deficit—specifically, impaired phonological processing—and the phonological deficit theory remains a key explanatory model for reading difficulties, as many affected individuals struggle to convert written information into phonological representations and process the phonological structures of language [5, 7]. However, recent findings indicate that DD is a heterogeneous disorder; wide individual variations in symptom severity, reading error patterns, and responses to instruction and treatment suggest that the disorder cannot be attributed to a single mechanism [2]. Recent studies emphasize the necessity of a multifactorial approach that considers the interaction among cognitive, linguistic, neurological, and environmental factors. Although phonological processing and linguistic skills play a fundamental role in reading development, other factors—such as naming speed, attention, working memory, and visual processing—may also contribute to individual differences in reading performance [5]. From this perspective, DD arises from multiple developmental pathways that can ultimately lead to a similar behavioral pattern: impaired reading ability. Furthermore, the role of visual and attentional factors in reading disorders has garnered significant attention in recent years. Emerging evidence indicates that some affected individuals may exhibit differences in visual information processing, motion processing, magnocellular system function, eye movements, and visual attention control [3]. Researchers emphasize that visual factors should not be viewed as the sole cause of DD ; rather, they are best examined within the framework of risk-resilience interaction models, wherein multiple developmental factors influence the formation of reading ability. In addition to examining cognitive mechanisms, understanding the distinctions between different reading modes is crucial for gaining better insight into DD. Oral reading and silent reading are two primary forms of reading activity; while closely related, they may rely on distinct cognitive processes [6]. Moreover, silent reading becomes increasingly important with age and the growing complexity of educational tasks, as a significant portion of learning in both school and university settings relies on this mode of reading. In recent years, advancements in cognitive neuroscience and modern technologies have enabled researchers to investigate the relationships between brain function, cognitive processes, and educational outcomes. The framework of educational neuroscience emphasizes the necessity of establishing connections between findings from cognitive science, neuroscience, and education, suggesting that neuroscientific data can be utilized to understand underlying mechanisms, improve diagnosis, predict academic performance, and design effective interventions [1]. Furthermore, recent studies have demonstrated that combining neuroimaging techniques with machine learning algorithms can enhance the ability to predict literacy skills and identify patterns associated with learning difficulties [4]. Given the complex and multidimensional nature of DD, contemporary research approaches focus on identifying the interplay among biological, cognitive, and environmental factors rather than seeking a single cause. Such an approach can facilitate the development of more precise models for early diagnosis, subtype classification, and the design of personalized interventions. Accordingly, this review article aims to examine recent findings regarding the multifactorial nature of DD, the roles of cognitive and visual factors, the distinctions between oral and silent reading, and the potential of cognitive neuroscience approaches to better understand this disorder.

Accordingly, the evidence in this review was organized within a multilevel framework comprising four interconnected domains: (1) cognitive, genetic, and neural mechanisms; (2) diagnostic and assessment approaches; (3) educational and rehabilitative interventions; and (4) artificial-intelligence-based and emerging

technological approaches. This framework was used to distinguish mechanistic evidence from evidence concerning diagnostic utility, intervention effectiveness, and emerging educational applications.

METHODS

This study was designed to review and synthesize existing evidence on DD, examining the subject from several key perspectives: cognitive and theoretical mechanisms, genetic factors, brain networks and function, diagnostic methods, therapeutic and educational interventions, and the application of new technologies and artificial intelligence. The literature searches were conducted between 1999 to 2026, with no publication-year restriction. The study selection process involved searching for sources, removing duplicates, screening titles and abstracts, evaluating full texts, extracting data, and finally selecting studies that had a direct and substantial connection to the review's core themes. To minimize error during article selection, three authors participated in the screening and review stages; ultimately, 56 articles were selected for data extraction and inclusion in the final synthesis.

Inclusion and Exclusion Criteria

Inclusion criteria were established to provide a relatively comprehensive overview of DD while ensuring the selected studies were clearly relevant to the article's main topic. Accordingly, the review included studies addressing DD—specifically DD—that examined at least one of the following key areas: cognitive processes and reading-related theories; genetic and biological factors; brain network structure and function; diagnostic and screening methods; educational or rehabilitation interventions; and the use of digital technologies, machine learning, and artificial intelligence. Given the breadth of the topic, the scope of the studies included was not restricted to a single research design; rather, a wide range of approaches—including experimental, quasi-experimental, cross-sectional, and observational studies, clinical trials, neuroimaging, genetic and genomic research, intervention studies, systematic reviews, meta-analyses, narrative reviews, and theoretical studies—were examined, provided their data were relevant to one of the review's key themes. Furthermore, no uniform age restriction was applied across all sections of the review, as the studies focused variously on children and adolescents, adults, or groups with a familial risk of DD or specific population demographics; excluding these studies would have resulted in the loss of significant evidence regarding development, genetics, and brain function.

Studies were excluded from the final analysis if they lacked a clear link to DD, fell outside the review's established scope, failed to provide sufficient information for evaluation or data extraction, or presented methodologies and results that were too ambiguous to allow for a proper interpretation of the findings. In instances where studies concerning acquired reading disorders—such as alexia or hemianopic DD—offered information relevant to technology or interventions, they were considered solely within that specific context, and their results were not directly generalized to DD.

Search and Study Selection Strategy

A literature search covering the years 1999 to 2026 was conducted across the PubMed, Web of Science Core Collection, and Google Scholar databases. To broaden the search scope, terms related to DD and reading disorders were combined with keywords associated with the article's core topics; the search encompassed areas such as phonological deficits, rapid naming, skill automatization, procedural learning, genetic and genomic factors, neuroimaging, brain connectivity, white matter, diagnosis and screening, EEG, eye-tracking, reading interventions, rehabilitation, virtual reality, neurofeedback, electrical brain stimulation, artificial intelligence, machine learning, deep learning, and adaptive learning methods.

Results obtained from the various databases were first imported into EndNote software to systematically manage references and identify and remove duplicates as much as possible. Subsequently, the remaining records were transferred to the Rayyan platform for screening, and three authors carried out the study review process. In the initial stage, article titles and abstracts were examined, and studies lacking a clear connection to the review's objectives were excluded; the full texts of potentially eligible articles were then evaluated, and final decisions were made based on inclusion and exclusion criteria.

In instances where disagreements arose among the authors regarding the inclusion or exclusion of a study, the article was re-examined, and a final decision was reached following discussion and consensus. Upon completion of the screening and full-text evaluation stages, a total of 56 articles were selected as included publications for the data extraction and final synthesis phases. In addition to these studies, several other sources were utilized to define concepts, outline background information, provide epidemiological data, and strengthen the article's theoretical discussion; however, these sources were not included in the primary set of 56 studies selected for data extraction.

Table 1 . Condensed search strategy

DD: cognitive mechanisms, genetics, brain networks, diagnosis, interventions and artificial intelligence.

Database platform /	Condensed search string
PubMed	("dyslexia "[Mesh] OR dyslexi*[tiab] OR "reading disorder"[tiab] OR "reading disorders"[tiab] OR "reading disability"[tiab] OR "reading disabilities"[tiab]) AND (phonolog*[tiab] OR "rapid naming"[tiab] OR automaticity[tiab] OR "procedural learning"[tiab] OR genetic*[tiab] OR genomic*[tiab] OR polygenic[tiab] OR neuroimag*[tiab] OR connectivity[tiab] OR "white matter"[tiab] OR diagnos*[tiab] OR screen*[tiab] OR EEG[tiab] OR "eye tracking"[tiab] OR intervention*[tiab] OR rehabilitat*[tiab] OR "reading instruction"[tiab] OR "virtual reality"[tiab] OR neurofeedback[tiab] OR tDCS[tiab] OR "artificial intelligence"[tiab] OR "machine learning"[tiab] OR "deep learning"[tiab] OR "adaptive learning"[tiab])
Web of Science Core Collection	TS=(dyslexi* OR "reading disorder*" OR "reading disabilit*") AND TS=(phonolog* OR "rapid naming" OR automaticity OR "procedural learning" OR genetic* OR genomic* OR polygenic OR neuroimag* OR connectivity OR "white matter" OR diagnos* OR screen* OR EEG OR "eye tracking" OR intervention* OR rehabilitat* OR "reading instruction" OR "virtual reality" OR neurofeedback OR tDCS OR "artificial intelligence" OR "machine learning" OR "deep learning" OR "adaptive learning")
Google Scholar Separate queries	dyslexia "phonological deficit" dyslexia "rapid automatized naming" dyslexia genetics dyslexia "brain connectivity" dyslexia diagnosis dyslexia "reading intervention" dyslexia "artificial intelligence" dyslexia "machine learning"

Characteristics of the Reviewed Studies

The final set of studies exhibited significant diversity in terms of design, study populations, measurement tools, and research objectives—a diversity that aligns with the multidimensional nature of DD. Some studies focused on children and adolescents with DD or those at risk, employing assessments of reading, phonological awareness, rapid naming, working memory, processing speed, and other cognitive functions. In contrast, another

group of studies utilized methods such as fMRI, resting-state fMRI, DTI, diffusion MRI, EEG, eye-tracking, and functional or structural connectivity analysis to investigate brain differences associated with DD.

Other articles addressed genetic factors, encompassing family and twin studies, candidate gene research, genomic analyses, genome-wide association studies, and investigations into the links between genetic factors and neurological characteristics. Regarding interventions, the studies employed various approaches, including cognitive training, reading-based therapies, neurofeedback, transcranial electrical stimulation, digital games, virtual reality, telerehabilitation, and interactive educational tools.

In recent years, some studies have also focused on the application of artificial intelligence and machine learning methods for screening, diagnosis, handwriting analysis, eye-movement assessment, EEG analysis, and the design of personalized educational tools. This diversity in the final studies made it possible to examine DD not merely as a reading difficulty, but also to consider the interrelationships among cognitive, neurological, genetic, educational, and technological factors.

Extraction of Data and Variables of Interest

Following the selection of the final studies, information from each article was systematically recorded in a data extraction table to facilitate comparison across studies. The extracted information included the article title, first author's name and year of publication, study type, number and characteristics of participants and comparison groups, tests and tasks employed, measurement tools and methods, a summary of key findings, and the overall conclusion of each study.

In addition to this general information, specialized data relevant to the specific topic of each article were also captured. For neuroimaging studies, this involved examining the imaging modality, the task performed, and patterns of brain activity or connectivity. In genetic studies, the study design, the specific genes or variants investigated, and the primary results were extracted. For intervention studies, details regarding the intervention type, characteristics of the intervention and control groups, program duration or implementation method, and observed changes in reading or cognitive functions were recorded. Finally, for studies involving artificial intelligence, the input data type, the computational method or algorithm used, and the system's primary objective—such as screening, classification, diagnosis, or educational support—were considered.

The extracted information was reviewed by the authors; whenever data appeared ambiguous, incomplete, or inconsistent, the original article was re-examined to minimize the risk of recording errors. In instances where an article failed to clearly report specific details—such as the exact number of participants, group specifics, or the full names of measurement tools—no attempts were made to estimate or infer missing data; only information verifiable from the article's text was included in the final table.

Primary Synthesis Set and Supplementary References

The primary evidence synthesis was restricted to the 56 studies that satisfied the predefined eligibility criteria and underwent structured data extraction and quality appraisal. Additional references were used only to define concepts, provide epidemiological or theoretical context, or support interpretation. These supplementary references were not included in the evidence matrix, risk-of-bias synthesis, or determination of the strength of evidence.

Quality Appraisal and Risk-of-Bias Assessment

The methodological quality and risk of bias of the 56 publications included in the primary synthesis were assessed according to the design of each study, because the reviewed evidence included a wide range of experimental, observational, neuroimaging, genetic, predictive-modeling, systematic-review, and narrative-review designs. Therefore, a single appraisal tool was not applied to all studies; instead, design-appropriate frameworks were used whenever possible, including ROBINS-I for non-randomized intervention studies, JBI tools for observational and cross-sectional studies, ROBIS for systematic reviews and meta-analyses, PROCAST for predictive-modeling studies, and SANRA for narrative reviews, while adapted appraisal approaches were

used for specialized neuroimaging and genetic studies when no single standard tool fully matched the study design.

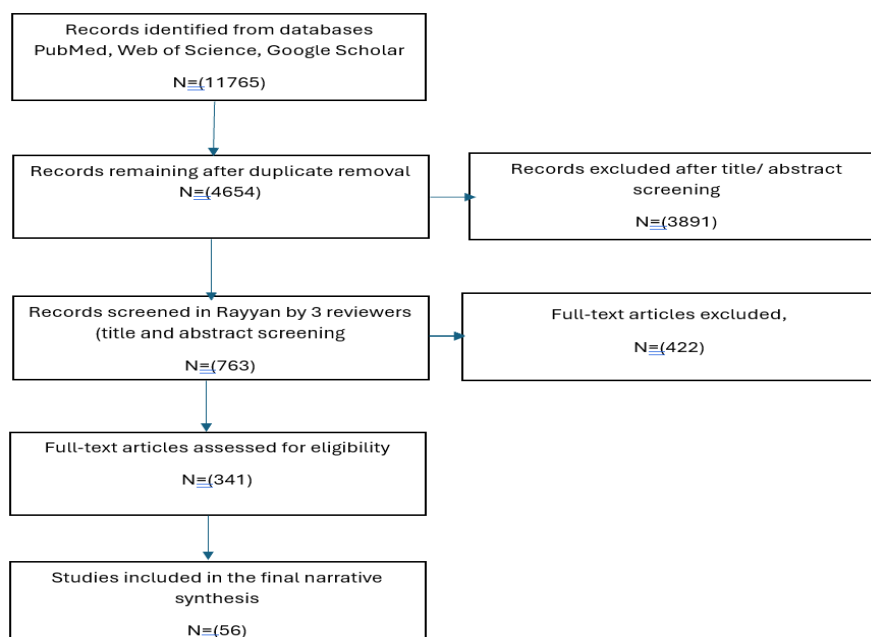
For each publication, the assessment focused on major sources of bias relevant to the corresponding design, including participant selection or randomization, confounding or deviations from the intended intervention, missing data, outcome or exposure measurement, and selective reporting or analytical bias. An overall risk-of-bias judgment was then assigned based on the combined appraisal of these domains. For theoretical papers and some narrative or conceptual publications, conventional study-level risk-of-bias ratings were considered not applicable because these articles did not include an independent empirical sample.

Risk-of-bias findings were not used as an automatic exclusion criterion after study inclusion; instead, they informed the interpretation of the evidence during the narrative synthesis. Findings from studies with small samples, uncontrolled designs, substantial confounding, incomplete reporting, lack of external validation, or other major methodological limitations were interpreted more cautiously and were not used alone to support strong diagnostic or therapeutic conclusions. In contrast, findings supported by more robust designs, clearer outcome measurement, and lower methodological concern were given greater interpretive weight when drawing the overall conclusions of the review

Narrative Synthesis of Heterogeneous Evidence

Because the included publications differed substantially in study design, population, outcome measures, and research purpose, a quantitative synthesis across all domains was not considered appropriate. The evidence was therefore synthesized narratively within the predefined domains of cognitive, genetic and neural mechanisms, diagnosis and assessment, intervention and rehabilitation, and artificial intelligence. Within each domain, studies were compared according to study design, population relevance, directness of the measured outcome, methodological quality, and consistency of findings. Diagnostic classification performance was distinguished from clinical diagnostic validity, while changes in cognitive or behavioral processes were distinguished from direct improvements in reading outcomes. Similarly, technical performance of artificial-intelligence models was not considered equivalent to external validation or educational effectiveness. Risk-of-bias findings were incorporated into the interpretation so that evidence from studies with major methodological limitations was given less interpretive weight when formulating the overall conclusions.

Figure 1. Flow diagram of literature search and study selection.



RESULTS

Theories Explaining Developmental Dyslexia

Developmental Dyslexia or DD is a complex reading disorder that varies in form and severity among individuals; its characteristics cannot be fully explained by a single cognitive deficit or the dysfunction of a specific brain region. Research indicates that reading difficulties may be linked to phonological processing, processing speed, skill automatization, procedural learning, and neural network development. Consequently, various theories can be viewed as perspectives that each explain a specific aspect of the reading development process and, in some respects, complement one another—though the strength of the supporting evidence varies across them [18, 20].

The Phonological Deficit Theory

The phonological deficit theory is a primary perspective for explaining reading difficulties in DD ; it posits that impairments in representing, processing, or accessing the sound structure of language can disrupt the learning of the link between written text and speech sounds. This connection is particularly crucial in languages with alphabetic writing systems, as learning to read requires the child to associate letters and orthographic combinations with the sounds of the language [20].

