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Binocular coordination of children with dyslexia and typically developing children in linguistic and non-linguistic tasks: evidence from eye movements

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Abstract

Given the increased evidence suggesting the presence of binocular coordination deficits in dyslexia, investigations of binocular eye movements are beneficial to clarify the underlying causes of reading difficulties. This systematic review aims to (a) synthesize the literature through the examination of binocular coordination in children with dyslexia by describing the normative development of stable binocular control and (b) outline future directions. Boolean expressions in the PubMed search were used to define papers. Following a literature search and selection process, 25 papers were included. Studies using binocular eye tracking during linguistic and nonlinguistic tasks in children with dyslexia and typical development 5–17 years of age are reviewed. The studies reviewed provided consistent evidence of poor binocular coordination in children with dyslexia, but the results associated with different task characteristics were less consistent. The relation between binocular coordination deficits and reading difficulties needs to be further elucidated in longitudinal studies which may provide future treatments targeting the binocular viewing system in dyslexia.

Highlights

- Binocular oculomotor control of eye movements in children with dyslexia diverges from the normal developmental pattern.
- Normal development of binocular control changes in different age groups.
- Future eye-tracking research investigating the binocular coordination of children with dyslexia should address the etiology of dyslexia using longitudinal design with large samples involving wide age range.

Keywords Binocular coordination · Children · Dyslexia · Eye movements · Eye-tracking

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Introduction

Definition and etiological theories of dyslexia

Dyslexia is characterized by impairment in reading that has persisted at least 6 months despite adequate opportunity for learning or appropriate institutional support. It is also known as reading disorder, and affects academic skills which are substantially and quantifiably below those expected for the individual's chronological age (American Psychiatric Association, 2013). It is the most common specific learning disorder, affecting around 5–17.5% of the population (Shaywitz & Shaywitz, 2005). First described as reading difficulty in 1887 (Berlin, 1887), dyslexia has been investigated for many years, yet the origin of dyslexia is still a topic of debate and many theories have been proposed.

Since reading requires many visual, auditory, and attentional processes, researchers have suggested diverse hypotheses for the etiology of dyslexia. Dyslexia was primarily explained by the Phonological Theory proposing that deficits in representation, storage, and/or retrieval of speech sounds could lead to reading disabilities (Snowling, 1998). An alternative to traditional explanations regarding the role of phonology in reading is the Self-teaching Theory. According to this theory, phonological recoding (print-to-sound translation) performs a self-teaching function that enables the acquisition of detailed orthographic representations necessary for fast, efficient visual word recognition (Share, 1995). One challenge to these etiological models related to phonological processing arises from the fact that single deficits in phonological processing are unlikely to fully account for dyslexia and that speed of processing impairments are an additional risk factor for dyslexia (Catts et al., 2002; Wimmer, 1993). In line with these ideas, some authors have suggested that deficits in the processes underlying the rapid recognition and retrieval of visually presented linguistic stimuli exist in dyslexia and proposed the Double-deficit Theory, in which the phonological deficits and naming-speed deficits represent two separable sources of dyslexia (Wolf & Bowers, 1999). On the other hand, some investigators claimed that sensorimotor deficits and learning difficulties affected phonological performance and reading ability. The visual theory represented a traditional perspective of dyslexia suggesting that visual impairments including poor vergence problems and binocular vision abnormalities cause difficulties in recognizing letters and words while reading (Lovegrove et al., 1980). The Crowding Theory has stressed the role of visual perceptual deficits, claiming that visual crowding causes reading difficulties affecting the oculomotor control (Gori & Facoetti, 2015). Another notion, the Cerebellar Theory has argued that dysfunction of the cerebellum which plays a crucial role in motor coordination, timing, and automatization of reading is responsible for dyslexia (Nicolson et al., 2001). Finally, an integration of these hypotheses, the Magnocellular Theory, has stated that the main underlying cause of dyslexia is abnormality in the oculomotor system, involving magno cells and related pathways for visual and other sensorimotor and phonological processes, and motor learning (Stein, 2001).

To gain further understanding of the etiology of dyslexia, investigations have focused on eye movements to clarify the relation between visual processing abnormalities and reading disabilities in children with dyslexia. A number of eye-tracking studies have examined different characteristics of eye movements, including low level of visuomotor control and other measurements. Although the majority of researchers record from only one of the eyes, a growing body of literature currently explores the binocular coordination of eye movements to investigate visual and oculomotor functions in dyslexia.

