Acta Psychologica 246 (2024) 104269

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Motor skills and capacities in developmental dyslexia: A systematic review and meta-analysis

G. Decarli [a], L. Franchin [a], F. Vitali [b,*]

[a] Department of Psychology and Cognitive Science, University of Trento, Rovereto, Italy
[b] Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Verona, Italy

ARTICLE INFO

Keywords:
Dyslexia
Learning disabilities
Reading disorders
Motor skills
meta-analysis

ABSTRACT

In recent decades, the connections between academic skills, such as reading, writing, and calculation, and motor skills/capacities have received increasing attention. Many studies provided evidence for motor difficulties in children and adolescents with dyslexia, prompting the need for a meta-analysis to combine these multiple findings. Therefore, we conducted a meta-analysis using PsycINFO, Pubmed, and SportDiscus as scientific databases. A total of 572 studies were analyzed following several stringent inclusion criteria, resulting in the inclusion of 23 peer-reviewed studies in the final analysis. Our results showed that children and adolescents with dyslexia displayed significant different performances in multiple motor tasks and these differences persisted also when the type of motor task was considered as moderator in the analysis. The present findings are in accordance with the literature that supports a close connection between reading disabilities and difficulties in motor skills/capacities.

1. Introduction

1.1. Developmental dyslexia

During the first years of school (i.e., primary, and secondary schools), academic success is mainly guided by children and adolescents' abilities to successfully read, proficiently write, and learn the basic principles of number literacy. However, some individuals encouter obstacles with one or more of these skills, leading them to experience negative feelings (such as anxiety, depression, and loneliness; see Bryan et al., 2004). In the context of learning disabilities, developmental dyslexia has been considered a disorder that affects reading skills. In particular, individuals with dyslexia exhibit difficulties in reading fluency and spelling with a persistence over time (at least 6 months), their performances are below the expected mean considering child's chronological age and grade, the difficulties begin usually in school-age years, and they are not better explained by other disabilities/disorders (see DSM-5; American Psychiatric Association, 2013). Current research suggests that individuals with dyslexia often struggle with mapping between the visual representation of words and their corresponding sounds during reading. This difficulty is associated with atypical activation in certain areas of the brain, such as the left temporoparietal cortex, inferior frontal gyrus, and occipitotemporal cortex (Peterson & Pennington, 2012; see for a more recent review Devoto et al., 2022), as well as atypical connectivity within the reading pathway in the left hemisphere (Finn et al., 2014; van der Mark et al., 2011; see for a review Gabrieli, 2009). The prevalence of dyslexia has been shown to vary a lot, depending on the criteria used for the diagnosis and on the inclusion criteria implemented in the studies (for a theoretical overview, see Peters & Ansari, 2019).

1.2. Connection between dyslexia and motor difficulties

Recently, the scientific literature has focused the attention on the understanding of the origins of learning disabilities as well as on their ramifications in other cognitive domains: some studies have provided evidence that children and adolescents with learning disorders can present difficulties that extend beyond the academic ones, including a variety of deficits in other skills, such as visuo-spatial skills (e.g., Bertoni et al., 2019; Decarli et al., 2020; Ronconi et al., 2020), or motor skills/capacities (e.g., Bellocchi et al., 2017). In particular, a growing number of studies have investigated whether there are connections between dyslexia and fine/gross motor difficulties. Specifically, it has been shown that children with reading disorders present constantly lower

* Corresponding author.
E-mail address: francesca.vitali@univr.it (F. Vitali).

https://doi.org/10.1016/j.actpsy.2024.104269
Received 29 October 2023; Received in revised form 9 April 2024; Accepted 10 April 2024
Available online 20 April 2024

gross motor skills over time: a 3-year longitudinal study has provided evidence that typically developing children better perform at each timepoint in locomotor and ball control skills (Westendorp et al., 2014). Moreover, we know that children with dyslexia can show problems in bead threading (i.e., how many beads can be threaded within a limited time), in pegboard (i.e., time to move some pegs from a row to another), and/or in balance tasks (Fawcett et al., 2001; Stoodley et al., 2005). The worse motor performances when comparing children with and without dyslexia were found especially in bead threading and in balance tasks (i.e., blindfold and dual balance; Nicolson & Fawcett, 1994). Starting from these findings, some authors have theorized a cerebellar deficit hypothesis (Nicolson et al., 2001; Stoodley & Stein, 2013) for dyslexia. According to them, cerebellar dysfunctions can lead children to show deficits in automatization, time estimation, and balance; these dysfunctions would in turn lead to reading deficits. Nicolson and Fawcett (1990) tested children with reading disorders and controls with a single task (i.e., balance) and dual-task (i.e., counting-backwards). Both groups showed similar performances in the single task, whereas children with dyslexia underperformed in the dual task. These results were taken as evidence that children with dyslexia might have a deficit in automatization skills. A critical perspective on the cerebellar theory has been proposed by Ramus et al. (2003). In their study, the authors compared the performances of a group of children with dyslexia and a matched control group across various tasks assessing both phonological skills and cerebellar function. The findings indicated that children with dyslexia exhibited on average a significant impairment in motor control tasks, although the incidence of these impairments was relatively low, affecting slightly more than half of the children with dyslexia. The authors proposed the hypothesis that part of these results could be attributed to the comorbidity of dyslexia with other disorders, such as ADHD and/or developmental coordination disorder (DCD).

Some researchers have found an association between dyslexia and deficits in handwriting. In a Chinese cross-sectional study, children with dyslexia were compared in multiple tasks such as writing to dictation, handwriting, orthographic, and motor skills/capacities (Cheng-Lai et al., 2013). These authors provided evidence for worse motor performances of children with dyslexia in fine manual control and coordination skills, but also in handwriting speed, Chinese character naming, and Chinese words dictation. Similarly, Pagliarini et al. (2015) found that children with reading disorders were slower in handwriting tasks. More recently, a study provided evidence of slower and less accurate performances in handwriting and graphic fluency among children with dyslexia compared to a control group (Martínez-García et al., 2021). In contrast to these results, others did not observe any distinction in legibility between the productions of children with dyslexia and controls (Martlew, 1992). Moreover, regarding handwriting fluency, some researchers found no differences in the speed production and pauses when comparing children with dyslexia to their typically age-matched peers (Martlew, 1992; Sovik & Arntzen, 1986).