Share emphasizes that a phonological deficit should not be equated solely with weak phonological awareness. Phonological awareness—defined as the ability to identify and manipulate the smallest sound units of language—represents only one component of a broader array of phonological skills. The evidence he discusses also encompasses difficulties in naming, word retrieval, phonological short-term memory, non-word repetition, and speech perception and production, while highlighting the link between this domain and rapid automatized naming [20]. From Share's perspective, certain phonological weaknesses may exist prior to the onset of formal reading instruction; consequently, not all phonological deficits in children with DD can be attributed to unsuccessful reading experiences. However, acknowledging the role of these deficits does not mean disregarding other factors, as the phonological deficit theory does not claim to explain all individual differences in reading ability or every characteristic of DD [20].

The Double-Deficit Hypothesis

In addition to phonological deficits, the double-deficit hypothesis posits that deficits in Rapid Automatized Naming (RAN)—often referred to simply as RAN—are also a factor; it views these two as relatively distinct elements associated with reading difficulties. According to this hypothesis, an individual may experience impairment in one or both of these domains, and their co-occurrence may be linked to more extensive or severe reading difficulties, although this association has not been consistently confirmed across all studies [19].

Using functional magnetic resonance imaging (fMRI), Norton et al. demonstrated that phonological performance is associated with activity in parts of the left frontoparietal network—including the inferior frontal gyrus and the inferior parietal lobule—whereas rapid naming performance is linked to activity in the right cerebellar lobule VI [19]. These findings support the relative distinctness of the neural substrates underlying these two abilities; however, the observed link between performance and brain activity does not, in itself, establish a causal relationship between them.

In the same study, the group with the double deficit exhibited less activity in the frontoparietal network associated with phonological processing compared to the group with a phonological deficit alone; reduced activity associated with rapid naming was also observed in the right cerebellum. Functional connectivity analysis revealed that the networks associated with phonological awareness and rapid naming are somewhat distinct; specifically, left fronto-parietal connections were more strongly associated with phonological ability, whereas connections involving the right cerebellum and prefrontal regions were more closely linked to rapid naming. Additionally, bilateral prefrontal regions may play a role in coordinating these two systems [19].

Despite these neural differences, the study's behavioral findings did not fully support the hypothesis that the presence of dual deficits invariably leads to more severe reading difficulties; although the dual-deficit group exhibited the lowest performance across a battery of tests, the differences between this group and certain single-deficit groups were not statistically significant. Thus, this research lends greater support to the relative distinctness of the cognitive and neural processes underlying phonological awareness and rapid naming, rather than demonstrating a simple, definitive relationship between the number of deficits and the severity of DD [19].

The Role of Rapid Automatized Naming in Reading

Rapid Automatized Naming (RAN) refers to the ability to rapidly and sequentially name familiar stimuli—such as letters, numbers, colors, or objects—and has garnered attention in DD research due to its association with reading speed and fluency. Norton et al. link this ability to the automatization of processes that are also crucial for reading, as the rapid naming task requires stimulus identification, access to relevant information, and response generation within a coordinated sequence [19].

Carioti et al., in their review of existing evidence, have also emphasized the role of rapid naming in predicting reading fluency, noting that the strength of this association may vary depending on the characteristics of the language and writing system [17]. From this perspective, rapid naming may reflect the efficiency of the rapid, coordinated processes required for reading; however, it should not be equated with phonological processing, as evidence supports both an overlap and a relative distinction between these two abilities [19].

Deficits in Automatization and Procedural Learning

In their theoretical framework, Nicolson and Fawcett have examined the challenges associated with DD in the context of skill automatization, procedural learning, and neural network functioning; their earlier work proposed the automatization deficit, cerebellar deficit, and procedural learning deficit hypotheses. According to this view, part of an individual's difficulty may stem from the process by which a skill is performed increasingly faster and with less need for conscious attention through practice [18].

Based on the procedural learning framework, potential difficulties are not limited to reading but may also manifest in the learning or automatization of other skills reliant on this system. In this view, the cerebellum is a component of the networks associated with learning and the automatization of skills; however, an explanation of DD cannot be limited to cerebellar function alone, as the nature of its connectivity with other brain regions is also significant [18].

The Delayed Neural Commitment Framework

Nicolson and Fawcett proposed the Delayed Neural Commitment (DNC) framework to explain the developmental aspects of DD. They suggest that, in addition to acquiring skills more slowly, some children may require more time to form, reorganize, and consolidate the neural networks necessary for reading [18].

This framework seeks to examine the development of language and speech networks, executive functions, and reading acquisition in relation to one another, thereby explaining how variations in network organization processes can influence the speed of skill acquisition and automatization. Consequently, DD is viewed here as a difference in the developmental trajectory and coordination of neural networks—though this remains a theoretical framework requiring further direct evidence to substantiate its components [18].

The Role of Neural Noise in the Delayed Neural Commitment Framework

A concept introduced by Nicolson and Fawcett to expand their framework is "neural noise." In their proposed model, this refers to increased intrinsic variability in neural processing and a reduced signal-to-noise ratio. Based on this premise, if neural processing lacks stability, the learning and automatization of skills may become more difficult, requiring the individual to engage in more extensive experience and practice to achieve a comparable level of performance [18]. However, in this article, neural noise is proposed as a foundational hypothesis to explain potential differences and should not be regarded as a definitive mechanism for all individuals with DD. The authors themselves emphasize that a significant portion of the evidence supporting this framework is

indirect, and the proposed link between neural variability, learning, and reading requires further investigation in future studies [18].

Multilevel and Network Perspective

The Nicolson and Fawcett framework shifts the focus from the functioning of a single region to the interplay of neural networks, proposing that understanding developmental disorders requires examining behavioral, cognitive, cerebral, network, and genetic levels in relation to one another. From this perspective, observed reading difficulties may stem from processes originating at various levels, the effects of which manifest over the course of development and learning [18].

This view aligns with Share's emphasis on the limitations of single-factor explanations; acknowledging the importance of phonological processing does not negate the role of non-phonological factors, and this ability can be viewed as a key component within the constellation of processes involved in reading development [20]. Nevertheless, the compatibility of multiple theories does not imply their equal validation, and any proposed association must be evaluated based on its own specific evidence.

An Integrated Model of Developmental Dyslexia Theories

By synthesizing these perspectives, a multi-level framework can be proposed wherein neurodevelopmental differences are linked to the formation and efficiency of brain networks. These characteristics may manifest at the cognitive level as phonological difficulties, deficits in rapid naming, or slow skill automatization, thereby impacting decoding and reading fluency [18–20]. This framework represents a synthesis of the theories reviewed and should not be viewed as a proven causal chain.

In this model, phonological processing plays a crucial role in learning sound-print associations; rapid naming is linked to reading speed and efficiency as a relatively distinct ability; and theories regarding procedural learning and delayed neural commitment attempt to explain the developmental and network-related aspects of these differences. Findings by Norton et al. regarding distinct patterns of brain activity and connectivity associated with phonological awareness and rapid naming further support the necessity of considering multiple cognitive pathways.[19]

Theoretical Summary

The theories reviewed indicate that understanding DD requires attention to a range of cognitive and developmental processes. While the phonological deficit theory emphasizes the role of processing the sound structure of language—without being limited to phonological awareness—it does not account for all variations in reading performance; the double-deficit hypothesis, conversely, introduces rapid naming as a relatively distinct factor alongside it [19, 20]. Frameworks concerning procedural learning and delayed neural commitment also attempt to link difficulties in learning and skill automatization to the formation and coordination of neural networks, although some of the supporting evidence remains indirect [18]. The findings of Carioti et al. also highlight the importance of considering linguistic background; in children from minority language backgrounds, reading deficits and rapid naming deficits did not necessarily co-occur, and the rapid naming of shapes task (RAN-Shapes) offered potential value in supplementing the assessment of reading difficulties [17]. Therefore, the interpretation of a child's performance should take into account their linguistic experience and overall ability profile, rather than relying on a single indicator.

Overall, DD can be viewed as a heterogeneous phenomenon characterized by diverse patterns of linguistic, cognitive, and developmental difficulties—patterns that no single existing theory fully explains. The value of an integrated approach lies in its ability to acknowledge the critical role of phonological processing while also allowing for the examination of rapid naming, skill automatization, and neural network development, thereby placing individual differences at the heart of the interpretation [18–20].

Genetic Factors in Developmental Dyslexia

Evidence from behavioral genetics, genomic studies, and neuroscience indicates that DD arises from a combination of genetic, neurological, and environmental factors; its onset cannot be attributed to a single gene or a specific biological pathway [30]. Family and twin studies were among the first to demonstrate the role of heredity in this disorder, establishing that a portion of individual differences in reading ability—and the likelihood of developing persistent reading difficulties—is linked to genetic factors. Furthermore, some genetic factors influencing normal variation in reading skills overlap with those associated with the risk of DD [30].

From this perspective, reading ability can be viewed as a continuum, with DD situated at the lower end; factors influencing individual differences in reading skills may lead to persistent difficulties when combined with other risk factors [30].

From Family Linkage Studies to the Identification of Candidate Genes

In the early stages of research, family linkage studies helped identify genomic regions potentially associated with DD. A notable finding in this field was the identification of the DYX3 locus on chromosome 2 in a Norwegian family; this finding, alongside others, supported the existence of heterogeneous genetic bases for DD [27].

With the expansion of studies on candidate genes—genes previously hypothesized to be linked to the disorder—researchers focused on genes such as *KIAA0319*, *DCDC2*, and *DYX1C1*. Their potential roles in neuronal migration, cortical development, and the organization of neural networks offered promising avenues for investigating the biological basis of reading difficulties.[35]

Functional studies have shown that certain variants—or differing forms of genetic sequences—can influence *KIAA0319* expression levels; for instance, Dennis et al. reported that the rs9461045 variant is associated with reduced expression of this gene, likely by altering transcriptional regulation [26]. However, a variant's association with gene expression does not in itself determine whether its impact on the likelihood of DD is uniform across all populations.

In this context, a meta-analysis revealed that the association of specific *KIAA0319* variants (including rs4504469) with DD varies across populations; furthermore, an association between rs9461045 and reduced risk has been reported in some populations [32]. These variations underscore the importance of considering population genetic background, the characteristics of the study subjects, and the definition of DD used, indicating that findings regarding candidate genes must be interpreted within the specific context of the research itself. Regarding DCDC2, meta-analysis results have also shown that certain variants—particularly rs807701—may be associated with an increased risk of DD ; however, the magnitude of these associations is typically limited, and the role of this gene should be examined alongside other genetic and environmental factors [36].

Interaction of Genes and Neurodevelopmental Pathways

Recent research has sought not only to identify statistical associations between genes and DD but also to investigate the underlying biological processes; in this context, studying the interactions between the products of candidate genes has become significant. Studies on *DYX1C1* and *DCDC2* have shown that the proteins encoded by these genes can interact with one another, and findings from animal models suggest they may play a role in ciliary function, cellular organization, and neurodevelopment [23].

These findings suggest potential pathways linking genetic background to nervous system development; however, it remains unclear in what proportion of individuals with DD these pathways are involved and how they relate to variations in reading skills. Consequently, the use of animal models, cell cultures, and neural organoids—three-dimensional models of neural tissue—has gained attention, enabling a more detailed examination of how genetic variations affect neuronal differentiation, cell migration, and the formation of neural connections [23, 35].

Genome-Wide Studies and the Polygenic Nature of Developmental Dyslexia

Genome-wide association studies (GWAS) have expanded the scope of research beyond a few candidate genes by examining a vast number of variants across the genome. These studies provide further evidence that the genetic contribution to DD is distributed across numerous common variants, each with a small effect. Despite this progress, genomic findings do not yet fully account for the estimated heritability of DD, and a portion of its genetic basis remains unknown [28]. In a study involving individuals with DD and a control group, Gialluisi et al. estimated the heritability based on single-nucleotide polymorphisms (SNPs) to be approximately 20% to 25% and reported a genetic overlap between DD and certain cognitive traits and neurodevelopmental disorders—particularly attention-deficit/hyperactivity disorder (ADHD) [28]. This estimate pertains to the contribution of the examined genetic differences to the variation among individuals in the studied population and should not be interpreted as the percentage of DD that is genetic in a specific individual.

To gain a more precise understanding of this polygenic architecture, research requires larger samples, the simultaneous analysis of multiple traits, and the use of polygenic risk scores; these scores combine the estimated effects of a large number of variants into a single index, enabling the study of their cumulative contribution.[31]

Imaging Genetics and the Association Between Genes and Brain Networks

Imaging genetics is an approach that integrates genetic data with brain imaging to elucidate the relationship between genetic variations and the structural or functional characteristics of the brain. Studies utilizing UK Biobank data have demonstrated that genetic variants associated with language abilities and DD can correlate with differences in the functional connectivity of language networks, thereby providing a basis for investigating the link between genetics and brain organization [22].

Research in this field has reported an association between the polygenic risk score for DD and a reduction in the typical left-hemisphere functional asymmetry; while this finding aligns with the role of genetic factors in the organization of language networks, it does not, on its own, establish a causal pathway linking genes, brain characteristics, and reading difficulties [22].

Furthermore, the reported association of genes such as *EPHA3* and a rare variant in *NIBAN1* with the traits under study suggests that, alongside the cumulative effect of common variants, rare genetic changes may also contribute to the biological differences associated with DD. However, replicating these results in independent samples is essential to clarify the significance of these findings and their relationship to DD subtypes [22].

Genetic Overlap with Other Neurodevelopmental Disorders

In some individuals, DD co-occurs with other neurodevelopmental disorders—most notably attention-deficit/hyperactivity disorder (ADHD)—and genetic studies indicate that this comorbidity may stem, in part, from shared genetic factors and pathways [29]. Gene network analysis has identified a set of genes potentially implicated in both disorders; among these, *OPRM1*, *CHRNA4*, and *SNCA* have been proposed for further investigation regarding pathways linked to synaptic signaling, neurodevelopment, and brain network function. However, the prioritization of these genes in network analysis does not constitute proof of a causal role [29].

Analyses based on Genomic Structural Equation Modeling (Genomic SEM) have also demonstrated that, in terms of genetic association patterns, DD clusters together with ADHD and attention and learning difficulties [25]. The identification of 49 shared genetic loci between DD and ADHD further supports the joint study of these disorders, as such an approach can help elucidate both their shared factors and their distinct biological differences [25].

Summary

The body of evidence indicates that DD has a polygenic and heterogeneous basis, and the role of genetic factors must be considered in the context of neurodevelopment and environmental conditions. Family and twin studies have demonstrated the contribution of heritability, while large-scale genomic research, polygenic risk scores,

and network analyses suggest that a significant portion of this contribution stems from the cumulative effect of numerous variants with small individual effects [28, 30, 31].

Genes such as *KIAA0319*, *DCDC2*, and *DYX1C1* have highlighted biological pathways worthy of investigation; however, none of them serves as the sole cause of DD, and findings related to them must be interpreted with due regard for study limitations and population differences [23, 26, 32, 36]. Further research in this field relies on integrating population genetics studies with cellular and organoid models, gene network analysis, and brain imaging to clarify the links between genetic variations, neural network development, and actual differences in reading skills [22, 35].

Diagnosis and Assessment of Developmental Dyslexia

Diagnosing DD is a multidimensional process requiring an examination of an individual's reading skills, developmental and educational history, and cognitive and linguistic characteristics. In recent years, research has sought to gain a more precise understanding of reading difficulties by incorporating behavioral and neurophysiological data. Despite advances in understanding this disorder, there is still no complete consensus regarding the definition and application of certain diagnostic criteria or the selection of the most appropriate assessment method; these differing perspectives can influence how individuals are identified, which tools are selected, and how results are interpreted [12].

In a comprehensive assessment, a diagnosis should not rely solely on the outcome of a single test or indicator; rather, it is essential to examine developmental history, academic performance, linguistic skills, cognitive abilities, and the individual's response to instruction and intervention in conjunction with one another. Cognitive tests can help identify an individual's strengths and weaknesses and provide a better understanding of reading difficulties in relation to their other abilities; however, findings from these tests must be interpreted alongside clinical and educational information and are insufficient on their own to confirm or rule out a diagnosis.[15]

One complementary assessment method involves analyzing the types of reading errors made, as indicators such as speed and accuracy reveal the extent of an individual's reading difficulty, whereas error analysis can provide deeper insight into how text is processed. For instance, some studies have shown that children with DD make more "guess-based" errors compared to their peers, sometimes predicting a word based on partial visual information or its morphological structure; this pattern may be linked to difficulties with precise text processing, response control, and the coordination of visual and linguistic processes, although the type of error alone does not determine the underlying mechanism [13]. Alongside behavioral assessments, electroencephalography (EEG) has also garnered attention for studying brain activity associated with DD. In a systematic review, Cainelli et al. reported that children with DD exhibit differences in brain electrical activity compared to control groups—both at rest and during reading-related tasks—including alterations in theta and alpha frequency bands and variations in left temporoparietal regions [9]. However, differences in EEG recording protocols, data analysis methods, and study quality complicate the comparison of results; consequently, this method currently serves primarily as a research tool for investigating potential markers of DD rather than a standalone diagnostic test [9].