Binocular coordination of eye movements: normative and atypical development

Saccades, vergence, and combined saccade-vergence movements occur during visual processing. Saccades are defined as rapid eye movements used to bring visual information onto the fovea, shifting eyes to the target (Duchowski & Duchowski, 2017). They are conjugate eye movements in which the two eyes move in the same direction (Liversedge et al., 2011). Vergence movements serve to change fixation point to the target in depth, aligning the fovea of two eyes with targets at different distances. These movements are disconjugate (in opposite direction in the two eyes), involving either a convergence or divergence of the two eyes to project the line of sight onto the object that is nearer or farther away. Combined saccade-vergence eye movements are frequently made when looking at objects requires the shifts of gaze both in direction and in depth (Liversedge et al., 2011; Purves et al., 2001) (Table 1).

Fixations are eye movements that stabilize the retina over a stationary object of interest (Duchowski & Duchowski, 2017). During visual fixation, small eye movements such as microsaccades, drift, and tremor change the gaze position (Martinez-Conde & Macknik, 2015). Discordance between the two eyes' positions during these motions may cause diplopia (double vision). Therefore, correct coordination between the eyes during gaze fixation is crucial for stable perception. In other words, fine binocular coordination of each fixational eye movement provides a single fusion by reducing binocular disparity (Otero-Millan et al., 2014).

As discussed in the nineteenth century, authors proposed different mechanisms for binocular coordination. First, von Helmholtz (1925) stated that this coordination is a learned process based on separate neural control of each eye. On the other hand, Hering (1977) suggested that the two eyes are inherently reined to each other and innervated by common neural commands. According to Hering's Law of Equal Innervation, while shifting fixations between two positions, the two eyes move equally in the same direction (version or saccadic component) or in opposite directions (vergence component). Nevertheless, subsequent research provided contrasting evidence, indicating asymmetries of eye movements between the two eyes (e.g., Collewijn et al., 1988; Ghassemi & Kapoula, 2013; Heller & Radach, 1999; Kapoula et al., 1986; Munoz et al., 1998).

Table 1 Definitions of eye-tracking measures

Measures	Definition
Saccade	Rapid eye movement between two consecutive fixations in the same direction (conjugate)
Vergence	Simultaneous movement of both eyes in opposite directions to obtain or maintain single binocular vision (disconjugate)
Convergence	Inward movement of both eyes toward each other (adduction)
Divergence	Outward movement of both eyes away from each other (abduction)
Fixation	Relatively stable state of eye movement between two saccades
Microsaccade	Small, jerk-like, straight and fast eye movement
Drift	Curvy, slow movements
Tremor	Small, quick, synchronized oscillations superimposed on drifts
Saccadic disconjugacy	Difference between saccade amplitude of right and left eyes
Post-saccadic disconjugacy	Difference between drift amplitude of right and left eyes

Saccadic and vergence movements have distinct anatomic and physiological characteristics, yet they generally co-occur simultaneously during in daily life circumstances (Bucci et al., 2009). The eyes converge at the end of the saccades and diverge during the saccades. The adducting eye (nasally directed) drifts in the same direction of the preceding saccades while the abducting eye (temporally directed) moves in the opposite direction immediately after the saccades, resulting in disconjugacy at the end of the saccades (Collewijn et al., 1988; Kapoula et al., 1986). Although this saccadic disconjugacy was thought to prevent fused single binocular vision, Collewijn et al. (1997) showed that the disconjugacy of saccades originate from the asymmetry between abducting and adducting saccadic movements that is found in the large majority of subjects with normal binocular functioning (Collewijn et al., 1997). Later researches have also suggested that the abducting eye makes a larger and faster movement than the adducting eye at the beginning of the saccade that causes the postsaccadic disconjugate drifts during fixations in normal development (e.g., Heller & Radach, 1999; Munoz et al., 1998; Yang & Kapoula, 2003).