A line of research has focused on the association between dyslexia and postural control. Razuk and Barela (2014) proposed children with dyslexia and controls to look at a target in a moving room when manipulating the distance between the child and the wall and considering the central/full vision. Results revealed that the clinical population oscillated more than controls in stationary and moving conditions; moreover, the removal of peripheral visual cues led to a deleterious postural control in children with dyslexia. The authors concluded that when sensory cues are less informative, children with dyslexia find more difficulties in processing stimuli, leading to worse motor performances. A critical interpretation of these deficits in dyslexia, posits that this association may be related to hyperactivity and inattention symptoms characteristic of ADHD (Rochelle & Talcott, 2006). In line with this hypothesis, some researchers conducted a study involving adults with dyslexia and a control group of similar age (Rochelle et al., 2009). The study encompassed cognitive, literacy, attention, and postural stability assessments. The authors found differences across groups in sway magnitude and sway variability. Importantly, these postural stability differences were found to be largely attributed to the effects of hyperactivity and inattention scores. In light of these findings, the disparities in postural stability among individuals with dyslexia and controls, might be linked to hyperactivity and inattention symptoms.

1.3. *The present study*

Given the contradictory results that have emerged in the literatue, our meta-analysis aims to make contributions to this field in several ways. Firstly, there has been a growing interest in the relationship between dyslexia and motor skills/capacities in recent decades. Many studies have shown that children experiencing difficulties in reading also encounter problems in multiple motor tasks. Importantly, to our knowledge, this work represents the first systematic attempt to investigate and synthesize these results. Secondly, implementing a meta-analytic approach provides a powerful tool for aggregating findings from different studies, allowing for an evaluation of the effect size and the strength of this association. In particular, our hypotheses were twofold. First, we expect to find that children and adolescents with dyslexia would exhibit impairments in multiple motor skills/capacities compared to age-matched controls (H1). Second, the presence of dyslexia would be associated with lower performances in various motor tasks, regardless of the grade level and type of motor skills/capacities (H2). In line with this hypothesis, many studies found problems in both fine and gross motor skills in developmental dyslexia (Fawcett et al., 1996; Nicolson & Fawcett, 1990, 1994). To these aims, we meta-analyzed the literature on this topic by assessing the peer-reviewed studies published in the years between 2000 and 2022.

2. Methods

2.1. *Screening of the studies and eligibility criteria*

The search for the studies was conducted during December 2022–January 2023, following the PRISMA rules (see Page et al., 2021). Key studies were collected using these scientific databases: PsycINFO, Pubmed, and SportDiscus. All studies were screened and included in the meta-analysis if six eligibility criteria were met. First, we decided to consider only the more recent studies whose publication years ranged between 2000 and 2022. The rationale behind this choice was to assess only the very recent studies considering connections between dyslexia and motor skills/capacities. Second, we decided to focus only on studies involving youth aged between 6- and 18-years old. This age range was chosen because learning disabilities, such as dyslexia, commonly emerge within school-aged populations. Therefore, our decision to include participants within the 6 to 18 years age range is aligned with the typical onset of learning difficulties. Furthermore, our aim was to focus our meta-analysis on a developmental population.

Third, only peer-reviewed articles written in English were examined, ensuring that the studies selected would have met high standards of quality, methodology, and validity. The choice to include only peer-reviewed studies highlights our goal of selecting findings with high standards of rigor and reliability. Indeed, peer-reviewed studies undergo an assessment by experts in the field, ensuring that the research methodology and data analysis meet stringent criteria. Fourth, we included only studies that assessed children and adolescents with a diagnosis of dyslexia made following a systematic testing, with the scores significantly below the normative data in reading tests (and not based on teachers' or parents' judgements; see DSM-5; American Psychiatric Association, 2013). Fifth, all the studies should present a typically developing control group (and not controls with other disabilities). Finally, we excluded single-case studies.

The keywords and search terms used were the following: dyslexia, reading disabilit*, reading difficult*, reading disord*, reading deficit*, reading impairment* and motor skill*, motor ability*, motor capacit*, motor development, motor disabilit*, motor activit*, motor problem*, motor performance*, physical activit*, sport. We decided to include "reading disorder" rather than the more general term "specific learning disorder" to enhance the relevance and the precision of our systematic review and meta-analysis. At this step, we searched only for titles and abstracts.

The keywords and search terms yielded a total of 572 studies published in the years between 2000 and 2022. We performed an initial screening of the studies' abstracts to assess the suitability of the articles in terms of eligibility and inclusion criteria for this study's aim. Out of these, 58 papers were excluded a priori because they were duplicates, while 428 articles were out of topic. As a result of this first screening process, 86 papers have been judged eligible to be read in full and considered for the present meta-analysis. A second screening process was then conducted, and we excluded 44 papers because they lacked to meet all the inclusion criteria: respectively, 3 studies used an older or younger population, 2 studies were not published in English, 21 studies implemented unsuitable methodologies (e.g., meta-analysis or reviews, single-case studies, etc.), and 18 studies tested clinical populations or controls that did not fit with the inclusion criteria (e.g., not a dyslexia sample, diagnosis based on teachers' and/or parents' judgements). Finally, we excluded 19 studies because they presented missing information (e.g., means or standard deviations of one/both control/dyslexia group). As a final result, a total of 23 studies met all the eligibility and inclusion criteria and were included in the present meta-analysis (see flow chart in Fig. 1, and Table 1).

2.2. Coding

Coding files included all the studies that met the eligibility and inclusion criteria, along with tests used to assess children and adolescents, sample characteristics, means and standard deviations (SDs) for each task. All the studies included in the present meta-analysis were analyzed by two expert coders. Specifically, the coders independently extracted means and SDs for each study, and these indices were subsequently compared to calculate the intercoder agreement. The agreement was very high, ranging from 99 % to 100 %.