Advancements in computational methods have enabled the analysis of EEG data using machine learning algorithms, and some studies suggest that this approach can assist in identifying patterns associated with learning disorders. Nevertheless, existing findings—including studies linking EEG to neuroinflammation, require broader validation for diagnostic application, and results concerning learning disorders in general should not be extrapolated to a diagnosis of DD without specific evidence [14].

Eye-tracking is another behavioral method of interest in this field; by recording gaze location, fixation duration, and eye movements during reading, it allows for the examination of gaze patterns and certain aspects of visual attention. In a study involving children aged 7 to 13, Vajs et al. converted gaze coordinates into images analyzable by the VGG16 neural network and proposed a model with approximately 87% accuracy for classifying individuals with DD versus a comparison group; however, this accuracy level is specific to the conditions and data of that study and does not, on its own, validate the model's performance across other populations [16].

Similarly, in a systematic review, Coenen et al. identified eye-tracking as a promising method for developing objective, non-invasive assessment tools, yet they cited variations in research design and the lack of standardized data recording and analysis methods as significant barriers to its widespread application [11]. Thus, while eye-movement data can provide supplementary information regarding reading behavior, its diagnostic value must be evaluated alongside reading test results and other individual data.

Machine learning algorithms have also been employed for initial screening; in some studies, combining methods such as Random Forest with SMOTE—a technique used to balance sample sizes across groups—has yielded favorable predictive performance. Nevertheless, to determine the generalizability of such models, it is essential to assess their performance on larger samples and independent populations, as successful results within a specific study do not necessarily guarantee similar performance in real-world educational and clinical settings.[10]

Alongside machine learning models, expert systems have also been designed to assist in the early identification of DD symptoms; for instance, Ashidiqi et al. introduced a system based on the "Certainty Factor" approach, which analyzes symptom-related information to provide an initial assessment. While such systems may help organize information and identify cases requiring further assessment, their validity and utility must be examined in real-world settings, and their output should not serve as the sole basis for diagnosis [8]. Overall, the assessment of DD relies on integrating information regarding reading performance, developmental and educational history, linguistic skills, and cognitive characteristics; furthermore, analyzing reading errors can contribute to a more precise understanding of the individual's difficulties [12, 13, 15]. Technologies such as EEG, eye-tracking, and machine learning models offer the potential to expand the scope of this assessment, though their readiness for diagnostic application varies.

Figure 2. Brain networks implicated in developmental dyslexia.

Brain Networks in Developmental Dyslexia

Cognitive neuroscience findings indicate that DD cannot be explained by damage to or dysfunction of a single, specific brain region; rather, the disorder is associated with differences in the organization and connectivity of networks responsible for processing visual information, language, attention, and cognitive control [37]. Neuroimaging studies have also demonstrated these differences in gray matter structure, white matter pathways, and the coordination of brain region activity, supporting the view that understanding reading difficulties requires considering the functioning of various regions and their interconnections [38, 40, 42].

Reading Network Organization and Functional Changes

Skilled reading relies on the cooperation of multiple brain regions, primarily in the left hemisphere. Within the established reading network, the occipito-temporal, temporo-parietal, and inferior frontal gyrus regions contribute—respectively—to the rapid recognition of written word forms, the mapping of letters to sounds, and language processing; however, the activity of these regions is not limited to a single task, and reading emerges from their interaction [44].

Functional connectivity research has shown that brain differences in DD are not merely a matter of activity levels in a specific region; the coordination between components of the reading network is also crucial. Using functional magnetic resonance imaging (fMRI) during both resting-state and task-based conditions, Schurz et al. reported reduced functional connectivity between left posterior temporal regions—including the fusiform gyrus and the inferior, middle, and superior temporal gyri—and the left inferior frontal gyrus in children and adults with DD [41]. Observing this difference in both conditions suggests that the weaker connectivity between these regions may extend beyond the specific demands of a reading task, although this observation alone does not determine the underlying cause or the persistence of the pattern throughout development.

In an analysis of whole-brain functional connectivity, Finn et al. also observed differences extending beyond the classic reading network; these included alterations in visual pathways, changes in connectivity between visual regions and frontal areas associated with attention, reduced connectivity involving the visual word form area in the left fusiform gyrus, and increased connectivity in certain regions of the right hemisphere [38]. These findings

support the view that reading difficulties may partly stem from how visual and linguistic information is integrated, implying that examining a single region is insufficient to fully explain the phenomenon.

Visual, Attentional, and Cognitive Control Networks

Beyond language processing, reading requires the accurate identification of visual cues and the direction of attention to relevant parts of the text; consequently, the interplay between visual and attentional networks can influence the speed and accuracy of this process. In children with DD, Zhou et al. reported altered functional connectivity among the visual word form area, the left intraparietal sulcus, and the middle frontal gyrus—differences that may reflect variations in the coordination of visual word processing, spatial attention, and cognitive control [46].

Studies on cognitive control networks have further demonstrated that differences in the functioning of fronto-parietal and cingulo-opercular networks—which are involved in regulating and maintaining control over cognitive activities—can be associated with deficits in phonological awareness, decoding, and reading skills [39]. Thus, reading difficulties in some individuals may be accompanied by challenges in coordinating linguistic processes and attentional resources; however, the existence of this association alone does not determine whether network-level differences are the cause of the reading problem or if they emerged during the course of development and reading experience.

Structural White Matter Connectivity and Communication Pathways

Alongside functional differences, diffusion imaging studies—such as Diffusion Tensor Imaging (DTI)—have shown that DD can be associated with differences in white matter pathways; these pathways facilitate communication between various brain regions, and examining them aids in understanding the structural basis of reading networks [42].

Using connectometry—a method employed to analyze structural connectivity patterns—Sihvonen et al. reported associations between reading skills and phonological processing and pathways such as the corpus callosum, the forceps major and minor, thalamic tracts, and cerebellar pathways [42]. They also observed differences in dorsal and ventral reading-related pathways in individuals with DD—differences linked to poorer reading performance—demonstrating that examining structural connections can yield insights beyond those gained from studying cortical regions in isolation.

Tschentscher et al. also reported reduced structural connectivity between the left medial geniculate nucleus of the thalamus and the motion-sensitive region of the left planum temporale; this finding extends the scope of differences observed in DD to include pathways connecting the thalamus and the auditory cortex, indicating that the networks involved are not limited to established cortical reading areas [43].

Structural Brain Changes

Structural studies have shown that DD is associated with differences in the gray matter of certain language- and reading-related regions, although the location and extent of these differences vary across studies. In a meta-analysis based on voxel-based morphometry (VBM), Richlan et al. reported reduced gray matter volume in the right superior temporal gyrus and the left superior temporal sulcus, noting an overlap between certain structural differences and reduced functional activity [40].

Similarly, in a multilingual meta-analysis, Yan et al. demonstrated that the left superior temporal gyrus is a region exhibiting convergent structural and functional differences across various languages, whereas the pattern of differences in other regions—such as the fusiform gyrus and the inferior frontal gyrus—varies according to the language's writing system [4].

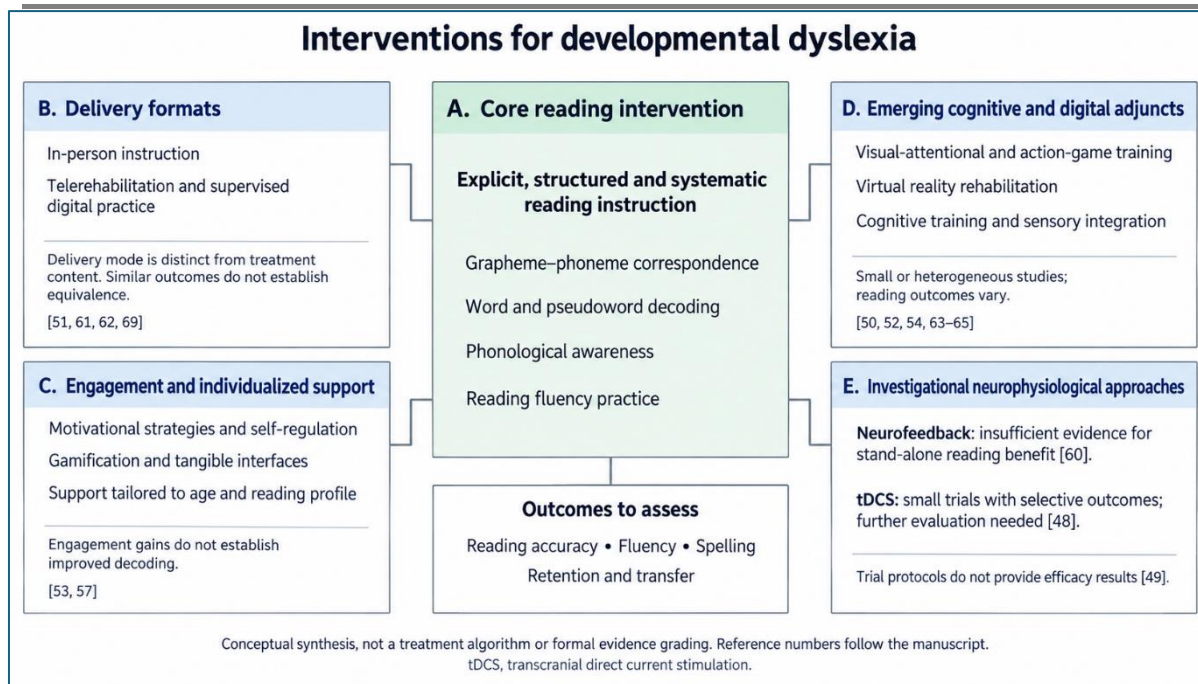


Figure 3. Intervention approaches for developmental dyslexia.

Intervention and Rehabilitation in Developmental Dyslexia

DD is characterized by persistent difficulties in learning and automating reading skills—specifically decoding accuracy and fluency—and may also be accompanied by spelling and reading comprehension issues. However, the nature and severity of these difficulties vary among individuals, necessitating the selection of interventions tailored to each person’s specific needs. Intervention methods range from direct reading instruction to cognitive, visual-attentional, and sensory exercises, as well as technology-based programs; yet, they differ in their objectives, outcome measures, and the strength of their scientific backing, meaning they cannot all be considered equally effective. Consequently, the child’s age, the severity of their difficulties, their cognitive profile, and their educational needs must be taken into account when selecting and designing an intervention program [51].

Educational Interventions and Direct Reading Instruction

Direct, structured, and systematic instruction in reading skills forms the core of interventions for DD. This typically encompasses explicit teaching of sound-letter correspondences, the enhancement of phonological awareness, decoding, the reading of words and non-words, and progressive fluency practice. The aim of such instruction is to enable the individual to convert written text into speech with greater accuracy and speed and, through sufficient practice, to gradually reduce the need for conscious effort in word recognition.

Alongside structured programs, some studies have investigated the use of simple instructional materials; for instance, Hasballah et al. examined the use of a basic reading instruction book with children who have DD and reported promising results. However, given the study design and sample limitations, these findings serve primarily as preliminary evidence regarding the potential of instructional materials tailored to a child’s needs [56]. Agustina et al. also examined the use of flashcards in a single-group study involving five children aged 8 to 11; they reported a statistically significant increase in mean scores from 10.4 in the pre-test to 20.8 in the post-test. However, the absence of a control group and the very small sample size preclude attributing this change to the intervention with certainty [47]. Thus, while educational books and flashcards can serve as simple, accessible tools for reading practice, determining their efficacy requires controlled studies with larger samples.

Multisensory and Sensory Integration Interventions

Some interventions target auditory and sensory processes associated with learning, aiming to create a more favorable foundation for learning by strengthening these abilities. However, assessing their impact on DD requires determining whether improvements in underlying skills actually translate into reading progress.

In a study involving 30 students with DD, Naghibosaddat, Hashemi Rezoni, and Salehian investigated the effects of sensory integration-based therapy on memory and auditory sensitivity. While they reported improvements in certain auditory components, the study's primary outcomes did not directly relate to reading performance [65]. Consequently, although these findings support the use of sensory integration to enhance specific learning-related processes, they are insufficient to establish it as a direct treatment for DD ; based on this study, its role is best viewed as a complementary intervention.

Cognitive Rehabilitation and Neurofeedback

Attention, working memory, and processing speed are among the abilities targeted in cognitive rehabilitation programs, as deficits in these areas can make learning and reading tasks more challenging for some children. However, improving these abilities does not necessarily translate to improved reading performance; thus, directly assessing reading metrics is essential to determine whether the intervention's effects transfer to reading skills.

In a quasi-experimental study featuring pre-test, post-test, follow-up, and control group assessments, Chegini et al. compared cognitive rehabilitation and neurofeedback in children aged 7 to 10. Each intervention group consisted of 15 children, and results indicated that the neurofeedback group demonstrated superior performance regarding certain cognitive indicators and anxiety levels [52]. Nevertheless, since the study's primary outcomes focused on attention, working memory, processing speed, and anxiety, the findings cannot be directly generalized to improvements in reading skills.

Similarly, in a systematic review of 12 studies, López-Zamora et al. concluded that current evidence is insufficient to confirm an independent effect of neurofeedback on improving reading in individuals with DD, noting that variations in methodologies and study designs complicate drawing definitive conclusions [60]. Consequently, neurofeedback is currently viewed primarily as a complementary method requiring further investigation, and the review's findings do not support its use as a standalone treatment for reading difficulties.

Video Games and Visual-Attentional Interventions

Video games have garnered attention in learning-related interventions due to their provision of repetitive practice, immediate feedback, and engaging activities; however, their therapeutic value must be evaluated based on changes in specific reading skills and the durability of those changes. In a study involving 79 preschool children at risk for DD and 41 children not at risk, Bertoni et al. investigated the effects of action video games by assigning the at-risk children to four groups: action games, non-action games, standard treatment, and a waiting list [50]. Among the outcomes examined, only phonological awareness showed greater improvement in the action game group compared to the comparison conditions—an effect that persisted at the six-month follow-up; however, since the participants had not yet entered formal reading instruction and did not have a definitive diagnosis of DD, the findings primarily highlight the method's potential for early support rather than confirming its efficacy in treating diagnosed DD.

Similarly, in a longitudinal experimental study, Tammasse et al. evaluated the Kinect-based LexiPal program and reported improvements in reading performance, although the study's design and limitations preclude concluding that the program is superior to standard instruction and treatment [67]. These studies indicate that visual-motor activities can be considered when designing supplementary exercises; however, comparing them against established interventions is essential to determine their actual contribution to reading progress.

Virtual Reality and Reading Rehabilitation

Virtual reality enables the delivery of exercises within an interactive environment, and some research has sought to examine its impact on the reading, writing, and cognitive performance of children with DD. In a study involving 28 children, Maresca et al. compared Virtual Reality Rehabilitation System (VRRS)-based rehabilitation with standard neuropsychological treatment, utilizing the Wechsler Intelligence Scale for Children (WISC-IV) and Italian reading and spelling tests for assessment [63]. The results of this study revealed significant differences in word reading, the spelling of homophones, and certain cognitive indicators; while the

study was notable for directly measuring reading and writing outcomes, the small sample size limits broad conclusions regarding the method's effectiveness [63]. In another study involving 24 children, Maresca et al. tracked intervention outcomes for up to a year and reported improvements in the virtual reality group compared to the control group—particularly in pseudoword reading and reading speed—some of which persisted a year later even without continued intervention [64].

These findings position virtual reality as a promising option to complement rehabilitation programs; however, the limited number of studies and small sample sizes mean that, in terms of scientific evidence, it cannot yet be considered on par with direct, structured reading instruction [63, 64].

Design of Virtual Reality Environments and Serious Games

A portion of virtual reality research focuses on identifying user needs and designing appropriate activities; when interpreting such studies, a distinction must be made between the introduction of a tool and the demonstration of its therapeutic efficacy. In the FORDYSVAR project, Rodríguez-Cano et al. conducted interviews with specialists, families, and children with DD to propose seven developmental domains for the design of virtual reality activities; consequently, the value of this qualitative research lies primarily in defining intervention goals and content, rather than providing direct evidence of improvements in reading [66].