Studies comparing binocular coordination in children and adults showed that binocular coordination of saccades and the quality of binocular alignment during fixation were poorer in children than adults indicating larger disconjugacies of saccades and post-saccadic drifts (Blythe et al., 2006; Fioravanti et al., 1995). These findings were later confirmed by a study conducted in different age groups of typically developing children indicating that disconjugacies decrease with age (Yang & Kapoula, 2003). Additionally, increased disconjugacies were more pronounced in children with dyslexia compared with chronologically age-matched controls (Bucci et al., 2012; Ghassemi & Kapoula, 2013; Jainta & Kapoula, 2011; Kapoula et al., 2009). Put another way, poor binocular coordination is generally observed in typically developing young children as well as in children with dyslexia.

Binocular coordination in children with dyslexia: nonlinguistic and linguistic tasks

A number of eye-tracking studies on binocular coordination during nonlinguistic tasks in children with dyslexia have indicated fixation instability, poor vergence control, and increased binocular disconjugacy of saccadic and postsaccadic drifts (e.g., Bednarek et al., 2006; Bucci et al., 2008a; Fowler et al., 1988). Researchers have conducted tracking tasks to stimulate and elicit visually guided saccades and visual recognition tasks on the basis of the magnocellular system and visuo-spatial attention process.

Reading is a complex process based on linguistic and visuo-attentional capacities and requires good performance of oculomotor behaviors. During reading, both eyes make saccadic movements to reach, fixations to read, and vergence movements to see clearly (Seassau & Bucci, 2013). Since assessments of binocular performance during reading would provide crucial evidence for the etiology of dyslexia, many researchers have investigated binocular coordination of eye movements in children with dyslexia while word reading (e.g., Cornelissen et al., 1992, 1993; Jiménez et al., 2020), sentence reading (Blythe et al., 2006), and text reading (Goulème et al., 2018; Jainta & Kapoula, 2011) considered to provide an approximate view of natural reading characteristics. Similar to nonlinguistic tasks, larger saccade disconjugacy and postsaccadic drifts were observed during linguistic tasks in children with dyslexia (Jainta & Kapoula, 2011; Jiménez et al., 2020).

In light of the above considerations, the aims of the current review are to (a) examine the literature on binocular coordination of eye movements during linguistic and non-linguistic tasks in children with dyslexia, (b) present a concise overview of binocular coordination in typically developing population from a developmental perspective, and (c) discuss the outcomes of mentioned studies on the basis of etiological theories by suggesting future directions.

Method

A literature search was conducted using Medline-PubMed. To identify papers, Boolean expressions were used, as follows: (binocular eye OR binocular coordination OR binocular control) AND (child*) AND ((dyslexi* OR reading difficult* OR reading disabilit* OR reading disorder) OR (normal OR typical OR control)). The search yielded a total of 1097 articles, which were screened to eliminate review papers, posters, presentations, theses, or book chapters.

Abstracts and full text articles were screened independently by two investigators to determine if they met these inclusion criteria: (a) published in English in a peer-reviewed journal, (b) lab-based studies (eye-tracking), (c) included a population of children, (d) included participants with normal development and dyslexia, and (e) presented binocular coordination of eye movements. Exclusion criteria were (a) case studies, (b) review papers, and (c) treatment studies. Studies including children with eye diseases, such as amblyopia, strabismus, and nystagmus, neurologic diseases, such as cerebral palsy and Friedreich's ataxia, other psychiatric disorders, such as attention deficit hyperactivity disorder, autism spectrum disorder, and developmental delay, and other diseases, such as deafness and familial adenomatous polyposis, were also excluded. This comprehensive review resulted in 25 papers, published between 1988 and 2020. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009) guidelines were used to determine study inclusion (see Fig. 1).

Results

Studies investigating binocular coordination in children with normal development and dyslexia were grouped by type of tasks described as nonlinguistic and linguistic, either separately or together and summarized in Tables 2, 3, and 4.