2.3. Statistical analyses

All analyses were conducted using the R (R Core Team, 2017) and the Meta-Analysis Package for R "metafor" version 3.0 (Viechtbauer, 2010). To assess overall group differences, we included in the analyses the outcomes derived from the motor skills/capacities' assessment. We compared two groups (i.e., children and adolescents with dyslexia vs children and adolescents with typical development) using standardized group differences. When multiple control groups were assessed, we selected the age-matched group. Similarly, we excluded studies in which there was not a chronological-matched control group, or in which the diagnosis of dyslexia was not performed using standardized tests (i.e.,

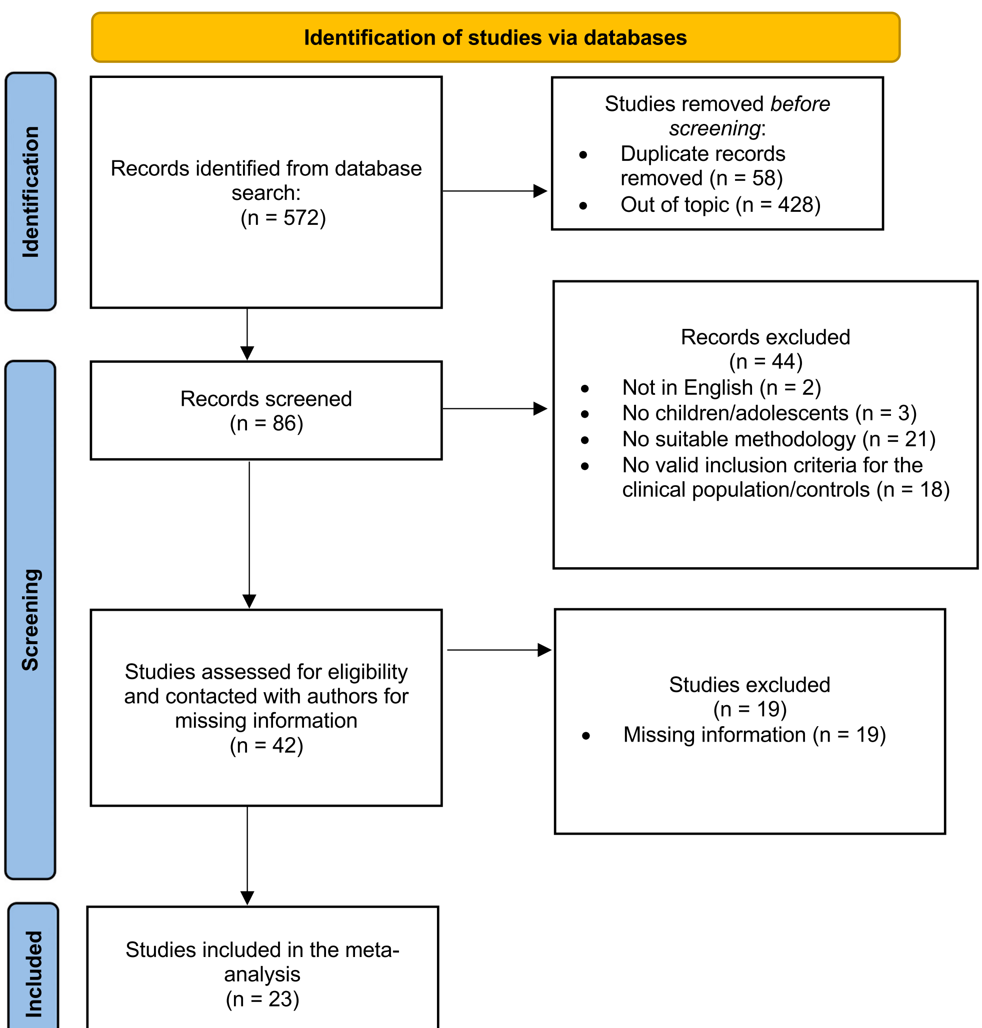

Fig. 1. Flow chart of search process, and eligibility and inclusion criteria, following the PRISMA guidelines (see Page et al., 2021).

Table 1
Included studies of the present meta-analysis and specific tests used to assess motor skills.

Study	Tests used to assess motor skills
Alamargot et al., 2020	First name-surname production Alphabet production
Bellocchi et al., 2017	Developmental Test of Visual Perception - 2 (DTVP-2)
Brookes et al., 2010	Balance test
Bucci et al., 2013	Platform for postural stability
Caldani et al., 2022	HTC Vive system
Cheng-Lai et al., 2013	Chinese Handwriting Assessment Tool (CHAT) Bruininks–Oseretsky test of motor proficiency - 2nd edition (BOT-2) Bender Gestalt test - 2nd edition
Fawcett et al., 2001	Static and dynamic cerebellar tests
Giovagnoli et al., 2016	Visual Motor Integration (VMI)
Jeffries & Everatt, 2004	Bangor Dyslexia Test (BDT) Dyslexia Screening Test (DST)
Lam et al., 2011	Chinese handwriting performance test (CHAT)
Logan & Getchell, 2010	Movement assessment battery for children (M-ABC)
Marchand-Krynski et al., 2017	Grooved Pegboard (GPB) Leonard Tapping Task (LTT)
Meng et al., 2019	Figure Drawing Task Two-character Chinese word copying test
Ramus et al., 2003	Cerebellar tests
Razuk & Barela, 2014	Postural control task
Stoodley et al., 2005	Balancing task
Sumner et al., 2014	Detailed Assessment of Speed of Handwriting
Thompson et al., 2015	Movement assessment battery for children (M-ABC 2)
van de Walle de Ghelcke et al., 2021	Visually guided pointing task
Vieira et al., 2009	Postural control task
White et al., 2006	Multiple motor tasks
Wu & Hwang, 2022	Movement assessment battery for children (M-ABC 2) Bipedal stance control
Yang & Hong-Yan, 2011	Serial reaction time tasks (SRTTs)

based on teachers' and/or parents' evaluations). To assess whether the two groups show or not distinct performances, we extracted means and SDs of each group and we computed the standardized mean difference, obtaining the Hedge's g effect size for each outcome. Hedges' g is particularly suitable for meta-analyses as it accounts for potential biases in small sample sizes, providing a more robust measure of effect size. Finally, we performed a multivariate model with random-effects at the study and at the estimate level, accounting for the dependency of multiple estimates and implementing the variance-covariance matrix for the studies. This model returns the estimate of pooled confidence intervals which accounts for the repeated measures. Then, we planned to explore potential sources of heterogeneity by introducing moderators (i.e., variables that may influence the variability in effect sizes across studies) into the model. Moderators included participants' grade level (see for performance differences across ages, Brookes et al., 2010) and type of motor skills (fine/gross; see Getchell et al., 2007).