Similarly, in a 2022 study, Guillen-Sanz et al. introduced “DixGame,” a virtual reality serious game for children aged 8 to 12 with DD; the game features activities targeting attention, visual agility, reading, and memory, while allowing for the gradual adjustment of exercise difficulty [55]. However, as the study focuses primarily on tool design, further intervention-based research is required to evaluate its impact on reading skills.

Digital Interventions, Gamification, and Multisensory Interfaces

Kariyawasam et al. introduced a mobile system designed for the screening and intervention of DD, dysgraphia, and dyscalculia, utilizing machine learning algorithms and neural networks for the screening component [58]. Although performance metrics regarding the system's classification capabilities were reported, these results must be distinguished from the efficacy of its educational activities; the ability to identify or classify a disorder does not, in itself, demonstrate that using the system leads to improved learning skills. In the realm of tangible user interfaces—which enable interaction with an application through physical objects—Jamali et al. conducted an experimental study involving 30 children with DD, comparing the DB3dT application with its non-tangible counterpart [57]. The usability score was 79.5% for the DB3dT application and 51% for the comparison version; children in the intervention group demonstrated greater engagement and learning performance, as well as longer interaction times and a stronger desire to repeat the activity.

These findings suggest that tangible, multisensory interfaces may help make exercises more engaging and boost child participation; however, since the study's primary outcomes focused on usability, engagement, and learning performance, specific assessments are required to draw conclusions regarding direct improvements in decoding and other reading skills [57].

Telerehabilitation

Telerehabilitation is a method of delivering specialized exercises and support that can facilitate access to services, though its outcomes depend on program content, exercise consistency, and the quality of supervision. In a critical review, Casalini and Pecini reported that, in some studies, the outcomes of remote interventions were comparable to those of in-person therapy, although questions remain regarding optimal exercise intensity and frequency, the role of the child's cognitive characteristics, and differences between online programs [51].

Lorusso et al. conducted a study involving 91 children with DD and/or spelling disorders to evaluate a four-week treatment program using the Tachidino application, which combined visual-attentional exercises with word and text decoding and encoding activities [61]. Children who initially presented with more severe difficulties showed greater progress across certain indicators, and the outcomes of the intervention were also assessed at a six-month follow-up.

In another study, Lorusso, Borasio, and Molteni compared the results of 38 children receiving in-person, multi-component therapy with 91 children receiving the remote “Tachidino” treatment; both programs lasted four weeks, and both groups showed improvements in reading speed and accuracy as well as writing accuracy, with analyses revealing no significant difference between the two methods [62]. In the Tachidino group, 80 children participated in the six-month follow-up, and the improvements were maintained; however, the absence of a significant difference between the groups is not, in itself, sufficient to prove the complete equivalence of the two methods.

Similarly, Verwimp et al. in the Netherlands compared 254 children receiving in-person therapy with 162 children receiving online therapy; they demonstrated that, despite the online group having fewer sessions, the rate of progress in reading and spelling was similar across both groups once the number of sessions was controlled for [69]. Overall, these findings support the feasibility of effectively delivering reading programs online; however, the choice of this method should be based on the child’s needs, the severity of the difficulty, the feasibility of regular practice, and the level of therapist supervision [51, 61, 62, 69].

Prism Adaptation and Cognitive Training

In a randomized trial, Conte et al. investigated the combination of prism adaptation (shifting the visual field to the right) and cognitive training in adolescents with DD, assigning 35 adolescents to the intervention group and 35 to the waitlist group [54]. After 10 weeks, the intervention group showed greater improvements in working memory, processing speed, and text reading speed; however, the difference between groups regarding word and non-word reading accuracy was not significant.

This pattern of results suggests that the impact of an intervention may manifest in reading speed and efficiency without necessarily altering all aspects of decoding to the same extent. Furthermore, since prism adaptation was administered alongside cognitive training, the independent contribution of each component cannot be determined from this study. Consequently, this approach is best considered a supplement to basic reading skills training [54].

Transcranial Direct Current Stimulation

Transcranial direct current stimulation (tDCS) is a method currently being investigated for modulating neural activity and has been employed in some studies on DD. In a crossover study involving 24 children and adolescents with DD, Battisti et al. examined the effects of five daily sessions of stimulation targeting the parieto-occipital regions; they reported that under active stimulation conditions, only pseudoword reading speed showed significant improvement relative to baseline, and this change persisted for up to one month [48].

However, improvement relative to baseline should not be interpreted as definitive proof of the stimulation’s specific effect without comparing it to control conditions; the researchers themselves noted limitations regarding sample size, inconsistent findings across studies, and a lack of data on medium- and long-term outcomes [48]. Another study by Battisti et al. outlines the protocol for a randomized, double-blind, sham-controlled trial designed to compare tDCS with high-frequency transcranial random noise stimulation (hf-tRNS); as this is a protocol report, it does not provide evidence regarding the results or efficacy of these methods [49].

Thus, while transcranial electrical brain stimulation remains a promising research-based approach, current evidence is insufficient to establish it as a primary treatment for DD [48, 49].

Motivational Interventions

A child’s level of engagement and motivation can influence the consistency of practice and the utilization of learning opportunities; consequently, some programs incorporate strategies for goal setting, self-regulation, and fostering interest in the activity alongside reading instruction. In a review and meta-analysis of reading interventions for children ranging from kindergarten to fifth grade, Cho et al. examined the role of motivational components; they demonstrated that interventions incorporating these elements—particularly the direct instruction of motivational strategies—yielded greater effects on certain reading outcomes [53]. While these findings support the inclusion of motivational factors in instructional design, caution is warranted regarding their

specific generalization to DD; motivational strategies should be implemented alongside systematic reading skills instruction.

Distinction Between Developmental Dyslexia and Acquired Reading Disorder

When reviewing rehabilitation studies, it is essential to distinguish between DD and acquired reading disorder; in the acquired form, reading difficulties arise following brain injury and may involve different underlying mechanisms and therapeutic requirements.

In a study involving 27 patients with reading disorders linked to hemifield visual deficits resulting from brain injury, Kerkhoff and Kraft reported improvements in reading and certain activities of daily living [59]. Although significant for post-injury rehabilitation, these results do not provide direct evidence regarding the treatment of DD.

Reading and Writing Interventions for Adults

DD-related difficulties may persist into adulthood, affecting education, professional activities, and the performance of daily tasks; consequently, the need for educational support does not cease upon the completion of schooling.

In a systematic review, Vender, Melloni, and Delfitto examined eight studies on reading interventions for adults with DD; the results indicated that instruction could lead to improvements in certain skills, including reading comprehension, spelling, and phonological abilities [68]. However, the limited number of studies highlights the need for further research to determine the most effective program, the required amount of practice, and the durability of the outcomes.

Summary

Based on the reviewed evidence, direct, structured, and systematic instruction in reading skills should constitute the core of any intervention program for DD; exercises targeting phonological awareness, sound-letter correspondence, decoding, and reading fluency should be tailored to the individual's skill level and needs. Alongside this instruction, cognitive rehabilitation, visual-attentional exercises, sensory activities, and motivational strategies may help improve associated abilities or boost engagement; however, evaluating their success must also involve directly assessing changes in reading performance.

Technologies such as video games, tangible interfaces, and virtual reality have opened up new possibilities for exercise design. Studies on virtual reality have reported promising results regarding certain reading and writing skills, although the limited number of studies and small sample sizes currently preclude definitive conclusions [50, 57, 63, 64]. In contrast, research on telerehabilitation has provided more substantial evidence regarding the feasibility of delivering reading programs outside of in-person clinical settings, demonstrating that—under appropriate conditions—children's progress in online instruction can be comparable to that achieved through in-person training [51, 61, 62, 69].

Neurofeedback and electrical brain stimulation also require further investigation; existing evidence is insufficient to confirm the independent efficacy of neurofeedback on reading, and positive findings from some tDCS studies have been constrained by limited sample sizes and methodological variations [48, 60]. Consequently, an individualized framework could be adopted wherein direct reading instruction forms the foundation of the program, and complementary methods are selected based on the individual's cognitive and educational needs, while the delivery mode—in-person or online—is determined separately. Within this framework, the choice of intervention should be based on the nature of the problem, age, severity of the disorder, expected outcome, and the quality of scientific evidence; furthermore, the individual's progress should be assessed over time so that the program can be modified based on their response to the training.

Applications of Artificial Intelligence in Developmental Dyslexia

Artificial intelligence, including machine learning and deep learning methods, has increasingly been used in DD research because these approaches can examine large amounts of information from different sources at the same time and may therefore help researchers and specialists identify patterns that are difficult to recognize through conventional assessment alone. In studies related to DD, artificial intelligence has been applied to reading performance, cognitive and linguistic assessments, handwriting, eye-movement patterns, and neurophysiological signals, while some studies have also explored its use for personalized educational support and progress monitoring. Although these developments are promising, the current evidence suggests that artificial intelligence should mainly be considered as a complementary tool that may support assessment and education, rather than as an independent method that can replace established diagnostic procedures or evidence-based reading interventions.

Validated and Emerging Capabilities

One of the most common uses of artificial intelligence in DD research is screening and classification, where machine-learning models are trained to identify patterns associated with reading difficulties by analyzing cognitive and linguistic measures, handwriting images, eye-tracking data, EEG signals, or combinations of several types of information. Some studies have reported high levels of classification performance within their own datasets; for example, Kurniawan and Tiaharyadini reported accuracies of approximately 93% and 94% for Random Forest and nearest-neighbor models, while Aldehim et al. reported an accuracy of 96.4% together with a high F1-score in a handwriting-based deep-learning model [70, 75]. These findings show that artificial intelligence can successfully identify statistical differences between groups under controlled research conditions, but they do not mean that such systems are already reliable enough to diagnose DD independently in everyday educational or clinical settings.

This distinction is important because the data used by artificial intelligence are often influenced by many factors other than DD itself; for example, handwriting can be affected by motor development and writing experience, eye movements can change according to task difficulty and reading level, and brain signals can vary depending on age, attention, recording conditions, and many other individual characteristics. For this reason, these measures are more useful when they are considered as additional sources of information rather than as specific markers of DD. Multimodal approaches, in which behavioral, linguistic, handwriting, eye-tracking, or neurophysiological data are combined, may provide a more complete picture of the learner's profile, but they also require larger datasets, more complex analyses, and more careful standardization across studies [77, 80].

Artificial intelligence has also been used to move beyond the simple question of whether DD is present or absent and instead to explore the type of educational support that may be more suitable for a particular learner. Benedetti et al., for example, identified different student profiles according to support needs, while Zingoni et al. used supervised machine learning to predict the selection of educational tools and strategies in a large group of students [71, 81]. These studies are useful because they suggest that artificial intelligence may eventually help support individualized education, although the ability to predict a suitable strategy should not be considered equal to evidence that the strategy itself improves reading performance.

Methodological Limitations and Generalizability

Despite the promising results reported in many studies, the current literature also contains important methodological limitations that make it difficult to determine how well these systems would perform outside the original research setting, because many studies have been based on relatively small samples, imbalanced groups, single datasets, or highly specific populations, while issues such as overfitting, variation in preprocessing methods, feature selection, and data-splitting procedures may also influence the reported results [77, 80]. In addition, model performance can vary according to the language being studied, the age of participants, the type of reading or writing task, and the characteristics of the educational system, which means that a model that performs well in one sample may not necessarily show the same level of accuracy in another population.

For this reason, overall accuracy should not be used as the only measure of model quality, because a high percentage of correct classifications can sometimes hide important weaknesses in identifying specific groups. Measures such as sensitivity, positive predictive value, F1-score, and area under the curve should therefore be considered together with the study design, sample characteristics, and validation procedures, especially when the intended use of the model involves educational or clinical decisions. The same caution is necessary when artificial intelligence is applied to EEG or neuroimaging data, since these methods can identify complex group-level patterns but may not yet provide information that is specific enough or stable enough to support individual diagnosis, particularly when findings from broader neurological research are transferred to DD without direct validation [73, 80].

Another important concern is that some studies may report strong performance because the model has been tested on data that are too similar to the data used during training, and in such cases the reported accuracy may reflect the structure of the dataset more than the true ability of the model to work in new populations. Therefore, the practical value of an artificial-intelligence system depends not only on how well it performs within one study, but also on whether it can maintain similar performance when applied to new participants, new schools, new languages, and different educational or clinical settings.

External Validation and Clinical or Educational Readiness

External validation is one of the most important requirements for deciding whether an artificial-intelligence system is ready for wider use, because performance obtained in the original research sample cannot automatically be expected to remain stable when the same model is applied to children with different linguistic, cultural, educational, or developmental backgrounds. For this reason, models intended for DD screening or support should be tested in independent samples that were not involved in model development and, whenever possible, in larger and multicenter datasets that include participants from different populations [70, 77, 80].

This issue is especially important for models based on handwriting, eye movements, EEG, or other indirect measures, because these signals can change according to the task, equipment, language, and characteristics of the participants. Therefore, high classification accuracy in a single dataset should mainly be interpreted as evidence that the method is technically promising, rather than as proof that it is ready for routine diagnostic use. Explainability methods such as Grad-CAM, SHAP, and LIME may help specialists understand which features contributed to a model's decision, and this can make model outputs easier to examine, but explainability does not replace external validation and does not prove that the feature highlighted by the model is a specific or causal marker of DD [70].

At the present stage, artificial-intelligence outputs should therefore be interpreted together with direct measures of reading performance, developmental and educational history, linguistic and cognitive assessment, and the judgment of trained specialists, because DD is a heterogeneous condition that cannot be fully described by a single numerical prediction. Human oversight remains essential, particularly when model outputs may influence decisions about diagnosis, educational placement, or intervention, and artificial intelligence should be used to support professional decision-making rather than to replace it.

Educational Utility and Human-Centered Support

The educational value of artificial intelligence may be broader than its role in screening, because adaptive systems can monitor a learner's responses over time, adjust the level of difficulty, provide immediate feedback, recommend learning materials, and help teachers or specialists follow progress more closely. Reviews of AI-assisted approaches have described the use of text-to-speech tools, speech-recognition systems, educational chatbots, adaptive learning environments, and personalized feedback, all of which may help make learning activities more accessible and responsive to individual needs [72].

However, it is important to distinguish technical prediction from real educational benefit, because a model that can accurately classify a student or recommend a learning strategy does not necessarily lead to improvement in reading accuracy, fluency, spelling, comprehension, or academic independence. For this reason, studies of AI-supported education should evaluate whether the use of these systems produces meaningful and sustained

changes in reading outcomes and whether these changes are greater than, or add value to, established educational approaches. Ochoa and Barrera, for example, reported improvements in selected educational outcomes, motivation, and self-efficacy after a 12-week AI-supported program, but the study included only 60 students from three schools and involved learners with different types of learning disorders, which limits the extent to which the findings can be generalized specifically to DD [76].

Similarly, systems that combine screening with gamified or adaptive learning activities may provide a useful framework for linking assessment and practice, but the presence of artificial intelligence within a program should not itself be considered evidence of intervention effectiveness. The real value of these systems depends on whether they improve learning in a measurable and lasting way, whether they are practical for teachers and families to use, and whether they can be adapted to the learner without creating excessive dependence on automated recommendations.

Overall, the evidence reviewed suggests that the most realistic role of artificial intelligence in DD at the present time is to complement established assessment and educational practice by helping organize complex information, support early screening, identify individual patterns, monitor progress, and assist in selecting or adapting educational tools, while its wider use will require stronger external validation, clearer reporting of methods, direct evidence of educational benefit, attention to privacy and fairness, and continued collaboration between artificial-intelligence systems and teachers, psychologists, speech and language specialists, families, and other professionals.

Table 2. Evidence Matrix of the 56 Publications Included in the Narrative Review

Developmental dyslexia (DD): cognitive/neural mechanisms, diagnosis, intervention, and artificial intelligence

Interpretation note. “Evidence Level” is a narrative confidence classification based on study design, the manuscript’s overall risk-of-bias appraisal, sample adequacy, population relevance, directness of the measured outcome, consistency of findings, and external validation where relevant; it is not a formal GRADE rating. “NR” indicates information not reported or not extracted in the supplied source table. Theoretical/review publications shown in the matrix are part of the 56-study primary synthesis but are distinguished from primary empirical studies; supplementary background references outside the 56-study synthesis are not included in this matrix.