Binocular coordination during nonlinguistic tasks

Over the past 4 decades, researchers have indicated oculomotor abnormalities in dyslexia. The first evidence was reported in the 1980s by Pavlidis (1981) who demonstrated erratic eye movements (frequent regressive saccades and unstable fixation pattern) during tracking tasks in children with dyslexia. Pavlidis suggested that reading difficulties in these children resulted from abnormal eye movements. Nevertheless, subsequent studies failed to confirm Pavlidis's suggestions, stating that no abnormal tracking eye movements were found in children with dyslexia (Fischer & Weber, 1990). In contrast, Biscaldi et al., (1994, 1998) found shorter mean latencies and more express saccades (saccades with extremely short reaction times) in adolescents with dyslexia than in those with normal development. Other studies confirmed these findings, indicating more premature saccades and express latencies in children with dyslexia (Bednarek et al., 2006; Bucci et al., 2008a). Besides these findings, increased numbers of intrusive saccades were also reported in this group (Fischer & Hartnegg, 2000). These findings could be attributed to poor fixation control as a

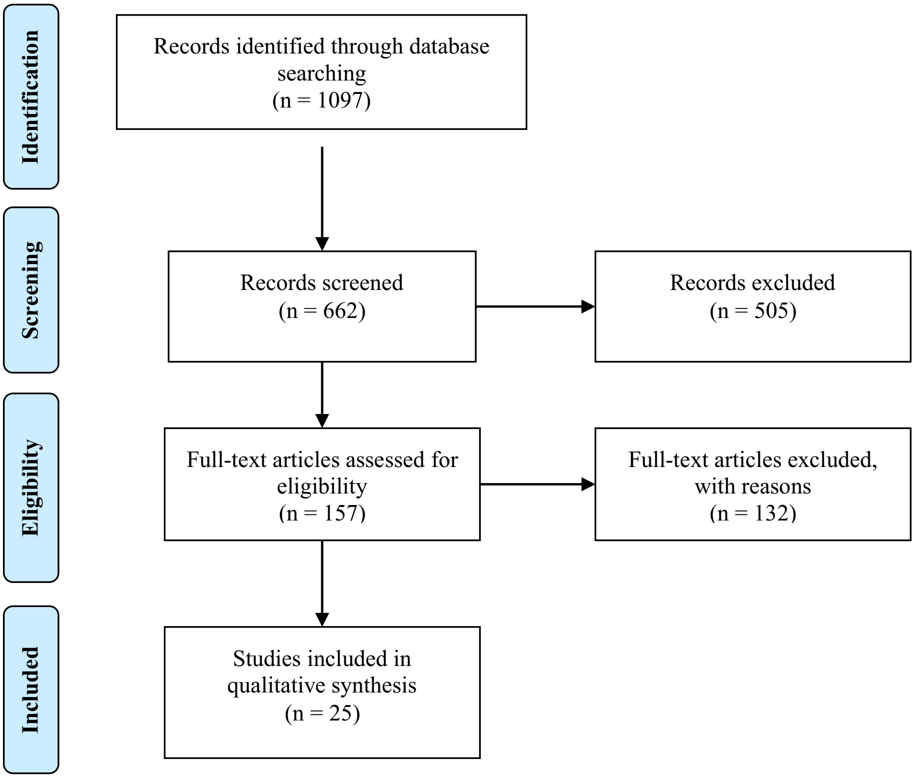

Fig. 1 PRISMA flow diagram for article selection

manifestation of the immaturity and/or deficiency of the visuo-spatial attention process and magnocellular system in dyslexia (Bednarek et al., 2006; Biscaldi et al., 1994, 1998; Bucci et al., 2008a). Apart from the above findings, a more recent study reported similar eye movements in terms of velocity and accuracy in children with dyslexia and controls, suggesting no dysfunction of ocular motor circuits in dyslexia (Bucci et al., 2009).

In addition to all these studies examining monocular eye movements, Stein and Fowler (1981) suggested that children with dyslexia failed to achieve stable binocular control. They identified “visual dyslexia” as a subgroup of these children who had difficulties with binocular integration. They presented binocular fixation instability among those with visual dyslexia using the Dunlop test (Dunlop et al., 1973), and suggested that poor binocular control of vergence eye movements might result in reading difficulties (Stein & Fowler, 1993). Fowler et al. (1988) measured binocular eye movements during a dot localization task in primary school children. They reported that children with dyslexia who had low fixation stability in the Dunlop test made more localization errors, a significantly greater number of inappropriate saccades, and larger amplitude than those made by nondyslexic children with stable binocular control. The same group (Stein et al., 1988) conducted another study and demonstrated that unstable children with dyslexia on the Dunlop test had reduced amplitudes of vergence eye movements whereas stable children with dyslexia and typical readers showed normal vergence responses to moving fusion stimuli. Stein et al. (2000) subsequently indicated that monocular occlusion might help children with dyslexia