3. Results

The motor skills/capacities between children and adolescents with dyslexia and controls were significantly different ($p < .001$) with the estimate of the pooled effect of 0.74 and a 95 % CI between 0.48 and 0.99 (see Fig. 2 and Supplementary Materials for separated analysis for positive vs. negative scores). Moreover, we performed the Q-test for heterogeneity ($Q(80) = 337.32, p < .001$; between studies heterogeneity variance: $\sigma^2 = 0.26$; $I^2 = 55.86$ %; within studies heterogeneity variance: $\sigma^2 = 0.13$; $I^2 = 27.17$ %).

Due to the significant between-studies heterogeneity, we performed moderator analyses to detect possible influences on the data. In particular, participants' grade level and motor skills/capacities tested in the studies were considered as moderators. Six types of motor skills/capacities were identified: handwriting, visual-motor integration, balance, coordination, dexterity, and stability. Moreover, we inserted in the analysis the distinction between gross/fine motor skills. We conducted a model selection analysis by evaluating all possible model combinations and selecting the best-fitting model. The Akaike Information Criterion

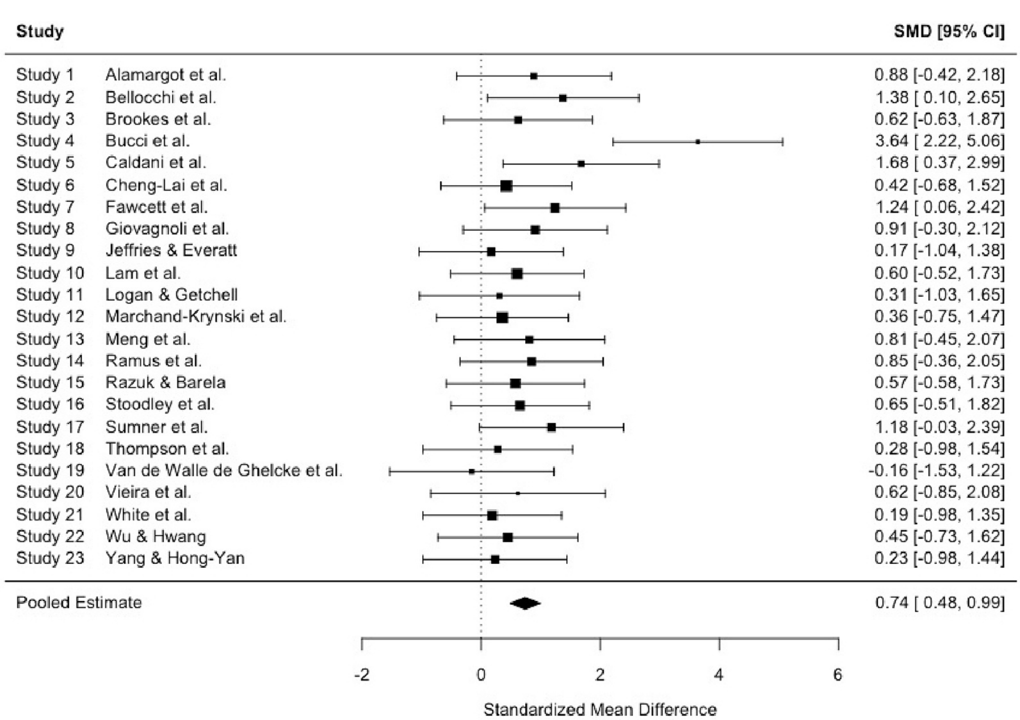

Fig. 2. Group differences in motor skills/capacities.
Note. SMD = Standardized Means Difference.

corrected for small sample sizes (AICc) was employed for this selection process. Results indicated that the best models were two: the one without moderators (AICc: 140.9), and the one with grade level as moderator (AICc: 141.19). Categorizing the motor skills in a different way (i.e., including hand movements, limb movements, visual-motor coordination, and body movements), the results remained unchanged. Therefore, the heterogeneity could not be explained by gross/fine motor skills and motor skills/capacities' type.

Moreover, Egger's regression test was performed to assess the publication bias of the studies included in the present meta-analysis (Egger et al., 1997), and we found a marginal significance of asymmetry ($z = 1.96$, $p = .05$). After excluding the study that presented extreme values, the Egger's regression test was not significant ($z = 0.33$, $p = .74$). Notably, the significant difference between children and adolescents with dyslexia and controls did not change after excluding this study (estimate of pooled effect: 0.62, $p < .001$, 95 % CI: 0.38, 0.90).

Finally, in order to address potential confounding factors, we conducted two separate analyses to ensure the robustness of our findings. Firstly, recognizing the potential influence of handwriting skills on our analysis, given its connection to literacy skills, we performed an additional analysis excluding studies specifically focused on handwriting (i.e., Alamargot et al., 2020; Cheng-Lai et al., 2013; Lam et al., 2011; Meng et al., 2019; Sumner et al., 2014). Remarkably, even after the exclusion of studies associated with handwriting skills, our results remained statistically significant ($p < .001$; 95 % CI: 0.40–1.08). Furthermore, since dyslexia has been associated with hyperactivity and inattention factors (see e.g., Rochelle et al., 2009), we conducted a second analysis. Specifically, we selected the studies involving a clinical sample with pure dyslexia (i.e., Bellocchi et al., 2017; Brookes et al., 2010; Bucci et al., 2013; Fawcett et al., 2001; Giovagnoli et al., 2016; Jeffries & Everatt, 2004; Marchand-Krynski et al., 2017; Meng et al., 2019; Razuk & Barela, 2014; Sumner et al., 2014; van de Walle de Ghelcke et al., 2021; Wu & Hwang, 2022; Yang & Hong-Yan, 2011). Notably, even after this selection, our results retained their significance ($p < .001$; 95 % CI: 0.39–1.29).

4. Discussion

A scientific literature search performed using the scientific databases PsycINFO, Pubmed, and SportDiscus was computed selecting recent papers published between the years 2000 and 2022. A total of 23 studies met all the eligibility and inclusion criteria and were meta-analyzed. The main finding of the present study was that children and adolescents with dyslexia displayed impairments in motor skills/capacities compared to age-matched controls. In particular, participants with dyslexia showed lower performances in multiple motor skills and capacities, such as handwriting, visual-motor integration, balance, coordination, dexterity, and stability. This finding aligns with our first hypothesis (H1) and provides further support for the connection between reading abilities and motor skills. In line with this, some studies reported a role of motor skills/capacities in the acquisition of academic skills (Knight & Rizzuto, 1993). For instance, Son and Meisels (2006) assessed a large cohort dataset and demonstrated that early kindergarten motor skills, particularly visual motor skills, significantly contributed to reading and mathematics achievement by the end of the first grade. These results support the hypothesis of an association between the acquisition of reading skills and motor skills/capacities, and suggest that motor skills/capacities may not only be linked to reading abilities but also to mathematical proficiency (see also Knight & Rizzuto, 1993; see the link between hand action and quantity perception: Decarli, Veggiotti, & de Hevia, 2022; Decarli, Rämä, et al., 2022).