No.	Study	Domain	Evidence Role	Design	Population	N	Primary Outcome / Measure	Principal Finding	Overall RoB	Evidence Level
1	Tammasso, 2022 The Effectiveness of Using Kinect-Based DD Therapy in Improving Reading Ability in Dyslexic Children: A Linguistic Study	Intervention / Rehabilitation	Primary empirical evidence	Longitudinal experimental / quantitative study	Children with DD ; treatment and control groups. The exact number in each group was not reported consistently in the extracted sections.	NR	Reading ability assessment and pre/post intervention comparison; language/reading-related tests associated with LexiPal	The LexiPal group showed better reading performance after the intervention; a treatment-versus-control difference was reported as evidence of effectiveness.	High	Promising complementary intervention evidence, but high RoB limits confidence.
2	Rodríguez-Cano, 2022 Development areas for intervention in DD :	Intervention / Rehabilitation	Primary empirical evidence	Qualitative descriptive / intervention-design study	Semi-structured interviews with DD specialists, families,	Variable	Semi-structured interviews ; qualitative /thematic	Seven intervention domains were identified for VR: phonological awareness, working memory,	Some concerns	Supportive evidence with some methodological concerns;

	A virtual reality proposal				and children; the exact total sample was not clearly reported in the extracted sections; expert review was also conducted.		content analysis	attention, visual-perceptual processing, auditory-perceptual processing, semantic/syntactic /lexical development, and motor development.		not definitive on its own.
3	Faudzi, 2022 Knowledge of DD among Teacher Trainees in Malaysia	Education / Implementation	Primary empirical evidence	Descriptive quantitative study	99 trainee teachers; 82 females and 17 males; no intervention/control groups.	99	36-item questionnaire covering general knowledge, symptoms /diagnosis, and treatment of DD	34% showed insufficient general knowledge, 23% insufficient knowledge of symptoms/diagnosis, and 32% insufficient knowledge of treatment; treatment knowledge also showed gaps.	Some concerns	Supportive evidence with some methodological concerns; not definitive on its own.
4	D'Mello, 2018 Cognitive Neuroscience of DD	Neural / Neuroimaging	Theory/Review	Review tutorial article	No independent participant s; literature review.	N/A	Review of behavioral and neuroimaging studies; no new experimental testing	DD is associated with differences in the structure and function of several neural circuits involved in reading; neuroimaging evidence supports early identification and potentially individualized intervention.	N/A	Contextual/theoretical evidence; conventional study-level RoB is not applicable .
5	Margulies, 2025 Policy Approaches to Improving Coverage of DD Screening, Testing and Treatment	Education / Implementation	Policy / implementation context	Policy report / white paper	No participant s; policy report.	N/A	No experimental tests; analysis of policies, laws, access pathways, and service coverage	Access to screening and treatment is insufficient and fragmented; the report emphasizes early identification, insurance coverage, and integration of services into healthcare systems.	N/A	Contextual policy evidence; informs access and implementation, not diagnostic or treatment efficacy.
6	Lorusso, 2024 Remote treatment	Intervention /	Primary empirical evidence	Retrospective comparative /	136 children aged 7–14 years; 82	136	Text, word, and pseudoword reading	Tachidino improved reading speed/accuracy and spelling	High	Supportive feasibility/effectiveness

	of DD: how ADHD comorbidity, clinical history and treatment repetition may affect its efficacy	Rehabilitation		intervention study with an untreated control condition	DD without ADHD and previous treatment, 30 from this group receiving two Tachidino cycles, 17 with ADHD, 22 with previous speech-language therapy;		speed/accuracy; dictated-word spelling accuracy; additional phonological-awareness analyses	accuracy; effects exceeded the untreated control; overall efficacy was not substantially reduced by ADHD or previous speech-language therapy; a second cycle also improved reading.		ess signal, but high RoB in a retrospective design limits causal inference.
7	Battisti, 2022 Effects of a short and intensive transcranial direct current stimulation treatment in children and adolescents with DD: A crossover clinical trial	Intervention / Rehabilitation	Primary empirical evidence	Randomized crossover clinical trial with sham stimulation	24 children/adolescents with DD; participants received active tDCS and sham conditions in counterbalanced periods.	24	Text, high-frequency/low-frequency word and pseudoword reading; visual-spatial and verbal n-back working memory; phoneme blending	Effects of tDCS were observed for selected reading-speed outcomes, particularly pseudoword reading; improvement was related to baseline verbal working memory and phoneme blending; responses were heterogeneous.	Some concerns	Supportive but not definitive evidence; some RoB concerns and replication/durability remain relevant.
8	Chegin, 2022 Comparison of the impact of cognitive rehabilitation and neurofeedback on attention, working memory, processing speed, and anxiety in DD	Intervention / Rehabilitation	Primary empirical evidence	Quasi-experimental study with pretest, posttest, and follow-up	30 children aged 7–10 years; neurofeedback and cognitive-rehabilitation intervention groups, with a control group according to the reported design.	30	Attention, working-memory, processing-speed, and anxiety measures	Both interventions affected cognitive variables; neurofeedback showed stronger results for attention, memory, processing speed, and anxiety reduction.	High	Preliminary adjunctive evidence; high RoB and outcomes are mainly cognitive rather than direct reading outcomes.
9	López-Zamora, 2025 Efficacy of neurofeedback in the treatment of DD : a	Intervention / Rehabilitation	Evidence synthesis	Systematic review	12 research articles included; the total pooled participant number was not reported in the	12	Extraction and comparison of neurofeedback-study outcomes; reading and	Neurofeedback alone did not provide sufficient evidence for improving reading; study designs and	Some concerns	Synthesis-level evidence indicates insufficient support for neurofeedback as a stand-

	systematic review				extracted abstract.		writing outcomes reported in primary studies	protocols were heterogeneous.		alone reading treatment.
10	Bertoni, 2024 Action video games normalise the phonemic awareness in pre-readers at risk for DD	Intervention / Rehabilitation	Primary empirical evidence	Randomized preventive intervention with active and passive controls	120 pre-readers; 79 at risk for DD: AVG=43, SNAVG=11, SPEECH=11, WAIT=14; 41 without risk for the initial comparison.	120	Phonemic Discrimination (PD), Pseudo-word Repetition (PWR), Rapid Automatized Naming of colours (RAN), Block Design	AVG specifically improved phonemic awareness; more than 80% of AVG children improved above the combined-control mean; the phonemic-awareness effect persisted to 6 months; no significant effects were found for PWR or RAN.	Some concerns	Supportive but not definitive evidence; some RoB concerns and replication/durability remain relevant.
11	Conte, 2024 Prismatic adaptation coupled with cognitive training as novel treatment for DD: a randomized controlled trial	Intervention / Rehabilitation	Primary empirical evidence	Randomized controlled trial	70 adolescents aged 13–17 years with DD; treatment=35, waitlist control=35.	70	WISC-IV; MT-Avanzate-3; DDE-2 or MT 16–19	Combined rightward rPA and cognitive training increased WMI, PSI, and text-reading speed; between-group differences in word and pseudoword reading accuracy were not significant.	Some concerns	Supportive but not definitive evidence; some RoB concerns and replication/durability remain relevant.
12	Agustina, 2023 The Effects of Using Flashcard Learning Media to Improve Reading Comprehension in Children with DD	Intervention / Rehabilitation	Primary empirical evidence	Single-group pretest–posttest experimental study	5 children with DD ; one group, no control.	5	Pretest and posttest reading/comprehension assessment; t-test comparison	Mean score increased from 10.4 at pretest to 20.8 at posttest; a significant difference was reported; reading and comprehension improved.	High	Preliminary evidence; small/non-randomized designs and high RoB limit causal confidence.
13	Hasballah, 2023 Effectiveness of Using Early Reading Book to Improve Emergent Literature for	Intervention / Rehabilitation	Primary empirical evidence	Single-group pretest–posttest experimental study	10 children with moderate DD characteristics; one group.	10	Pre/post early-literacy/reading assessment; paired-samples t-test	30 sessions over about 1.5 months; mean score increased from 5.10 to 12.60; $p<0.001$; letter recognition and simple-word reading improved.	High	Preliminary evidence; small/non-randomized designs and high RoB limit causal confidence.

	Children with DD									
14	Jamali, 2023 Learning Engagement of Children with DD Through Tangible User Interface: An Experiment	Intervention / Rehabilitation	Primary empirical evidence	Quasi-experimental / User-Centered Design study	30 children with DD ; control=15 using non-tangible DisleksiaB elajar, treatment=15 using tangible DB3dT.	30	On-task time; performance checklist; user-experience assessment	DB3dT produced longer engagement; SUS usability was 79.5% versus 51%; performance/engagement scores were also higher in the treatment group; tangible elements increased activity appeal.	High	Preliminary evidence; small/non-randomized designs and high RoB limit causal confidence.
15	Naghibosadati, 2021 The effectiveness of sensory integration-based therapy on auditory memory and auditory sensitivity of students with DD	Intervention / Rehabilitation	Primary empirical evidence	Quasi-experimental study with pretest, posttest, and follow-up	30 students with DD ; experimental and control groups according to the study design; the exact group sizes were not explicitly available in the extracted material.	30	Auditory-memory and auditory-sensitivity tests	After eight 90-minute sessions, auditory memory and auditory sensitivity improved; effects were maintained at one-month follow-up.	High	Preliminary evidence; small/non-randomized designs and high RoB limit causal confidence.
16	Vouglanis, 2024 The use of ICT in the education of students with alexia/acquired DD	Digital / Educational Technology	Theory/Review	Review / descriptive article	No participants; review/discussion of ICT use in education and rehabilitation of acquired alexia/ DD .	N/A	No experimental tests; review of technologies and educational/rehabilitation applications	ICT can facilitate access, personalization, feedback, and interaction; its use in acquired reading disorders should be matched to individual needs.	N/A	Indirect for DD because the source concerns acquired reading disorders.
17	Kerkhoff, 2024 The Effects of a Novel Treatment for Hemianopic DD on Reading, Symptom Load, and Return to Work	Intervention / Rehabilitation	Primary empirical evidence	Intervention study with multiple-baseline design in chronic patients	27 patients with hemianopic DD ; no independent control group; patients experienced untreated baseline and treatment periods.	27	Reading battery at four time points; functional everyday-reading tasks; eye-movement assessment	Significant and sustained improvement in reading measures was reported; effects generalized to everyday reading; symptom load decreased; approximately 63% returned to work.	High	Indirect for DD because the source concerns acquired reading disorders.

18	Al Dahhan, 2020 Understanding the biological basis of DD at a neural systems level	Neural / Neuroimaging	Primary empirical evidence	Experimental neuroimaging study	34 adults; controls=18, DD=16.	34	Letter/object naming-speed tasks with visual and phonological similarity manipulations; reading/decoding and phonological-awareness measures	The DD group showed poorer naming speed, longer fixations, and more regressions; greater and more bilateral activation of the reading network and involvement of the amygdala and hippocampus were observed.	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
19	Cho, 2023 Motivational practices in reading interventions for students with or at risk for DD	Intervention / Rehabilitation	Evidence synthesis	Literature review and meta-analysis	53 studies across 51 articles; 70 treatment conditions; 186 effect sizes. This is not an independent human sample.	53	Extraction of reading/spelling/comprehension outcomes; calculation of Hedges' g and moderator analyses	Fewer than half of the 70 treatment conditions reported motivational strategies; motivational strategies showed descriptively larger effects; after controlling for variables, strategy type was not significant in many analyses.	Some concerns	Synthesis-level evidence; conclusions should reflect heterogeneity and the appraisal concerns of the included literature.
20	Carioti (2022) Rapid Automatized Naming as a Universal Marker of DD in Italian Monolingual and Minority-Language Children	Cognitive / Theoretical	Primary empirical evidence	Original Research; cross-sectional group-comparison study	Total N=127 primary-school students (Grades 3–5): mGR = 64; mPR = 20; MLC = 43. Grade-specific: Grade 3: mGR 17, mPR 8, MLC 21; Grade 4: mGR 24, mPR 7, MLC 10; Grade 5: mGR 23, mPR 5, MLC 12.	127	Single-word reading; pseudoword reading; text reading	mPR performed significantly worse than mGR and MLC across reading measures. MLC had lower reading accuracy than mGR in several measures, but did not differ from mGR on RAN-Shapes. All three RAN matrices correlated with reading measures, with stronger associations for reading fluency (rho approximately .47–.61). All three matrices significantly predicted m...	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
21	Norton (2014) Functional Neuroanatomy	Cognitive /	Primary empirical evidence	Original empirical research; cross-	Total N=90 right-handed, native	90	RAN-RAS Letters and	The phonological gradient followed Control > PHONOdef >	Some concerns	Supportive associative/mechanistic

	mical Evidence for the Double-Deficit Hypothesis of DD	Theoret ical		sectional fMRI neuroimagin g study	English-speaking children, age 8.2–12.6 years: Control = 39; RANdef = 10; PHONode f = 27; DOUBLED ef = 14.		Numbers; CTOPP Elision and Blending Words; Word Identificat ion	DOUBLEdef in left inferior frontal and inferior parietal regions. The RAN gradient followed Control > RANdef > DOUBLEdef, including right cerebellar lobule VI. The DOUBLEdef group showed the greatest abnormalities in functional connectivity. RAN-deficit children could show relatively preserved untine...		stic evidence; some RoB concerns and design limits prevent causal interpretat ion.
2 2	Nicolson (2019) Developme nt of DD : The Delayed Neural Commitme nt Framework	Cogniti ve / Theoret ical	Theory/r eview	Hypothesis and Theory paper; theoretical framework with synthesis/re-presentation of three earlier empirical studies	No single new participant sample for the 2019 paper. It represents three earlier studies.	N/A	Across the re-presented studies: IQ and literacy testing; phonologi cal discrimina tion/segm entation; nonsense-word repetition	The re-presented evidence indicates slower skill acquisition in DD , slower attainment of asymptotic performance, poorer speed/accuracy, and difficulties in changing previously automatized mappings. The authors integrate earlier automatization-deficit, cerebellar-deficit, and procedural-learning accounts into the Delayed Neural Commitment framework.	N/A	Contextua l/theoretic al evidence; conventio nal study-level RoB is not applicable .
2 3	Share (2021) Common Misconcept ions about the Phonologic al Deficit Theory of DD	Cogniti ve / Theoret ical	Theory/r eview	Review / Discussion Paper; theoretical and literature-based analysis	Not applicable: no new participant sample or primary experiment al cohort. The paper is a discussion/ review of the phonologic al deficit	N/A	No new experimen tal tests. The paper reviews evidence concernin g phonemic awareness , pseudoword reading/na ming,	The paper argues that the phonological deficit hypothesis is not equivalent to phonemic awareness alone. It emphasizes broader spoken-language phonological weaknesses that can precede literacy, and distinguishes	N/A	Contextua l/theoretic al evidence; conventio nal study-level RoB is not applicable .

					hypothesis and its empirical literature.		phonological recoding, spoken-language phonology, phonological memory, spee...	reading itself from proximal reading subskills such as phonological recoding and phonemic awareness.		
24	Emily S. Finn — 2014 Disruption of Functional Networks in DD : A Whole-Brain, Data-Driven Analysis of Connectivity	Neural / Neuroimaging	Primary empirical evidence	Comparative experimental fMRI study; whole-brain data-driven functional connectivity analysis	Young readers: 75 (32 dyslexic, 43 nonimpaired). Older readers: 104 (40 dyslexic, 64 nonimpaired).	75	Reading classification using GORT-IV, TOWRE and Woodcock-Johnson; in-scanner word/non word rhyming task; edge-wise t tests and Network-Based Statistic.	NR	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
25	Aleksi J. Sihvonen — 2021 Structural White Matter Connectometry of Reading and DD	Neural / Neuroimaging	Primary empirical evidence	Cross-sectional observational study; diffusion MRI, connectometry and differential tractography	44 Finnish-speaking adults: 23 dyslexic and 21 typically reading controls.	44	Word, pseudoword and text reading; Pig Latin; non-word span	NR	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
26	T. L. Richards — 2015 Contrasting Brain Patterns of Writing-Related DTI Parameters, fMRI Connectivity, and DTI-fMRI Connectivity Correlation	Neural / Neuroimaging	Primary empirical evidence	Comparative multi-group experimental study; DTI and fMRI	40 children in grades 4–9: 9 controls, 14 dysgraphia, 17 DD.	40	DASH Copy Sentence Best and Fast Writing; WIAT-3 Spelling Dictated Words; TOC Sight Spelling	NR	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.