Table 2 Binocular coordination of eye movements during nonlinguistic tasks

Authors	Subjects	Age	Eye movement measurement	Main findings
Fowler et al. (1988)	10 dyslexics, 10 controls	7–10 years	Number and amplitude of saccades	Poor fixation stability in dyslexics
Stein et al. (1988)	39 dyslexics (24 unstable, 15 stable DT), 24 controls	8–11 years	Amplitude of vergence	Disordered vergence control in unstable dyslexics
Eden et al. (1994)	26 dyslexics, 12 backward readers, 39 controls	10–12 years	Fixation stability, vergence amplitude and saccades	Binocular instability in dyslexics and backward readers
Fioravanti et al. (1995)	12 typical children, 4 typical adults	5–13 years 25–39 years	Saccade amplitude, duration and peak velocity and post-saccadic drifts	Increased disconjugacy of saccades and post-saccadic drifts in children
Fischer and Hartnegg (2000)	262 dyslexics,99 controls	7–17 years	Number of saccades	Increased number of saccades in dyslexics
Yang and Kapoula (2003)	14 typical children, 10 typical adults	5–12 years 22–44 years	Amplitude of saccade, and postsaccadic drift	Increased disconjugacy of saccades and post-saccadic drifts in children
Bucci et al. (2008a)	16 dyslexics, 14 controls	10–13 years	Latency of saccades, vergence, combined movements and vergence amplitude	Increased saccadic latency, reduced vergence amplitude in dyslexics
Kapoula et al. (2009)	15 dyslexics, 8 controls; 7 adults	9–12 years 21–27 years	Amplitude of saccades and postsaccadic drifts	Increased disconjugacy of saccades and drifts in dyslexics
Bucci and Seassau (2014)	69 typical children	6–15 years	Number, latency, and velocity of vertical saccades and vergence amplitude	Increased latency of vertical saccades in young children
Tiadi et al. (2014)	56 dyslexics, 56 controls	10–12 years	Latency and velocity of vertical saccades and vergence amplitude	Increased latency, reduced velocity of saccades, and reduced vergence amplitude in dyslexics
Tiadi et al. (2016)	55 dyslexics, 110 controls (55 chronological and 55 reading age-matched)	7–14 years	Number of saccades	Increased number of unwanted saccades in dyslexics

Table 3 Binocular coordination of eye movements during linguistic tasks

Authors	Subjects	Age	Eye movement measurement	Main findings
Corneliessen et al. (1992)	32 children failed and 32 children passed Dunlop test	7–14 years	Number of word and nonword errors	Increased number of non-word errors under binocular viewing in Dunlop-failed children
Cornelissen et al. (1993)	20 typical children, 10 typical adults	9–11 years 24–36 years	Fixation vergence error and amplitude of saccade	Increased vergence instability in children
Blythe et al. (2006)	12 typical children, 12 typical adults	7–11 years 18–21 years	Fixation disparity	Poor binocular control in children
Jainta and Kapoula (2011)	13 dyslexics, 7 controls	8–13 years	Amplitude of disconjugate saccades and postsaccadic drifts, fixation disparity	Increased saccade disconjugacy and disconjugate drifts in dyslexics
Seassau and Bucci (2013)	69 typical children, 10 typical adults	6–15 years 24–39 years	Number and amplitude of saccades and amplitude of disconjugate saccades and postsaccadic drifts	Increased disconjugacy of saccades and drifts in children
Goulème et al. (2018)	36 dyslexics, 36 controls	7–13 years	Vertical and horizontal amplitudes of saccades and fixations	Increased vertical disconjugacy in dyslexics
Jiménez et al. (2020)	58 dyslexics, 58 controls	6–10 years	Latency of vergence response	Increased latency and amplitude of vergence response

Table 4 Binocular coordination of eye movements during both nonlinguistic and linguistic tasks