In addition, the results of the present meta-analysis can be interpreted as additional support for the cerebellar hypothesis (Nicolson et al., 2001). According to this theory, a connection emerges among cerebellar anomalies, phonological challenges, and reading difficulties. Specifically, the lack of fluent articulatory skills is expected to result in impairments in the phonological loop and deficits in phonological awareness, preventing children from acquiring fluent and accurate reading skills. Moreover, these cerebellar impairments can also be linked to motor difficulties. Therefore, one possibility is that the association between reading and motor disabilities stems from a shared deficit in cerebellar function.

This association is also supported at the neural level by considering dyslexia as a multifactorial condition with cognitive challenges extending beyond language-specific brain areas and not limited to a dysfunctional phonological system. Accordingly, neuroanatomical studies have revealed widespread structural and functional abnormalities in the brains of individuals with dyslexia compared to controls (e.g., Richlan et al., 2009). These widespread abnormalities would lead to experience difficulties not only in the reading domain but also in other abilities, such as motor skills/capacities.

Finally, another evidence that aligns with our results arises from the studies on DCD. Deficits in motor coordination can interfere with academic achievement, and, in particular, can negatively influence reading, spelling, and numerical abilities (e.g., Cheng et al., 2011; Dewey et al., 2002; Gomez et al., 2017). Acknowledging the high comorbidity between dyslexia and DCD, it becomes relevant to clarify the specific role of DCD in the link between dyslexia and motor performance. In our meta-analysis, a substantial number of studies included a separate group with DCD for comparative analysis or controlled the clinical group for comorbidities, ensuring that the observed differences between groups were attributed to dyslexia (and its associated reading difficulties) rather than to other deficits. Nevertheless, we acknowledge the importance of further investigating this interesting research question in future studies.

Our results are also in accordance with studies testing the efficacy of motor training and exercise-based treatment in children with reading disabilities (Emami Kashfi et al., 2019; Reynolds & Nicolson, 2007; for failure in observing an efficacy in perceptual-motor training, see also Kavale & Mattson, 1983). These studies demonstrated that improving motor skills/capacities yields benefits not only within the motor domain but also extends to other cognitive abilities, including those closely tied to reading and academic skills (for example, improvements in executive functions can be relevant for reading development; see Best et al., 2009).

Another important finding of this study is that the impairments in children and adolescents with dyslexia persisted also when we included type of motor skill and capacity, and fine/gross motor skills as possible moderators of the differences between the two groups (see H2). A moderation effect of the participants' grade level was found. In particular, motor performances of children and adolescents with dyslexia and controls seem to diverge more strongly during the primary school if compared with the secondary schools. An interpretation of this result could be that older children/adolescents might be able to better compensate their difficulties, allowing to minimize, at least in part, the consequences of motor and/or reading disorders (e.g., Shaywitz & Shaywitz, 2005).

It should be noticed that our meta-analysis encompasses studies from diverse orthographic backgrounds. Therefore, it is important to highlight that the association between dyslexia and motor skills/capacities may vary across different languages and across different levels of the orthographic systems, potentially influencing the strength of the observed link.

To sum up, this study offers valuable insights to better understand the link between dyslexia and motor skills and capacities. However, it is important to acknowledge some limitations that should be noticed. One limitation lies in the method used for the literature search. The study focused on three specific scientific databases, namely PsycINFO, Pubmed, and SportDiscus, while omitting other databases such as Web of Science. Consequently, there is a possibility that relevant studies pertaining to the association between dyslexia and motor skills/capacities may have been overlooked, limiting the inclusiveness and comprehensiveness of the literature review. Connected to this point, it is important to acknowledge that studies yielding negative results may not be published to the same extent as positive ones. This bias could impact the overall understanding of the relationship between dyslexia and motor skills/capacities, and it underscores the need for a cautious interpretation of our results.

Furthermore, the literature search was confined to studies published between 2000 and 2022. While this deliberate timeframe selection allowed for a concentration on recent studies, it may have excluded earlier research that could have provided additional perspectives into the studied relationship.

Despite these limitations, this study contributed to our understanding of the association between dyslexia and motor skills and capacities. It is crucial for future research to address these limitations, exploring the broader context of this association.

4.1. Conclusions

We found that significant differences emerged in multiple motor skills and capacities in children and adolescents with dyslexia compared to typically developing children and adolescents. This result persisted also when we tested the type of motor skills and capacities as moderators of the effect. Therefore, the findings of the present study may support an association between disabilities in reading and motor skills/capacities (e.g., Cheng et al., 2011; Dewey et al., 2002; Gomez et al., 2017).

School and physical activity (PA; i.e., sport, and physical education) contexts follow extremely interconnected paths (e.g., Vitali et al., 2019). Like school, PA contexts and youth sport in particular require children to attend and participate in organized, competitive activities determined by rules, and performed individually or in teams. All of this plays an important role in both academic and sports/motor paths offering youth opportunities for enjoyment and increasing self-efficacy, two main constructs proposed within many motivational theories in any human endeavor, school, sport and PA included (e.g., Morano et al., 2019), and promoting the psychophysical development of children and adolescents (Côté & Fraser-Thomas, 2007). On one hand, school should promote several learning and growth experiences, but also personal, social, cognitive, and emotional development. On the other hand, PA, and sport participation in particular can improve skills learning and capacities development, together with the improvement of cardiorespiratory and cardiovascular functions, and physical and motor capacities such as muscular strength, muscular endurance, speed, flexibility (e.g., Boreham & Riddoch, 2001; Kristensen et al., 2010). Together, school and sport activities may provide youth participants with enjoyable experiences, opportunities to increase self-efficacy, self-esteem, and subjective well-being (e.g., Vitali et al., 2019; for a systematic review, see Eime et al., 2013). Thus, the connection we found could be very functional to foster reading and motor skills/capacities both in typical and atypical children and adolescents, with a particular attention for youth with special needs.