	s in Children With and Without Dysgraphia or DD									
27	Tzipi Horowitz-Kraus — 2018 Decreased Functional Connectivity in the Fronto-Parietal Network in Children With Mood Disorders Compared to Children With DD During Rest: An fMRI Study	Neural / Neuroimaging	Primary empirical evidence	Four-group comparative study; resting-state fMRI	57 total: 14 mood disorders, 11 behavioral disorders, 15 DD, 17 healthy controls.	57	CTOPP Elision for phonological awareness; WJ-III Letter-Word Identification and Word Attack for reading/decoding; four-group ANOVA	NR	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
28	K. E. Waldie — 2017 Reading Network in DD: Similar, Yet Different	Neural / Neuroimaging	Primary empirical evidence	Comparative experimental study; fMRI and Partial Least Squares (PLS)	Final sample: 47 (11 DD, 11 dyscalculia, 13 comorbid DD +dyscalculia, 12 controls). For analysis, DD +comorbid formed Reading Difficulty (24), while dyscalculia +controls formed Normal Reading (23).	47	Rhyming and line-judgment tasks; Woodcock-Johnson Word ID and Word Attack; CTOPP Phonemic Reversal	NR	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
29	N. Tschentscher — 2019 Reduced Structural Connectivity Between Left Auditory Thalamus	Neural / Neuroimaging	Primary empirical evidence	Comparative observational study; DTI-based probabilistic tractography	24 male adults: 12 DD and 12 neurotypical controls.	24	Raven matrices; spelling; reading speed	NR	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits

	and the Motion-Sensitive Planum Temporale in DD									prevent causal interpretation.
30	Matthias Schurz — 2015 Resting-State and Task-Based Functional Brain Connectivity in DD	Neural / Neuroimaging	Primary empirical evidence	Comparative experimental study; resting-state and task-based fMRI	29 German-speaking adolescents /young adults: 15 dyslexic and 14 nonimpaired readers; resting-state data were unavailable for 3 controls.	29	Sentence reading-speed test; word and nonword reading; object RAN	NR	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
31	Véronique Quaglino — 2008 Differences in Effective Connectivity Between Dyslexic Children and Normal Readers During a Pseudoword Reading Task: An fMRI Study	Neural / Neuroimaging	Primary empirical evidence	Comparative experimental study; fMRI and Structural Equation Modeling for effective connectivity	18 French-speaking children: 6 dyslexic, 6 chronological-age-matched controls, 6 reading-level-matched controls.	18	Alouette reading test; Raven PM47 for nonverbal intelligence; reading and dictation/phonological assessments	NR	High	Exploratory associative evidence; high RoB limits confidence.
32	Wei Zhou — 2015 Altered Connectivity of the Dorsal and Ventral Visual Regions in Dyslexic Children: A Resting-State fMRI Study	Neural / Neuroimaging	Primary empirical evidence	Comparative experimental study; resting-state fMRI and seed-based functional connectivity	47 children: 21 dyslexic and 26 age-matched controls; mean age approximately 12 years in both groups.	47	Reading fluency; lexical decision; Rapid Automated Naming	NR	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
33	Xi Yu — 2022 Patterns of Neural Functional Connectivity in Infants	Neural / Neuroimaging	Primary empirical evidence	Observational cohort study; resting-state fMRI in infants with multivariate pattern/class	98 infants aged 4–13 months: 35 with familial history of DD and 63 without	98	Mullen Scales of Early Learning; home language/literacy environment	NR	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns

	at Familial Risk of DD			ification analysis	familial history.		nt and socioeconomic questionnaires; seed-based FC			and design limits prevent causal interpretation.
34	Hensler, 2010 Behavioral Genetic Approach to the Study of DD	Genetic / Molecular	Primary empirical evidence	Behavioral genetics; twin study with DeFries–Fulker extremes analysis	1,024 first-grade twins: 382 MZ and 642 DZ students (512 twin pairs). DD subgroup: 159/1,024 (72 MZ, 87 DZ), defined as ≤15th percentile on SAT-10 Reading.	1	Stanford Achievement Test–10 Reading; MZ/DZ intraclass correlations; probandwise concordance	Reading heritability = 0.53; shared environment = 0.25; non-shared environment = 0.21. DD probandwise concordance = 0.58 MZ vs 0.32 DZ. Group heritability for DD = 0.59.	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
35	Fagerheim, 1999 A new gene (DYX3) for DD is located on chromosome 2	Genetic / Molecular	Primary empirical evidence	Familial linkage analysis / genome-wide linkage study	One large Norwegian multigenerational family with 80 members; genome-wide linkage search initiated in 36 family members. DD was modeled under three diagnostic models.	80	Genome-wide linkage analysis; three diagnostic models; non-parametric multipoint linkage analysis	A DD -linked region was identified at chromosome 2p15–p16. Maximum LOD scores were 3.54, 2.92 and 4.32 across diagnostic models; the most likely interval was 4 cM between D2S2352 and D2S1337.	Some concerns	Supportive evidence with some methodological concerns; not definitive on its own.
36	Shao, 2016 Opposite Associations between Individual KIAA0319 Polymorphisms and DD Risk across Populations: A Stratified Meta-Analysis by the Study Population	Genetic / Molecular	Evidence synthesis	Stratified genetic meta-analysis	Seven case-control studies: 2,711 cases and 2,991 controls; five TDT studies involving 943 families; 10 reports ultimately eligible after overlap/ex	2711+	Case-control association analysis; transmission disequilibrium testing (TDT); meta-analysis	No overall significant association for the six markers. rs4504469 showed opposite effects across populations; rs9461045 was protective in the Asian subgroup. Significant between-study heterogeneity was observed for several markers.	Some concerns	Synthesis-level evidence; conclusions should reflect heterogeneity and the appraisal concerns of the included literature.

					clusion handling.					
3 7	Zhong, 2013 Meta-analysis of the Association Between DCDC2 Polymorphisms and Risk of DD	Genetic / Molecular	Evidence synthesis	Genetic meta-analysis	Four case-control studies: 941 cases and 1,183 controls; five TDT studies: 1,119 families. Included studies covered British, German, American, Canadian and UK samples.	941 +	Case-control association analysis; transmission disequilibrium testing (TDT); fixed/random-effects meta-analysis	rs807701 C allele was associated with increased DD risk overall (OR = 1.13, P = .016). rs793862 was significant in TDT studies but not case-control studies. Sensitivity analyses indicated instability for some pooled estimates.	Some concerns	Synthesis-level evidence; conclusions should reflect heterogeneity and the appraisal concerns of the included literature.
3 8	Bieder, 2023 Genetic and protein interaction studies between the ciliary DD candidate genes DYX1C1 and DCDC2	Genetic / Molecular	Primary mechanistic / exploratory evidence	Molecular/cellular functional study with zebrafish and brain-organoid models	No human participant cohort. Experimental models included cultured human/cellular systems, brain organoids and zebrafish genetic models.	N/A	Protein-protein interaction assays; genetic interaction experiments; transcriptional-regulation assays	DYX1C1 and DCDC2 physically interacted and also interacted with CPAP/CENPJ. Combined genetic disruption in zebrafish exacerbated ciliary phenotypes, and reciprocal transcriptional effects were observed.	Some concerns	Mechanistic/exploratory evidence; relevance to human DD requires independent biological or clinical validation.
3 9	Zaki, 2024 Genetic Modifications of DD and Its Representation Using In Vivo, In Vitro Model	Genetic / Molecular	Theory/review	Narrative review of genetic, in vivo and in vitro models	Not applicable; literature-based review rather than a single participant cohort.	N/A	Literature synthesis of genetic association, animal-model, cellular and organoid studies	Reviews candidate genes including DYX1C1, ROBO1, DCDC2 and KIAA0319 and their reported roles in neuronal migration, axon guidance, cilia and neurodevelopment. Highlights limitations of animal models and the potential of organoids.	N/A	Contextual/theoretical evidence; conventional study-level RoB is not applicable.
4 0	Gialluisi, 2021 Genome-wide association study reveals new insights into the	Genetic / Molecular	Primary empirical evidence	Case-control genome-wide association study (GWAS) and genetic-correlation/polygenic-	After QC: 2,274 DD cases and 6,272 controls from nine European-ancestry population	2	Single-variant, gene-level and pathway-level GWAS; fixed-effects	SNP-based heritability was estimated at 20–25%. Gene-level signals implicated LOC388780 and VEPH1. DD risk was associated with PGSs for	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design

	heritability and genetic correlates of DD			score analysis	s/six languages. Dataset totals: AGS 1,454 (1,047:407), Finland 324 (161:163), France 163 (106:57), Hungary 241 (90:151), Netherlands 284 (136:148), ENall1 3,313 (554:2,759), ENall2 2,767 (180:2,587).		meta-analysis; SNP-based heritability	ADHD, bipolar disorder, schizophrenia, cross-disorder susceptibility, education, intelligence and transverse temporal-gyrus cortical thickness.		limits prevent causal interpretation.
41	Amelink, 2024 Imaging genetics of language network functional connectivity reveals links with language-related abilities, DD and handedness	Genetic / Molecular	Primary empirical evidence	Imaging-genetics study using resting-state fMRI, multivariate GWAS and exome-wide analysis	29,681 UK Biobank participants with resting-state imaging data; no DD case-control subgroup was the primary sampling frame.	29	Resting-state functional-connectivity analysis; multivariate GWAS; exome-wide association analysis	Identified 14 common-variant genomic loci for language-network connectivity and seven additional genes suggested by rare protein-altering variants. Genetic predispositions to lower language ability, DD and left-handedness were associated with reduced leftward connectivity asymmetry.	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
42	He, 2023 Associative gene networks reveal novel candidates important for ADHD and DD comorbidity	Genetic / Molecular	Primary mechanistic / exploratory evidence	Bioinformatic associative gene-network and gene-prioritization study	No direct participant cohort. Network resources contained 599 ADHD genes/proteins and 167 DD genes/proteins; combined ANDSystem/GeneCards analysis yielded 213	N/A	Gene-network reconstruction; GeneCards relevance ranking; Endeavour and ToppGene prioritization	The ADHD network contained 599 genes/proteins and the DD network 167. OPRM1, CHRNA4 and SNCA received the highest predicted priority for comorbidity; DRD2, CNTNAP2 and GRIN2B were also prominent.	Some concerns	Mechanistic/exploratory evidence; relevance to human DD requires independent biological or clinical validation.

					genes/proteins.					
43	Ciulkinyte, 2025 Genetic neurodevelopmental clustering and DD	Genetic / Molecular	Primary empirical evidence	Genomic Structural Equation Modeling (GenomicSEM) using GWAS summary statistics	GWAS summary statistics for 10 psychiatric /neurodevelopmental traits; combined source datasets represented 453,408 cases and 2,374,026 controls, restricted to European ancestry.	453,408 +	Linkage disequilibrium score regression ; exploratory factor analysis; confirmatory GenomicSEM	A five-factor genomic model best captured the genetic structure. DD and ADHD loaded on an attention-and-learning factor. Forty-nine shared loci mapping to 174 genes were implicated, including 40 loci and 121 genes not previously identified in the individual-trait GWAS.	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
44	Schumacher, 2007 Genetics of DD : The evolving landscape	Genetic / Molecular	Theory/review	Narrative review of behavioral, linkage and molecular genetics	Not applicable; review of familial, twin, linkage and candidate-gene studies.	N/A	Literature synthesis rather than a new participant test battery	Reviews substantial familial aggregation and heritability, with inherited contributions estimated broadly at 40–80%. Discusses candidate loci/genes including DYX1C1, DCDC2, KIAA0319, ROBO1 and DYX3.	N/A	Contextual/theoretical evidence; conventional study-level RoB is not applicable.
45	Yang, 2024 DD genes are selectively targeted by diverse environmental pollutants	Genetic / Molecular	Primary mechanistic / exploratory evidence	Systematic in silico bioinformatics/network analysis	No human or animal participant cohort. Analysis used 131 publicly reported DD susceptibility genes and 95 environmental compounds.	131	Gene–chemical overlap analysis; observed/expected enrichment; hypergeometric probability testing	Chemical targets per DD -risk gene set ranged from 1 to 109. Thirty-five chemicals showed significant enrichment, with observed/expected ratios from 1.147 for atrazine to 66.901 for dibenzo(a,h)pyrene.	Some concerns	Mechanistic/exploratory evidence; relevance to human DD requires independent biological or clinical validation.
46	Perugini, 2024 DD Polygenic Scores	Genetic / Molecular	Primary mechanistic / exploratory	Population-based twin/sibling molecular-	Australian Brisbane Adolescent Twin Study	1542	Reading/speaking assessment; diverse cognitive	Poor reading most strongly with verbal measures (R^2 up to 6.2%).	Some concerns	Supportive associative/mechanistic

	Show Heightened Prediction of Verbal Working Memory and Arithmetic		ry evidence	genetic study	population sample of MZ twins, DZ twins and non-twin siblings of European ancestry; 734–1,542 participants depending on phenotype, from an initial pool of 1,648 subjects/608 families.		tests; polygenic-score association analyses	DD explained the phenotypic covariance with most working-memory measures and was most predictive of arithmetic performance ($R^2 \approx 2.9\%$).	PGS	evidence; some RoB concerns and design limits prevent causal interpretation.
47	Wang, 2022 A predictive model for Chinese children with DD—Based on a genetic algorithm optimized back-propagation neural network	AI / Diagnostic Prediction	Primary empirical evidence	Predictive modeling / artificial-intelligence classification study	399 Chinese children in grades 3–6, aged 7–13 years: 187 with DD and 212 typically developing controls. Training set = 280 (70%); testing set = 119 (30%).	399	Reading accuracy; phonological awareness; pseudocharacter accuracy	GA-optimized BPNN achieved approximately 94% overall prediction accuracy. Reading accuracy was the strongest predictor, followed by phonological awareness, pseudocharacter accuracy, morphological awareness, reading fluency, rapid digit naming and noncharacter reaction time.	High	Promising internal predictive performance, but high RoB and no external validation limit clinical readiness.
48	Rinne, 2024 DD susceptibility genes DNAAF4, DCDC2, and NRSN1 are associated with brain function in fluently reading adolescents and young adults	Genetic / Molecular	Primary empirical evidence	Preregistered imaging-genetics study	267 Finnish-speaking, fluent-reading adolescents/young adults (124 females) aged 13–25 for fMRI/sMRI. Genetic data were available for 186;	178	Sentence-processing fMRI task; resting/seed-based functional-connectivity analyses; genotype–brain activity association models	Variation in DD-susceptibility genes was associated with activity and/or connectivity in language-related brain regions including MTG, IFG and IPS, despite the participants being fluent readers without learning disabilities.	Some concerns	Supportive associative/mechanistic evidence; some RoB concerns and design limits prevent causal interpretation.
49	Dennis, 2009 A Common Variant Associated	Genetic / Molecular	Primary mechanistic / exploratory	Genetic association plus molecular	Human association sample: 264 unrelated	Variable	Quantitative-trait SNP association; linkage-	Three upstream SNPs were associated with reading-related traits. The	Some concerns	Supportive associative/mechanistic

	with DD Reduces Expression of the KIAA0319 Gene		ry evidence	functional study	UK nuclear families; initial association sample = 89 families;		disequilibrium/haplotype analysis; genomic sequencing	rs9461045 risk allele reduced KIAA0319 reporter expression and created a likely OCT-1 binding site; OCT-1 knockdown restored expression toward the non-risk haplotype.		evidence; some RoB concerns and design limits prevent causal interpretation.
50	Chapman, 2025 Targeted analysis of DD - associated regions on chromosomes 6, 12 and 15 in large multigenerational cohorts	Genetic / Molecular	Primary empirical evidence	Targeted sequencing and quantitative-trait association study	Three family cohorts. UW: 2,079 individuals /284 families (1,347 with quality DNA;	816	Targeted capture/multiplexed next-generation sequencing; common-variant association tests; rare-variant aggregate tests	No large-effect pathogenic coding variants were confirmed. Associations were observed for CYP19A1, a KIAA0319–DCDC2 haplotype and rare GRIN2B exonic variants; DNAAF4 showed no significant association.	Some concerns	Supportive evidence with some methodological concerns; not definitive on its own.
51	Kershner, 2016 Network dynamics in DD : Review and implications for remediation	Neural / Neuroimaging	Evidence synthesis / theoretical context	Narrative neurobiological review and theoretical synthesis	No new participant cohort; synthesis of neurobiological and DD literature.	N/A	Network-level evidence concerning phonological processing, frontostriatal-parietal cognitive-control systems, posterior corpus callosum, left arcuate fasciculus, and implications for remediation.	The review proposes an Interactive Specialization account in which DD reflects atypical coordination of distributed neural networks, especially cognitive-control circuitry, the posterior corpus callosum, and the left arcuate fasciculus, and argues that remediation should consider interactions among these systems.	N/A	Contextual/theoretical evidence supporting a distributed-network account of DD ; useful for conceptual synthesis but does not provide direct evidence of intervention efficacy.
52	Kujala et al., 2021 Voxel and surface based whole brain analysis shows	Neural / Neuroimaging	Primary empirical evidence	Cross-sectional case-control structural MRI study using voxel- and surface-based	Finnish-speaking adults: 23 with DD and 22 typical readers; groups	45	Whole-brain gray-matter volume and cortical-thickness	Adults with DD showed reduced gray-matter volume and cortical thickness in the left insula and reduced gray-matter volume in	Some concerns	Supportive cross-sectional neuroanatomical evidence, strengthened by