Authors	Subjects	Age	Eye movement measurement	Main findings
Lennerstrand et al. (1993)	86 dyslexics, 86 controls	9 years	Amplitude of saccades and disconjugate saccades	Larger amplitude of saccades, higher saccadic asymmetry in dyslexics
Bucci and Kapoula (2006)	8 typical children, 8 typical adults	7 years 24 years	Amplitude and velocity of saccades and post-saccadic drifts	Increased saccade disconjugacy and disconjugate drifts in children
Prado et al. (2007)	10 dyslexics, 10 controls	7–10 years	Number and amplitude of saccades	Poor fixation stability in dyslexics
Bucci et al. (2008b)	18 dyslexics, 13 controls	9–13 years	Saccades and post-saccadic drifts	Increased disconjugacy of saccades and drifts in dyslexics
Kirkby et al. (2011)	8 dyslexics, 8 controls; 11 adults	9–12 years 20–27 years	Amplitude of saccades, fixation disparity	Increased amplitude of saccades and fixational disparity in dyslexics
Bucci et al. (2012)	12 dyslexics, 19 controls (9 chronological and 10 reading age-matched)	7–12 years	Number and amplitude of saccades and amplitude of disconjugate saccades and postsaccadic drifts	Increased disconjugacy of saccades and drifts in dyslexics
Seassau et al. (2014)	43 dyslexics, 42 controls	8–13 years	Number and amplitude of saccades and amplitude of disconjugate saccades and postsaccadic drifts	Increased disconjugacy of saccades and drifts in dyslexics

to gain stable binocular control and improve their reading skill, and thus, it could be an effective treatment for the vast majority of dyslexic subjects, known as having "visual dyslexia."

In accordance with the studies of Stein et al. (1988, 2000), Eden and colleagues (1994) investigated binocular viewing during visual tasks including fixation and tracking, claiming that the abnormal eye movements observed in children with dyslexia could be attributed to language problems. According to their findings, children with dyslexia had lower vergence amplitudes and worse fixation stability than children with normal development. Moreover, children with dyslexia exhibited poor performance when pursuing targets. The deficiencies were observed in all children with dyslexia independent of their language ability. However, the backward-reading children performed similarly to children with dyslexia in terms of eye movement behaviors. Thus, Eden et al. concluded that the underlying deficit in the binocular control of eye movements might not be specific to children with dyslexia and might not be caused by language problems alone.

First examinations of developmental trends in binocular coordination were reported by Fioravanti et al. (1995) who indicated poor saccadic control in school-age children. They found larger disconjugacy of saccades and postsaccadic drifts in the youngest children than in older children and adults. Further investigation showed deficient binocular control in children (5–12 years old) when compared to adults (22–44 years old) during nonlinguistic tasks (Light-Emitting Diode-LED fixation) showing that saccade disconjugacy was more severe at near rather than far distances (Yang & Kapoula, 2003). The authors concluded that because of the immaturity of saccade-vergence interaction, children had difficulties tailoring the saccade commands with their eyes converged at close viewing to maintain the large convergence angle during saccades and fixations.

Binocular coordination of saccades during nonlinguistic tasks in dyslexia was studied by Kapoula et al. (2009) who designed two tasks: (a) tracking a single target as a control condition and (b) exploring paintings spontaneously as an experimental condition. They reported that children with dyslexia had more disconjugacy levels of saccades and postsaccadic drifts than controls in both conditions. Additionally, divergent disconjugacy of saccades and convergent drift during fixation were correlated in nondyslexic children, as evidence for stereotyped pattern in which postsaccadic disconjugacy occurred during fixation to reduce saccadic disconjugacy, yet children with dyslexia did not show this pattern. Kapoula et al.'s study revealed that binocular coordination disabilities were related to an intrinsic physiological problem, independent of the process of reading in children with dyslexia.

Regarding the interaction between saccade and vergence systems during combined eye movements, vergence dysfunctions would also be expected related to the binocular coordination deficits in dyslexia. From this point of view, Bucci and her colleagues (Bucci et al., 2008a) recorded pure saccades at far and near distances, pure vergence, and also combined eye movements by using spatial and temporal paradigms. They found more express latencies for all eye movements in children with dyslexia, and also longer latencies for saccades (pure and combined) at far versus near distances in children with dyslexia. These findings could indicate difficulties in the transition between vergence and saccade initiations and deficits in visual attention functions among these children. In addition, according to orthophoric evaluation of vergence fusion abilities, children with dyslexia had reduced amplitude of divergence and convergence, indicating vergence disabilities (Bucci et al., 2008a) which were also supported by further studies (Bucci et al., 2008b; Seassau et al., 2014).