This topic has become a really stimulating field of research, still not completely explored and more research is needed to disentangle the processing beyond the reciprocal influence of these cognitive and motor abilities. Regarding atypical development, future research could investigate the different and specific profile of each learning disability (not only reading) in association with the motor skills acquisition and capacities development. For example, dyslexia could present a different profile in fine vs. gross motor skills compared to dyscalculia or spelling disorders. Moreover, it would be interesting to address the potential interference of motor skills acquisition and capacities development in academic achievement also during typical development.

CRediT authorship contribution statement

G. Decarli: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **L. Franchin:** Writing – review & editing, Resources, Funding acquisition, Supervision. **F. Vitali:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

Acknowledgements

We would like to thank Sara Benetollo and Matilde Piccoli for helping in the studies' collection and analysis. This work was supported by a grant from Fondazione Cassa di Risparmio di Trento e Rovereto (Caritro), Trento, Italy [grant number 2022.0366] to L.F.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2024.104269.

References

Alamargot, D., Morin, M.-F., & Simard-Dupuis, E. (2020). Handwriting delay in dyslexia: Children at the end of primary school still make numerous short pauses when producing letters. *Journal of Learning Disabilities, 53*(3), 163–175. https://doi.org/10.1177/0022219420903705

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Arlington, VA: American Psychiatric Publishing. https://doi.org/10.1176/appi.books.9780890425596

Bellocchi, S., Muneaux, M., Huau, A., Lévêque, Y., Jover, M., & Ducrot, S. (2017). Exploring the link between visual perception, visual–motor integration, and reading in normal developing and impaired children using DTVP-2. *Dyslexia, 23*(3), 296–315. https://doi.org/10.1002/dys.1561

Bertoni, S., Franceschini, S., Ronconi, L., Gori, S., & Facoetti, A. (2019). Is excessive visual crowding causally linked to developmental dyslexia? *Neuropsychologia, 130*, 107–117. https://doi.org/10.1016/j.neuropsychologia.2019.04.018

Best, J. R., Miller, P. H., & Jones, L. L. (2009). Executive functions after age 5: Changes and correlates. *Developmental Review, 29*(3), 180–200.

Boreham, C., & Riddoch, C. (2001). The physical activity, fitness and health of children. *Journal of Sports Sciences, 19*(12), 915–929. https://doi.org/10.1080/026404101317108426

Brookes, R. L., Tinkler, S., Nicolson, R. I., & Fawcett, A. J. (2010). Striking the right balance: Motor difficulties in children and adults with dyslexia. *Dyslexia, 16*(4), 358–373. https://doi.org/10.1002/dys.420

Bryan, T., Burstein, K., & Ergul, C. (2004). The social-emotional side of learning disabilities: A science-based presentation of the state of the art. *Learning Disability Quarterly, 27*(1), 45–51. https://doi.org/10.2307/1593631

Bucci, M., Bui-Quoc, E., & Gerard, C. L. (2013). The effect of a stroop-like task on postural control in dyslexic children. *PLoS One, 8*(10), Article e77920. https://doi.org/10.1371/journal.pone.0077920

Caldani, S., Baghdadi, M., Peyre, H., Khoury, E., Delorme, R., & Bucci, M. P. (2022). Poor visuo-spatial orientation and path memorization in children with dyslexia. *Nordic Journal of Psychiatry, 76*(3), 195–201. https://doi.org/10.1080/08039488.2021.1943705

Cheng, H. C., Chen, J. Y., Tsai, C. L., Shen, M. L., & Cherng, R. J. (2011). Reading and writing performances of children 7–8 years of age with developmental coordination disorder in Taiwan. *Research in Developmental Disabilities, 32*(6), 2589–2594. https://doi.org/10.1016/j.ridd.2011.06.017

Cheng-Lai, A., Li-Tsang, C. W. P., Chan, A. H. L., & Lo, A. G. W. (2013). Writing to dictation and handwriting performance among Chinese children with dyslexia: Relationships with orthographic knowledge and perceptual-motor skills. *Research in Developmental Disabilities, 34*(10), 3372–3383. https://doi.org/10.1016/j.ridd.2013.06.039

Côté, J., & Fraser-Thomas, J. (2007). Youth involvement in sport. In R. Crocker (Ed.), *Sport psychology: A Canadian perspective* (pp. 270–298). Toronto: Pearson.

Decarli, G., Paris, E., Tencati, C., Nardelli, C., Vescovi, M., Surian, L., & Piazza, M. (2020). Impaired large numerosity estimation and intact subitizing in developmental dyscalculia. *PLoS One, 15*(12), Article e0244578. https://doi.org/10.1371/journal.pone.0244578

Decarli, G., Rämä, P., Granjon, L., Veggiotti, L., & de Hevia, M. D. (2022). Electrophysiological evidence for a number–action mapping in infancy. *Brain Sciences, 12*(11), 1480. https://doi.org/10.3390/brainsci12111480

Decarli, G., Veggiotti, L., & de Hevia, M. D. (2022). The link between number and action in human infants. *Scientific Reports, 12*(1), 3371. https://doi.org/10.1038/s41598-022-07389-9

Devoto, F., Carioti, D., Danelli, L., & Berlingeri, M. (2022). A meta-analysis of functional neuroimaging studies on developmental dyslexia across European orthographies: The ADOD model. *Language, Cognition and Neuroscience, 37*(3), 285–314. https://doi.org/10.1080/23273798.2021.1970200

Dewey, D., Kaplan, B. J., Crawford, S. G., & Wilson, B. N. (2002). Developmental coordination disorder: Associated problems in attention, learning, and psychosocial adjustment. *Human Movement Science, 21*(5–6), 905–918. https://doi.org/10.1016/S0167-9457(02)00163-X

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *BMJ, 315*(7109), 629–634. https://doi.org/10.1136/bmj.315.7109.629

Eime, R. M., Young, J. A., Harvey, J. T., Charity, M. J., & Payne, W. R. (2013). A systematic review of the psychological and social benefits of participation in sport for children and adolescents: Informing development of a conceptual model of health through sport. *International Journal of Behavioral Nutrition and Physical Activity, 10*(1), 98. https://doi.org/10.1186/1479-5868-10-98

Emami Kashfi, T., Sohrabi, M., Saberi Kakhki, A., Mashhadi, A., & Jabbari Nooghabi, M. (2019). Effects of a motor intervention program on motor skills and executive functions in children with learning disabilities. *Perceptual and Motor Skills, 126*(3), 477–498. https://doi.org/10.1177/0031512519836811

Fawcett, A. J., Nicolson, R. I., & Dean, P. (1996). Impaired performance of children with dyslexia on a range of cerebellar tasks. *Annals of Dyslexia, 46*, 259–283.