	reading skill associated grey matter abnormalities in DD			morphometry	were balanced on age, education, sex, and total brain volume.		measures, with reading, phonological-processing, working-memory, and IQ assessments.	the left superior temporal gyrus and several subcortical/medial temporal regions; greater volume/thickness in significant regions was associated with better reading and phonological performance.		converging VBM/SBM analyses and covariate control, but limited by the modest sample and inability to establish developmental direction or causality.
53	McGrath & Stoodley, 2019 Are there shared neural correlates between DD and ADHD? A meta-analysis of voxel-based morphometry studies	Neural / Neuroimaging	Evidence synthesis	Systematic voxel-based morphometry meta-analysis using activation likelihood estimation (ALE)	DD meta-analysis: 15 studies (417 cases, 416 controls). ADHD meta-analysis: 22 studies (898 cases, 763 controls).	DD : 833 ; AD HD : 1,661	Gray-matter differences in DD and ADHD and statistical conjunction of ALE maps to test shared neuroanatomical correlates.	The overall pattern indicated largely distinct gray-matter correlates for DD and ADHD; a shared right-caudate region appeared only under the more lenient statistical threshold, suggesting that neural overlap is limited and requires independent replication.	Some concerns	Synthesis-level evidence supporting mostly distinct structural correlates; the right-caudate overlap should be treated as tentative because it depended on a more lenient threshold and because imaging-study heterogeneity remains relevant.
54	Morken et al., 2017 Reading in DD across literacy development: A longitudinal study of effective connectivity	Neural / Neuroimaging	Primary empirical evidence	Longitudinal fMRI study with Dynamic Causal Modelling across pre-literacy, emergent-literacy, and literacy stages	Children followed at ages 6, 8, and 12 years. Analyzed samples varied by wave: age 6, 6 DD /12 typical; age 8, 10 DD /20 typical; age	18 at age 6; 30 at age 8; 27 at age 12	Effective connectivity among five reading-network regions (IFG, precentral gyrus, STG, IPL, occipito-temporal cortex), alongside longitudinal	Group differences were concentrated in connections involving the inferior frontal gyrus and occipito-temporal cortex. The DD group showed marked connectivity changes from ages 6 to 8 followed by convergence toward the typical pattern by age 12,	High	Important longitudinal mechanistic evidence for delayed reading-network development, but confidence is limited by small age-

					12, 10 DD /17 typical.		al literacy performan ce.	although literacy differences remained and increased.		specific samples, changing participant compositi on across waves, attrition, and model-stability concerns.
5 5	Richlan, 2020 The functional neuroanatomy of DD across languages and writing systems	Neural / Neuroimaging	Evidence synthesis / contextual review	Mini review / narrative cross-linguistic neuroimaging synthesis	No new participant cohort; review of functional and structural neuroimaging evidence across alphabetic, syllabic, and logographic writing systems.	N/A	Cross-linguistic patterns of functional underactivation/over activation and structural abnormalities in core reading-network regions.	The review concludes that dyslexic underactivation in core left-hemisphere reading regions, particularly occipito-temporal, temporo-parietal, and inferior-frontal areas, is broadly similar across languages, while orthography- and writing-system-specific variations are also present.	N/A	Useful contextual synthesis for identifying language-general and language-specific neuroimaging patterns; because it is a narrative mini-review rather than a formal meta-analysis, it should not be treated as quantitative evidence of effect size or diagnostic accuracy.
5 6	Yan et al., 2021 Convergent and divergent brain structural and functional abnormalities associated with DD	Neural / Neuroimaging	Evidence synthesis	Multimodal coordinate-based meta-analysis of structural and functional neuroimaging studies across writing systems	110 papers contributing 119 experiments; 92 functional experiments and 27 structural experiments across alphabetic and morpho-syllabic languages. Functional analyses included	119 experiments; functional analysis N=2,728	Voxel-wise meta-analysis of brain activation and gray-matter volume, cross-language comparisons, multimodal conjunction analyses, and jack-knife	Convergent structural and functional abnormalities were identified in the left superior temporal gyrus across languages. Additional differences on writing system, including stronger left inferior-frontal abnormalities in morpho-syllabic languages and greater left	Some concerns	Broad synthesis-level neuroimaging evidence with cross-linguistic and sensitivity analyses; findings support both shared and writing-system-specific

					2,728 participants (1,358 DD; 1,370 controls).		sensitivity testing.	middle-temporal/fusiform functional reductions in alphabetic languages.		neural patterns, but interpretation should account for study heterogeneity and coordinate-based meta-analytic assumptions.
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Abbreviations: AI, artificial intelligence; DD, developmental dyslexia; EEG, electroencephalography; fMRI, functional magnetic resonance imaging; NR, not reported/not extracted; RoB, risk of bias.

Table 3. Risk-of-Bias Assessment for the 56 Publications Included in the Narrative Review

No.	Author & Year	Article Title	Study Design	Appraisal Framework	D1 Selection / Randomization	D2 Confounding / Deviations	D3 Missing Data	D4 Outcome / Exposure Measurement	D5 Selective Reporting / Analysis	Overall RoB	Main Rationale
1	Tammasse, 2022	The Effectiveness of Using Kinect-Based DD Therapy in Improving Reading Ability in Dyslexic Children: A Linguistic Study	Longitudinal experimental / quantitative	ROBINS-I (adapted)	Some concerns	High	Some concerns	Low	Some concerns	High	Allocation/randomization and exact group sizes were not clearly reported in the review table; non-randomized intervention effects may be confounded.
2	Rodríguez-Cano, 2022	Development areas for intervention in DD : A virtual reality proposal	Qualitative descriptive / intervention-design	JB1 Qualitative (adapted)	Some concerns	N/A	Some concerns	Low	Some concerns	Some concerns	Qualitative design is appropriate for development needs, but sample size/selection details were not clearly reported in the review table.
3	Faudzi, 2022	Knowledge of DD among Teacher Trainees in Malaysia	Descriptive quantitative / cross-sectional	JB1 Analytical Cross-Sectional	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Single trainee-teacher sample may limit representativeness; confounding and recruitment details are not available in the review table.
4	D'Mello, 2018	Cognitive Neuroscience of DD	Review / tutorial article	SANRA / narrative-review appraisal	N/A	N/A	N/A	N/A	N/A	N/A	Narrative/tutorial source; a conventional study-level RoB judgment is not directly applicable.
5	Marгуlie, s,	Policy Approaches to Improving Coverage of DD Screening,	Policy report / white paper	Policy-document critical appraisal	N/A	N/A	N/A	N/A	N/A	N/A	Policy/white-paper source; not an empirical study and not suitable for conventional study-level RoB grading.

	20 25	Testing and Treatment									
6	Loruso, 2024	Remote treatment of DD: how ADHD comorbidity, clinical history and treatment repetition may affect its efficacy	Retrospective comparative intervention	ROBINS-I	High	High	Some concerns	Low	Some concerns	High	Retrospective non-randomized comparisons, overlapping subgroups, and baseline clinical differences create substantial confounding/selection concerns.
7	Battisti, 2022	Effects of a short and intensive transcranial direct current stimulation treatment in children and adolescents with DD: A crossover clinical trial	Randomized crossover clinical trial with sham	RoB 2 (crossover-adapted)	Some concerns	Low	Some concerns	Low	Some concerns	Some concerns	Randomized, sham-controlled crossover design is a strength, but small sample size and incomplete reporting of all RoB domains in the review table prevent a low-risk judgment.
8	Chengini, 2022	Comparison of the impact of cognitive rehabilitation and neurofeedback on attention, working memory, processing speed, and anxiety in DD	Quasi-experimental pretest-posttest-follow-up	ROBINS-I	High	High	Some concerns	Low	Some concerns	High	Non-random assignment and small groups create substantial confounding and selection concerns.
9	López-Zamora, 2025	Efficacy of neurofeedback in the treatment of DD : a systematic review	Systematic review	ROBIS	Some concerns	N/A	Some concerns	Low	Some concerns	Some concerns	The review table does not report the full search, duplicate assessment, or study-level quality appraisal; included studies were heterogeneous.
10	Bertoni, 2024	Action video games normalise the phonemic awareness in pre-readers at risk for DD	Randomized preventive intervention	RoB 2	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Randomized controlled design is strong, but unequal/small intervention subgroups and limited reporting of allocation/blinding in the review table warrant caution.
11	Conte, 2024	Prismatic adaptation coupled with cognitive training as novel treatment for DD: a randomized controlled trial	Randomized controlled trial	RoB 2	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	RCT design and balanced groups reduce bias, but wait-list control and unreported blinding/allocation details in the review table preclude a low-risk rating.
12	Agustina, 2023	The Effects of Using Flashcard Learning Media to Improve Reading Comprehension in Children with DD	Single-group pretest-posttest	ROBINS-I (single-group adapted)	High	High	Some concerns	Low	Some concerns	High	Very small sample (n=5), no control group, and pretest-posttest design make regression to the mean, maturation, and expectancy effects difficult to exclude.

13	Hasbullah, 2023	Effectiveness of Using Early Reading Book to Improve Emergent Literature for Children with DD	Single-group pretest-posttest	ROBINS-I (single-group adapted)	High	High	Some concerns	Low	Some concerns	High	Small sample (n=10) and no control group make causal attribution highly uncertain.
14	Jamali, 2023	Learning Engagement of Children with DD Through Tangible User Interface: An Experiment	Quasi-experimental / user-centered design	ROBINS-I	High	High	Some concerns	Some concerns	Some concerns	High	Small non-randomized groups and outcomes emphasizing usability/engagement introduce confounding and measurement expectancy concerns.
15	Naghibosadat, 2021	The effectiveness of sensory integration-based therapy on auditory memory and auditory sensitivity of students with DD	Quasi-experimental pretest-posttest-follow-up	ROBINS-I	High	High	Some concerns	Low	Some concerns	High	Small quasi-experimental sample, unclear exact group sizes, and non-random allocation increase selection/confounding risk.
16	Vuglanis, 2024	The use of ICT in the education of students with alexia/acquired DD	Review / descriptive article	SANRA / narrative-review appraisal	N/A	N/A	N/A	N/A	N/A	N/A	Narrative/descriptive review; conventional study-level RoB is not directly applicable.
17	Kerkhoff, 2024	The Effects of a Novel Treatment for Hemianopic DD on Reading, Symptom Load, and Return to Work	Multiple-baseline intervention without independent control	ROBINS-I / single-case-series adapted	High	High	Some concerns	Low	Some concerns	High	No independent control group; time, spontaneous adaptation, repeated testing, and other co-interventions cannot be fully separated from treatment effects.
18	AlDahhan, 2020	Understanding the biological basis of DD at a neural systems level	Comparative experimental neuroimaging	JB1 Case-Control / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Small case-control neuroimaging sample may be vulnerable to selection, multiple-comparison, and residual-confounding bias.
19	Cho, 2023	Motivational practices in reading interventions for students with or at risk for DD	Literature review and meta-analysis	ROBIS	Some concerns	N/A	Some concerns	Low	Some concerns	Some concerns	Large evidence synthesis, but the review table does not provide enough information to verify search completeness, study-quality appraisal, or publication-bias handling.
20	Carrion, 2022	Rapid Automatized Naming as a Universal Marker of DD in Italian Monolingual and Minority-Language Children	Cross-sectional group-comparison	JB1 Analytical Cross-Sectional	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Cross-sectional design limits causal interpretation; language background and group differences may introduce residual confounding.

21	No rto n, 20 14	Functional Neuroanatomical Evidence for the Double-Deficit Hypothesis of DD	Cross- sectional fMRI neuroimaging	JBICase-Control / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Cross-sectional subgrouping and relatively small deficit subgroups may increase selection/precision concerns despite a well-defined comparison design.
22	Ni col son, 20 19	Development of DD : The Delayed Neural Commitment Framework	Hypothesis and theory paper	Theoretical-paper appraisal	N/A	N/A	N/A	N/A	N/A	N/A	Theory paper re- synthesizing earlier studies; conventional study- level RoB is not applicable.
23	Sh are , 20 21	Common Misconceptions about the Phonological Deficit Theory of DD	Review / discussion paper	SANRA / narrative- review appraisal	N/A	N/A	N/A	N/A	N/A	N/A	Discussion/review paper without a new participant sample; conventional study- level RoB is not applicable.
24	Fi nn , 20 14	Disruption of Functional Networks in DD : A Whole-Brain, Data-Driven Analysis of Connectivity	Comparati ve experiment al fMRI	JBICase-Control / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Cross-sectional neuroimaging comparisons and data-driven analyses may be sensitive to sample selection, analytic flexibility, and multiple testing.
25	Si h v on en, 20 21	Structural White Matter Connectometry of Reading and DD	Cross- sectional diffusion MRI	JBICase-Control / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Small cross- sectional imaging sample and multiple tract analyses create precision and analytic-flexibility concerns.
26	Rich ards, 20 15	Contrasting Brain Patterns of Writing-Related DTI Parameters, fMRI Connectivity, and DTI-fMRI Connectivity Correlations in Children With and Without Dysgraphia or DD	Comparati ve multi- group DTI/fMRI	JBICase-Control / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Very small diagnostic subgroups, especially controls, may produce unstable estimates and residual confounding.
27	Hor owitz- Kraus, 20 18	Decreased Functional Connectivity in the Fronto- Parietal Network in Children With Mood Disorders Compared to Children With DD During Rest: An fMRI Study	Four-group comparati ve resting- state fMRI	JBICase-Control / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Multiple small clinical groups and possible differences in comorbidity/medica tion or developmental factors may confound between- group comparisons.
28	Wal die, 20 17	Reading Network in DD : Similar, Yet Different	Comparati ve experiment al fMRI	JBICase-Control / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Small heterogeneous diagnostic groups and regrouping for reading analyses may introduce classification and analytic-selection concerns.

29	Tschent sch he r, 20 19	Reduced Structural Connectivity Between Left Auditory Thalamus and the Motion-Sensitive Planum Temporale in DD	Comparative observational DTI	JB1 Case-Control / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Very small all-male sample limits precision and representativeness; residual confounding cannot be excluded.
30	Sc hu rz, 20 15	Resting-State and Task-Based Functional Brain Connectivity in DD	Comparative resting-state/task fMRI	JB1 Case-Control / neuroimaging adapted	Some concerns	Some concerns	Some concerns	Low	Some concerns	Some concerns	Small sample and missing resting-state data for three controls create some missing-data and precision concerns.
31	Qu agl in o, 20 08	Differences in Effective Connectivity Between Dyslexic Children and Normal Readers During a Pseudoword Reading Task: An fMRI Study	Comparative fMRI / structural equation modeling	JB1 Case-Control / neuroimaging adapted	High	High	Some concerns	Low	High	High	Extremely small groups (n=6 each) with complex connectivity 1059odelling create substantial overfitting, confounding, and analytic-instability concerns.
32	Zh ou , 20 15	Altered Connectivity of the Dorsal and Ventral Visual Regions in Dyslexic Children: A Resting-State fMRI Study	Comparative resting-state fMRI	JB1 Case-Control / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Moderate but still small imaging sample; seed-based analyses and cross-sectional design leave residual confounding and analytic-flexibility concerns.
33	Yu , 20 22	Patterns of Neural Functional Connectivity in Infants at Familial Risk of DD	Observational cohort resting-state fMRI	JB1 Cohort / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Familial-risk classification is not equivalent to later DD diagnosis, and observational infant imaging may retain residual familial/environmental confounding.
34	He nsl er, 20 10	Behavioral Genetic Approach to the Study of DD	Twin study / behavioral genetics	JB1 Cohort / genetic epidemiology adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Large twin sample is a strength, but threshold-based DD classification and assumptions of twin 1059odelling may affect estimates.
35	Fa ge rh ei m, 19 99	A new gene (DYX3) for DD is located on chromosome 2	Familial linkage / genome-wide linkage	Genetic association/linkage appraisal	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Single extended family and multiple diagnostic models limit external generalizability; findings require replication in independent pedigrees.
36	Sh ao, 20 16	Opposite Associations between Individual KIAA0319 Polymorphisms and DD Risk across Populations: A Stratified Meta-	Genetic meta-analysis	ROBIS	Some concerns	N/A	Some concerns	Low	Some concerns	Some concerns	Between-study heterogeneity and population-specific opposite effects reduce robustness; full search/appraisal details are not available in the review table.