In addition to these studies examining horizontal eye movements, there are also a few studies that investigated saccades in the vertical plane (Bucci & Seassau, 2014; Tiadi et al., 2014, 2016). Bucci and Seassau explored the development of vertical saccades in typically developing children 6–15 years of age. According to their findings, latencies of vertical saccades decreased with the age of children parallel with the development of the cortical networks involved in saccade preparation, although the gain and peak velocity values of vertical saccades were stable during childhood indicating that the cerebellum and brainstem structures were well developed early (Bucci & Seassau, 2014). As for studies in dyslexia, Tiadi et al. (2014) conducted an oculomotor paradigm to elicit vertical saccades, showing that children with dyslexia made more anticipatory and express saccades than non-dyslexic children. They reported that the dyslexic group had significantly longer latency of saccades which could arise from visuo-attention deficits and slower velocity of saccades which could be related to impairment of extraocular muscles and/or immaturity of cortical structures that control eye movements. Also, smaller convergence and divergence amplitudes were found in children with dyslexia, showing reduced vergence capacities (Tiadi et al., 2014).

In accordance with the previous findings, Tiadi et al. (2016) found that children with dyslexia had significantly higher numbers of unwanted saccades and more saccades toward the end of fixation periods than both groups of nondyslexic children. In addition, non-dyslexic children had fewer unwanted saccades as their age increased, while developmental changes in saccade performance were not observed in children with dyslexia. On the basis of this evidence, Tiadi and colleagues concluded that visual fixation incapability in children with dyslexia could result from impaired attention abilities and an immaturity of the cortical areas.

Binocular coordination during linguistic tasks

During the 1990s, researchers claimed that atypical development of eye dominance is related to the capability to maintain a steady fixation as well as affecting reading ability. Corneliessen et al. (1992) investigated the effect of unstable binocular control on reading among children who failed the Dunlop test which was used as a reference eye test to assess the stability of ocular dominance and vergence capabilities. Children were asked to read single words with both eyes open and with one eye occluded. They found that children made fewer nonword reading errors under monocular viewing when compared to binocular viewing conditions. They suggested that failure to fuse two disparate retinal inputs caused visual confusion and led to reading errors. As a consequence of these results, it could be interpreted that children with reading difficulties could benefit from monocular occlusion (Cornelissen et al., 1992), as confirmed by further investigations (Stein et al., 2000).

In a follow-up study, Cornelissen et al. (1993) recorded children's and adult readers' binocular eye movements while reading single words. First, they indicated that adults had smaller disparity magnitudes of fixations (vergence errors) than children at 9–11 years of age. In addition, no difference in the disparity values was found between two groups of children, children with dyslexia and controls, who had unstable and stable binocular control based on the assessments using the Dunlop test. They concluded that vergence control during reading fixations was not directly related to reading difficulties (Cornelissen et al., 1993).

In the later years, some investigators aimed to compare binocular oculomotor control abilities during reading in different developmental stages (Blythe et al., 2006; Fioravanti et al., 1995; Seassau & Bucci, 2013; Yang & Kapoula, 2003). Blythe et al. recorded binocular eye movements in children and adults while reading sentences. They reported greater disparity magnitudes in children (7–11 years) than in adults (18–21 years). Children tended to make divergent movements during fixations, whereas adults had convergent movements which were usually considered corrective for the residual disparity from the preceding saccade. All in all, they suggested that children had immature binocular control and poor binocular alignment which improved with age (Blythe et al., 2006), providing support for a developmental perspective of binocular control as indicated by other studies (Fioravanti et al., 1995; Seassau & Bucci, 2013; Yang & Kapoula, 2003).

In 2011, Jainta and Kapoula suggested that the disparity between fixation points of the two eyes while reading would negatively impact binocular coordination. They examined saccades and vergence control during text reading in children with dyslexia and compared them with same-aged controls. Larger saccade disconjugacy and postsaccadic drifts were observed in children with dyslexia, with no correlations between them. As a result, they concluded that visuomotor imperfections might lead to fixation instability and thus, perturbations in fusional process might complicate letter/word identification, resulting in reading difficulties (Jainta & Kapoula, 2011).