Fawcett, A. J., Nicolson, R. I., & Maclagan, F. (2001). Cerebellar tests differentiate between groups of poor readers with and without iq discrepancy. *Journal of Learning Disabilities, 34*(2), 119–135. https://doi.org/10.1177/002221940103400203

Finn, E. S., Shen, X., Holahan, J. M., Scheinost, D., Lacadie, C., Papademetris, X., … Constable, R. T. (2014). Disruption of functional networks in dyslexia: A whole-brain, data-driven analysis of connectivity. *Biological Psychiatry, 76*(5), 397–404. https://doi.org/10.1016/j.biopsych.2013.08.031

Gabrieli, J. D. (2009). Dyslexia: A new synergy between education and cognitive neuroscience. *Science, 325*(5938), 280–283. https://doi.org/10.1126/science.1171999

Getchell, N., Pabreja, P., Neeld, K., & Carrio, V. (2007). Comparing children with and without dyslexia on the movement assessment battery for children and the test of gross motor development. *Perceptual and Motor Skills, 105*(1), 207–214. https://doi.org/10.2466/pms.105.5.207-214

Giovagnoli, G., Vicari, S., Tomassetti, S., & Menghini, D. (2016). The role of visual-spatial abilities in dyslexia: Age differences in children's reading? *Frontiers in Psychology, 7*. https://doi.org/10.3389/fpsyg.2016.01997

Gomez, A., Piazza, M., Jobert, A., Dehaene-Lambertz, G., & Huron, C. (2017). Numerical abilities of school-age children with Developmental Coordination Disorder (DCD): A behavioral and eye-tracking study. *Human Movement Science, 55*, 315–326. https://doi.org/10.1016/j.humov.2016.08.008

Jeffries, S., & Everatt, J. (2004). Working memory: Its role in dyslexia and other specific learning difficulties. *Dyslexia, 10*(3), 196–214. https://doi.org/10.1002/dys.278

Kavale, K., & Mattson, P. D. (1983). "One jumped off the balance beam": Meta-analysis of perceptual-motor training. *Journal of Learning Disabilities, 16*(3), 165–173. https://doi.org/10.1177/002221948301600307

Knight, D., & Rizzuto, T. (1993). Relations for children in grades 2, 3, and 4 between balance skills and academic achievement. *Perceptual and Motor Skills, 76*, 1296–1298.

Kristensen, P. L., Moeller, N. C., Korsholm, L., Kolle, E., Wedderkopp, N., Froberg, K., & Andersen, L. B. (2010). The association between aerobic fitness and physical activity in children and adolescents: The European youth heart study. *European Journal of Applied Physiology, 110*(2), 267–275. https://doi.org/10.1007/s00421-010-1491-x

Lam, S. S. T., Au, R. K. C., Leung, H. W. H., & Li-Tsang, C. W. P. (2011). Chinese handwriting performance of primary school children with dyslexia. *Research in Developmental Disabilities, 32*(5), 1745–1756. https://doi.org/10.1016/j.ridd.2011.03.001

Logan, W. S., & Getchell, N. (2010). The relationship between motor skill proficiency and body mass index in children with and without dyslexia: A pilot study. *Research Quarterly for Exercise and Sport, 81*(4), 518–523. https://doi.org/10.1080/02701367.2010.10599713

Marchand-Krynski, M.-È., Morin-Moncet, O., Bélanger, A.-M., Beauchamp, M. H., & Leonard, G. (2017). Shared and differentiated motor skill impairments in children with dyslexia and/or attention deficit disorder: From simple to complex sequential coordination. *PLoS One, 12*(5), Article e0177490. https://doi.org/10.1371/journal.pone.0177490

Martínez-García, C., Afonso, O., Cuetos, F., & Suárez-Coalla, P. (2021). Handwriting production in Spanish children with dyslexia: Spelling or motor difficulties? *Reading and Writing, 34*(3), 565–593.

Martlew, M. (1992). Handwriting and spelling: Dyslexic children's abilities compared with children of the same chronological age and younger children of the same spelling level. *British Journal of Educational Psychology, 62*(3), 375–390. https://doi.org/10.1111/j.2044-8279.1992.tb01030.x

Meng, Z.-L., Wydell, T. N., & Bi, H.-Y. (2019). Visual-motor integration and reading Chinese in children with/without dyslexia. *Reading and Writing, 32*(2), 493–510. https://doi.org/10.1007/s11145-018-9876-z

Morano, M., Bortoli, L., Ruiz, M. C., Vitali, F., & Robazza, C. (2019). Self-efficacy and enjoyment of physical activity in children: Factorial validity of two pictorial scales. *PeerJ, 7*, Article e7402. https://doi.org/10.7717/peerj.7402

Nicolson, R. I., & Fawcett, A. J. (1990). Automaticity: A new framework for dyslexia research? *Cognition, 35*(2), 159–182. https://doi.org/10.1016/0010-0277(90)90013-A

Nicolson, R. I., & Fawcett, A. J. (1994). Comparison of deficits in cognitive and motor skills among children with dyslexia. *Annals of Dyslexia, 44*(1), 147–164. https://doi.org/10.1007/BF02648159

Nicolson, R. I., Fawcett, A. J., & Dean, P. (2001). Developmental dyslexia: The cerebellar deficit hypothesis. *Trends in Neurosciences, 24*(9), 508–511. https://doi.org/10.1016/S0166-2236(00)01896-8

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *International Journal of Surgery, 88*, Article 105906. https://doi.org/10.1186/s13643-021-01626-4

Pagliarini, E., Guasti, M. T., Toneatto, C., Granocchio, E., Riva, F., Sarti, D., … Stucchi, N. (2015). Dyslexic children fail to comply with the rhythmic constraints of handwriting. *Human Movement Science, 42*, 161–182. https://doi.org/10.1016/j.humov.2015.04.012

Peters, L., & Ansari, D. (2019). Are specific learning disorders truly specific, and are they disorders? *Trends in Neuroscience and Education, 17*, Article 100115. https://doi.org/10.1016/j.tine.2019.100115

Peterson, R. L., & Pennington, B. F. (2012). Developmental dyslexia. *The Lancet, 379*(9830), 1997–2007. https://doi.org/10.1016/s0140-6736(12)60198-6

R Core Team. (2017). R: A language and environment for statistical computing. In *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/.