		Analysis by the Study Population									
37	Zh on g, 20 13	Meta-analysis of the Association Between DCDC2 Polymorphisms and Risk of DD	Genetic meta-analysis	ROBIS	Some concerns	N/A	Some concerns	Low	Some concerns	Some concerns	Small number of studies and instability in sensitivity analyses warrant caution even though meta-analytic methods were used.
38	Bi ed er, 20 23	Genetic and protein interaction studies between the ciliary DD candidate genes DYX1C1 and DCDC2	Molecular/cellular functional study with zebrafish and organoids	Preclinical experimental RoB (adapted)	Some concerns	Some concerns	Some concerns	Low	Some concerns	Some concerns	Preclinical models support mechanism but the review table does not report randomization, blinding, replication structure, or complete experimental-quality safeguards.
39	Za ki, 20 24	Genetic Modifications of DD and Its Representation Using In Vivo, In Vitro Model	Narrative review	SANRA / narrative-review appraisal	N/A	N/A	N/A	N/A	N/A	N/A	Narrative review; conventional study-level RoB is not directly applicable.
40	Gi all uis i, 20 21	Genome-wide association study reveals new insights into the heritability and genetic correlates of DD	Case-control GWAS / genetic correlation	Genetic association appraisal / STREGA-informed	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Large multi-cohort dataset and QC are strengths; European-ancestry restriction, phenotype heterogeneity, population stratification, and multiple testing remain potential concerns.
41	A me lin k, 20 24	Imaging genetics of language network functional connectivity reveals links with language-related abilities, DD and handedness	Imaging-genetics / multivariate GWAS	Genetic association + imaging appraisal	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Very large sample is a strength, but UK Biobank selection, ancestry restrictions, and multiple correlated imaging/genetic tests may affect generalizability and false-positive control.
42	He , 20 23	Associative gene networks reveal novel candidates important for ADHD and DD comorbidity	Bioinformatic gene-network study	Bioinformatics critical appraisal (adapted)	Some concerns	Some concerns	N/A	Low	Some concerns	Some concerns	Findings depend on completeness and bias of curated databases and network-prioritization assumptions; no direct independent clinical validation was described in the review table.
43	Ci ul ki ny te, 20 25	Genetic neurodevelopmental clustering and DD	Genomic Structural Equation Modeling	Genetic summary-statistics appraisal	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Large summary-statistics base is a strength; European-ancestry restriction, possible sample overlap, and model specification may influence results.

44	Sc hu ma ch er, 20 07	Genetics of DD : The evolving landscape	Narrative review	SANRA / narrative-review appraisal	N/A	N/A	N/A	N/A	N/A	N/A	Narrative review; conventional study-level RoB is not directly applicable.
45	Ya ng , 20 24	DD genes are selectively targeted by diverse environmental pollutants	In silico bioinformatics/network analysis	Bioinformatics critical appraisal (adapted)	Some concerns	Some concerns	N/A	Low	Some concerns	Some concerns	Results are database- and model-dependent, with no direct human exposure/outcome validation in the reviewed study.
46	Pe ru gi ni, 20 24	DD Polygenic Scores Show Heightened Prediction of Verbal Working Memory and Arithmetic	Population-based twin/sibling molecular-genetic study	Genetic epidemiology appraisal	Some concerns	Some concerns	Some concerns	Low	Some concerns	Some concerns	Phenotype-specific sample sizes varied and the sample was restricted to European ancestry; missingness and family structure may influence estimates.
47	W an g, 20 22	A predictive model for Chinese children with DD—Based on a genetic algorithm optimized back-propagation neural network	Predictive modelling / AI classification	PROBAST	Some concerns	Some concerns	Low	Low	High	High	Single 70/30 train-test split and no external validation create substantial overfitting/optimism risk despite reported high accuracy.
48	Ri nn e, 20 24	DD susceptibility genes DNAAF4, DCDC2, and NRSN1 are associated with brain function in fluently reading adolescents and young adults	Preregistered imaging-genetics study	Genetic association + imaging appraisal	Some concerns	Some concerns	Some concerns	Low	Some concerns	Some concerns	Preregistration is a strength; genotype-specific missingness, modest genetic sample size, and multiple imaging outcomes still warrant caution.
49	De nn is, 20 09	A Common Variant Associated with DD Reduces Expression of the KIAA0319 Gene	Genetic association plus molecular functional study	Genetic association appraisal / STREGA-informed	Some concerns	Some concerns	Some concerns	Low	Some concerns	Some concerns	Initial family samples were modest; molecular validation strengthens inference, but association results may be vulnerable to winner's curse and population-specific effects.
50	Ch ap ma n, 20 25	Targeted analysis of DD-associated regions on chromosomes 6, 12 and 15 in large multigenerational cohorts	Targeted sequencing / quantitative-trait association	Genetic association appraisal	Some concerns	Some concerns	Some concerns	Low	Some concerns	Some concerns	Large family cohorts and QC are strengths; phenotype heterogeneity, variable analytic samples, candidate-region focus, and multiple testing remain concerns.
51	Ke rsh ne r, 20 16	Network dynamics in DD : Review and implications for remediation	Narrative / theoretical neurobiological synthesis	SANRA / narrative-review appraisal	N/A	N/A	N/A	N/A	N/A	N/A	Narrative theoretical synthesis; conventional empirical-study RoB is not directly applicable.
52	Ku jal a,	Voxel and surface based whole brain analysis shows reading skill	Cross-sectional	JB1 Case-Control / neuroimaging adapted	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns	Small cross-sectional imaging sample; multiple whole-brain

	20 21	associated grey matter abnormalities in DD	structural MRI								measures and residual confounding may affect robustness.
53	M cG rat h, 20 19	Are there shared neural correlates between DD and ADHD? A meta-analysis of voxel-based morphometry studies	Systematic VBM meta-analysis	ROBIS	Some concerns	N/A	Some concerns	Low	Some concerns	Some concerns	Meta-analysis is large relative to individual imaging studies, but heterogeneity, thresholding choices, and publication bias cannot be evaluated from the summary alone.
54	M or ke n, 20 17	Reading in DD across literacy development: A longitudinal study of effective connectivity	Longitudinal fMRI / dynamic causal modeling	JB1 Cohort / neuroimaging adapted	High	High	High	Low	Some concerns	High	Very small age-specific samples and changing sample sizes across time points create serious attrition, precision, and model-stability concerns.
55	Ri chl an, 20 20	The functional neuroanatomy of DD across languages and writing systems	Mini review / narrative neuroimaging review	SANRA / narrative-review appraisal	N/A	N/A	N/A	N/A	N/A	N/A	Narrative mini-review; conventional study-level RoB is not directly applicable.
56	Ya n, 20 21	Convergent and divergent brain structural and functional abnormalities associated with DD	Multimodal neuroimaging meta-analysis	ROBIS / neuroimaging meta-analysis appraisal	Some concerns	N/A	Some concerns	Low	Some concerns	Some concerns	Large evidence base is a strength, but study heterogeneity, coordinate-based meta-analytic assumptions, and publication/selection bias cannot be fully assessed from the review table.

Note. Because the included publications represent heterogeneous study designs, the domain labels shown in this table are harmonized reporting categories used to summarize design-specific appraisal results; they do not replace the original domains of ROBINS-I, JBI, ROBIS, PROCAST, or SANRA.

DISCUSSION

The aim of this review was to synthesize cognitive, genetic, and neurological findings and examine their relevance to the diagnosis and intervention of DD; while each of these domains accounts for aspects of reading difficulties, understanding the broad individual differences requires an examination of the relationships between these levels. The body of evidence reviewed supports the view that DD can arise through diverse developmental pathways; consequently, similarities in reading difficulties among individuals do not necessarily imply identical underlying factors or educational needs. However, acknowledging this heterogeneity should not lead to the assumption that all proposed mechanisms are scientifically equivalent or that every cognitive or neurological difference constitutes a direct cause of the disorder [2, 5, 18, 20].

At the cognitive level, phonological processing remains central to explaining difficulties in learning letter-sound correspondences; however, variations in naming speed, skill automatization, and visual attention indicate that reading difficulties cannot be attributed to a single component across all individuals. Findings regarding the relative distinctness of phonological processing and rapid naming support the separate assessment of these abilities, although existing evidence does not demonstrate a simple, consistent relationship between the number of cognitive deficits and the severity of DD ; indeed, two individuals with similar reading performance may exhibit distinct patterns on cognitive tests [17, 19, 20]. Frameworks such as procedural learning and delayed neural commitment offer useful explanations for the developmental aspects of these differences; yet, given that some supporting evidence is indirect, it is preferable to regard them as testable models rather than definitive

explanations for all cases of DD [18]. Genetic findings also present a similar picture of heterogeneity, indicating that the risk of DD is associated with a constellation of genetic factors whose effects must be interpreted alongside developmental conditions, linguistic experience, and learning opportunities. Variations in the association between specific genetic variants and DD across different populations demonstrate that identifying a genetic link is insufficient on its own to predict an individual's status or determine their educational needs; furthermore, the heritability of a trait does not imply that its developmental trajectory is immutable [28, 30, 32, 36]. While neuroimaging-genetics studies have enabled researchers to examine the relationship between genetic background and the organization of language networks, translating these findings into a clear causal chain—from gene to reading performance—requires more direct evidence and longitudinal studies that track biological and behavioral changes over the course of development [22].

At the level of the brain, the reviewed findings highlight the importance of coordination between distinct regions, as reading emerges from the interplay of visual, linguistic, and attentional processes; differences in the connectivity between these processes may manifest even when the overall organization of the reading network appears similar across groups. Reduced connectivity between left posterior and frontal regions, altered connectivity involving the visual word form area, and variations in white matter pathways are all consistent with a network-based perspective on DD, yet these findings do not imply the existence of a uniform neural pattern across all individuals [38, 41, 42, 46]. Additionally, the association of activity in specific right-hemisphere regions and the insula with superior reading performance suggests the potential use of compensatory or alternative pathways; however, confirming the compensatory role of these regions requires demonstrating that changes in their activity over time genuinely correlate with reading improvement, rather than merely reflecting task difficulty or increased individual effort [44]. A key issue in integrating cognitive and neurological evidence is determining the direction of the relationship between observed differences and the experience of reading; the mere presence of a difference in individuals with DD does not clarify whether that difference predated reading difficulties, arose as a consequence of reduced reading experience, or emerged as part of the individual's adaptation to learning challenges. While evidence regarding certain phonological deficits prior to formal instruction supports the view that they play a foundational role, the simultaneous consideration of age, skill level, task type, and writing system remains essential for interpreting many findings in this field [20, 41, 45]. From this perspective, discrepancies across studies do not necessarily invalidate the field; rather, they may indicate that research has captured different stages of a developmental process, and comparing findings without accounting for sample characteristics and assessment tools yields an overly simplistic picture of DD.

The implication of this multi-level perspective for diagnosis is that assessment must begin with actual reading performance and the individual's developmental and educational history, subsequently utilizing linguistic and cognitive tests or research tools tailored to the specific assessment question. While analyzing reading errors and assessing abilities such as phonological processing and rapid naming can help clarify an individual's needs, a group difference observed in a cognitive test, eye-movement pattern, or EEG index does not, in itself, demonstrate sufficient accuracy for individual diagnosis [9, 11, 13, 15, 17]. Therefore, the value of a new tool should be judged based on the information it adds to existing assessments and whether that information leads to better educational decisions, rather than merely on its ability to distinguish between two groups in a research setting.

Regarding interventions, it is essential to distinguish between the direct improvement of reading skills and changes in processes such as attention, memory, motivation, or engagement; improving an underlying ability—while potentially beneficial for the child—does not necessarily translate to reduced decoding difficulties or increased reading fluency. Accordingly, direct and systematic instruction in reading skills holds a central place in this review, and cognitive, sensory, and technological methods must be interpreted in light of the specific outcomes actually measured; for instance, results concerning auditory memory, anxiety, or increased task engagement are insufficient on their own to demonstrate effectiveness in reading [52, 57, 65]. This distinction is also relevant to the use of action games with pre-reading children, as improvements in phonological awareness among at-risk groups should not be generalized—without supplementary evidence—to effective DD treatment for children with a confirmed diagnosis [50]. Telerehabilitation is significant for another reason: it can transform how training and practice are accessed; however, the online delivery method itself should not be equated with the intervention content. While similar progress reported across in-person and online groups supports the

feasibility of delivering services in various formats, the absence of a statistically significant difference is insufficient to prove equivalence; results must be interpreted with due regard for baseline group differences, the number of sessions, professional supervision, and follow-up [51, 62, 69]. Regarding virtual reality, neurofeedback, and brain stimulation, preliminary findings must be evaluated alongside sample sizes, the nature of comparison groups, and the durability of effects; positive results in a limited number of outcomes or improvements relative to baseline do not, in themselves, justify widespread adoption or the replacement of standard reading instruction [48, 60, 63, 64].

Artificial intelligence holds promise for organizing multimodal data and identifying individual differences, yet the gap between a model's performance on research datasets and its utility in educational settings remains a critical issue. High classification accuracy may depend on sample characteristics, language, task type, and data-splitting methods; consequently, without independent validation, such accuracy cannot be considered an indicator of clinical readiness. Furthermore, analyses of handwriting or other indirect indicators must be interpreted in conjunction with validated diagnostic criteria and reading performance metrics [70, 77, 80]. Studies proposing educational tools and strategies represent a significant step toward developing personalized support; however, the accurate prediction of a recommendation is not synonymous with proving its efficacy. Future research must examine how utilizing model outputs—compared to standard support—impacts reading outcomes, academic independence, and the overall learning experience [71, 81]. Given these considerations, the primary value of the multilevel framework lies in its ability to generate clearer questions for research and practice, rather than simply aggregating a larger number of factors within a single model. For instance, one could investigate whether incorporating neural indices alongside behavioral data improves the prediction of response to instruction in independent samples, whether distinct profiles of phonological processing and rapid naming correspond to differing instructional needs, and whether changes in brain network connectivity during an intervention are associated with sustained improvements in reading [17, 19, 22, 41]. Addressing these questions requires longitudinal studies, samples diverse in terms of language and age, direct assessment of reading outcomes, and transparent reporting of analytical methods to distinguish between an approach's theoretical potential and its actual utility for the learner.

In interpreting this discussion, the limitations of the review itself must also be acknowledged. Because this was a broad narrative review encompassing heterogeneous study designs, populations, outcomes, and appraisal frameworks, direct quantitative comparison across all studies was not appropriate. Although structured searching, study selection, data extraction, and quality appraisal were undertaken, the breadth of the review and inclusion of diverse evidence types necessarily limit the comparability of findings across domains. Consequently, the conclusions should be viewed as a narrative synthesis of evidence rather than a quantitative estimate of effectiveness, a formal ranking of interventions, or the validation of a single causal model.

Across the reviewed domains, confidence in the findings was not uniform. Evidence supporting direct, structured reading instruction was more consistent because reading outcomes were measured directly and findings were supported across multiple study designs. In contrast, evidence for neurofeedback, brain stimulation, virtual reality, and several AI-based approaches was more heterogeneous and frequently limited by small samples, indirect outcomes, lack of independent validation, or methodological concerns. Accordingly, these approaches were interpreted as complementary or emerging rather than equivalent alternatives to established reading intervention.

CONCLUSION

Developmental dyslexia is best understood within a multi-level framework that examines genetic and developmental factors, brain network organization, and cognitive and linguistic processes alongside learning experiences; no single level suffices to explain all individual differences, and similar reading difficulties do not necessarily imply identical developmental pathways. This perspective underscores the necessity of comprehensive assessment and attention to the individual's specific needs, while genetic, neurological, and computational findings must be interpreted for decision-making purposes in light of their validity and added value.

Regarding intervention, direct, structured, and systematic reading instruction must remain the core of educational programs, with complementary methods and emerging technologies evaluated based on evidence of genuine, sustained reading improvement. Tele-rehabilitation and artificial intelligence offer the potential to enhance access, monitoring, and the personalization of support; however, realizing this potential depends on validation across independent populations, consideration of linguistic differences, and an examination of educational outcomes in real-world settings. The field's future trajectory lies in more precisely linking the understanding of underlying mechanisms with the learner's needs, ensuring that advancements in measurement and data analysis lead to clearer decisions and more effective support for individuals with DD.

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The authors disclose the following financial interests and/or personal relationships that could be perceived as potential conflicts of interest.

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Declaration of AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used Claude (Anthropic) to translate portions of the manuscript from Persian into English and to improve the linguistic clarity, grammar, and stylistic fluency of the English text. ChatGPT (OpenAI) was also used to assist in creating and refining the figures and graphical illustrations. After using these tools, the author(s) reviewed and edited all content as necessary and takes full responsibility for the content of the publication.

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