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain, 126*(4), 841–865. https://doi.org/10.1093/brain/awg076

Razuk, M., & Barela, J. A. (2014). Dyslexic children suffer from less informative visual cues to control posture. *Research in Developmental Disabilities, 35*(9), 1988–1994. https://doi.org/10.1016/j.ridd.2014.03.045

Reynolds, D., & Nicolson, R. I. (2007). Follow-up of an exercise-based treatment for children with reading difficulties. *Dyslexia, 13*(2), 78–96. https://doi.org/10.1002/dys.331

Richlan, F., Kronbichler, M., & Wimmer, H. (2009). Functional abnormalities in the dyslexic brain: A quantitative meta-analysis of neuroimaging studies. *Human Brain Mapping, 30*(10), 3299–3308. https://doi.org/10.1002/hbm.20752

Rochelle, K. S., & Talcott, J. B. (2006). Impaired balance in developmental dyslexia? A meta-analysis of the contending evidence. *Journal of Child Psychology and Psychiatry, 47*(11), 1159–1166. https://doi.org/10.1111/j.1469-7610.2006.01641.x

Rochelle, K. S., Witton, C., & Talcott, J. B. (2009). Symptoms of hyperactivity and inattention can mediate deficits of postural stability in developmental dyslexia. *Experimental Brain Research, 192*, 627–633. https://doi.org/10.1007/s00221-008-1568-5

Ronconi, L., Melcher, D., & Franchin, L. (2020). Investigating the role of temporal processing in developmental dyslexia: Evidence for a specific deficit in rapid visual segmentation. *Psychonomic Bulletin & Review, 27*, 724–734. doi:10.3758%2Fs13423-020-01752-5.

Shaywitz, S. E., & Shaywitz, B. A. (2005). Dyslexia (specific reading disability). *Biological Psychiatry, 57*(11), 1301–1309. https://doi.org/10.1016/j.biopsych.2005.01.043

Son, S. H., & Meisels, S. J. (2006). The relationship of young children's motor skills to later reading and math achievement. *Merrill-Palmer Quarterly, 52*, 755–778.

Sovik, N., & Arntzen, O. (1986). A comparative study of the writing/spelling performances of "normal," dyslexic, and dysgraphic children. *European Journal of Special Needs Education, 1*(2), 85–101. https://doi.org/10.1080/0885625860010201

Stoodley, C. J., Fawcett, A. J., Nicolson, R. I., & Stein, J. F. (2005). Impaired balancing ability in dyslexic children. *Experimental Brain Research, 167*(3), 370–380. https://doi.org/10.1007/s00221-005-0042-x

Stoodley, C. J., & Stein, J. F. (2013). Cerebellar function in developmental dyslexia. *The Cerebellum, 12*(2), 267–276. https://doi.org/10.1007/s12311-012-0407-1

Sumner, E., Connelly, V., & Barnett, A. L. (2014). The influence of spelling ability on handwriting production: Children with and without dyslexia. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(5), 1441–1447. https://doi.org/10.1037/a0035785

Thompson, P. A., Hulme, C., Nash, H. M., Gooch, D., Hayiou-Thomas, E., & Snowling, M. J. (2015). Developmental dyslexia: Predicting individual risk. *Journal of Child Psychology and Psychiatry, 56*(9), 976–987. https://doi.org/10.1111/jcpp.12412

van de Walle de Ghelcke, A., Skoura, X., Edwards, M. G., Quercia, P., & Papaxanthis, C. (2021). Action representation deficits in adolescents with developmental dyslexia. *Journal of Neuropsychology, 15*(2), 215–234. https://doi.org/10.1111/jnp.12220

van der Mark, S., Klaver, P., Bucher, K., Maurer, U., Schulz, E., Brem, S., … Brandeis, D. (2011). The left occipitotemporal system in reading: Disruption of focal fMRI connectivity to left inferior frontal and inferior parietal language areas in children with dyslexia. *NeuroImage, 54*(3), 2426–2436. https://doi.org/10.1016/j.neuroimage.2010.10.002

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software, 36*(3). https://doi.org/10.18637/jss.v036.i03

Vieira, S., Quercia, P., Michel, C., Pozzo, T., & Bonnetblanc, F. (2009). Cognitive demands impair postural control in developmental dyslexia: A negative effect that can be compensated. *Neuroscience Letters, 462*(2), 125–129. https://doi.org/10.1016/j.neulet.2009.06.093

Vitali, F., Robazza, C., Bortoli, L., Bertinato, L., Schena, F., & Lanza, M. (2019). Enhancing fitness, enjoyment, and physical self-efficacy in primary school children: A DEDIPAC naturalistic study. *PeerJ, 7*, Article e6436. https://doi.org/10.7717/peerj.6436

Westendorp, M., Hartman, E., Houwen, S., Huijgen, B. C. H., Smith, J., & Visscher, C. (2014). A longitudinal study on gross motor development in children with learning disorders. *Research in Developmental Disabilities, 35*(2), 357–363. https://doi.org/10.1016/j.ridd.2013.11.018

White, S., Milne, E., Rosen, S., Hansen, P., Swettenham, J., Frith, U., & Ramus, F. (2006). The role of sensorimotor impairments in dyslexia: A multiple case study of dyslexic children. *Developmental Science, 9*(3), 237–255. https://doi.org/10.1111/j.1467-7687.2006.00483.x

Wu, C. Y., & Hwang, S. (2022). Visual occlusion effects on bipedal stance control in Chinese-speaking children with dyslexia. *Neuroscience Letters, 782*, Article 136678. https://doi.org/10.1016/j.neulet.2022.136678

Yang, Y., & Hong-Yan, B. (2011). Unilateral implicit motor learning deficit in developmental dyslexia. *International Journal of Psychology, 46*(1), 1–8. https://doi.org/10.1080/00207594.2010.509800