A recent study by Jiménez et al. (2020) confirmed these results by indicating poor vergence responses to a word detection task among children with dyslexia. Longer latencies and lower amplitudes of vergence movements were detected in children with dyslexia versus the control group, which might support the attention deficiencies in the etiology of dyslexia (Jiménez et al., 2020). However, a substantial body of research has explored binocular horizontal eye movements. Recent evidence by Goulème et al. (2018) suggests that vertical movements also play a crucial role in identifying letters or words and changing lines during text reading. Goulème et al. measured disconjugacies both in horizontal and vertical planes in children with dyslexia versus controls. There was no difference between the two groups in terms of horizontal disconjugacies during both saccades and fixations. Children with dyslexia had larger vertical disconjugacies than controls, only for postsaccadic drifts, not for saccades. In addition, no effect of reading age on disconjugacies in either plane was found, similar to the study by Seassau et al. (2014) who showed no effects of age on horizontal disconjugacies. Poor binocular vertical coordination during postsaccadic fixations in which the recognizing and understanding the processing of words occurred during text reading could be due to impaired visuo-attentional abilities.

Binocular coordination during linguistic and nonlinguistic tasks

Several studies (e.g., Bucci et al., 2008b, 2012; Ghassemi & Kapoula, 2013; Prado et al., 2007) have investigated binocular coordination in children with dyslexia during both reading and nonreading tasks, and aimed to present differences between these conditions and reveal the causes and consequences of dyslexia.

Lennerstrand et al. (1993) conducted a study to compare binocular control of eye movements between children with dyslexia and controls (mean age 9 years) using tracking and reading tasks. They reported larger saccadic movements during tracking and higher saccadic asymmetries between two eyes in the dyslexic group. Similarly, Prado et al. (2007) examined the binocular eye movements of children with dyslexia during reading a text and visual searching, and compared them with nondyslexic readers. Children with dyslexia processed the same low number of letters in both letter search and reading conditions, whereas the nondyslexic subjects tended to fixate far more letters in reading than in searching. This finding could be interpreted as visual attentional difficulties perhaps affecting both reading and visual searching in dyslexic readers and similar fixation pattern was observed in reading and nonreading conditions for children with reading incapability (Prado et al., 2007).

Comparable results were reported by Bucci et al. (2008a) who examined horizontal saccades and postsaccadic drifts in LED tracking and single-word reading tasks. They showed poor quality of binocular coordination during and after the saccades regardless of the conditions. For both tasks, children with dyslexia (mean age 11 years) had larger saccade disconjugacies as well as larger disconjugate drifts controls (mean age 12 years). The negative correlation between disconjugacy of saccade and post-saccadic drift amplitudes was found in the control group, while no relation was found in the dyslexic group, indicating deficient binocular coordination. Vergence amplitude changes were larger and more variable in children with dyslexia than in controls. Conjugate postsaccadic drifts, measured from the mean amplitude of right eye and left eye, were larger in children with dyslexia compared to the control group. The dyslexic group had higher variability in conjugate components of fixation and more corrective saccades, which indicates the difficulty to maintain the optimal position of two eyes, namely fixation instability. Consequently, vergence abnormalities accompanying poor binocular coordination of saccades in dyslexia might indicate visual processing difficulties, involving both visuo-attentional and oculomotor systems. Saccade-vergence interaction deficits could be related to the impaired or/and immature oculomotor learning systems, involving the magnocellular pathway (parietal cortex) and the cerebellum (Bucci et al., 2008b).

Another study conducted by Bucci et al. (2012) confirmed task-independent binocular coordination deficits in children with dyslexia who were compared with chronological age-matched (mean age 11 years) and reading age-matched (mean age 8 years) control groups during both visual search and text reading tasks. Chronological age-matched nondyslexic children had smaller disconjugacies during and after the saccades compared with others. Children with dyslexia had similar binocular coordination and fixation patterns as reading age-matched nondyslexic children. Additionally, similar oculomotor characteristics were found in terms of both conditions for children with reading incapability, while children with adequate reading skills had different fixation patterns in the reading and visual search conditions. Interpretation of this finding may indicate that searching is required to identify and count the letters in the words which could be more difficult than reading, and that skipping letters could be more possible because of a well-developed linguistic process. Based on all findings from the studies discussed, the magnocellular pathway and oculomotor learning systems as well as visual-attentional processing seem to be affected in dyslexia (Bucci et al., 2012).

In accordance with these studies, Ghassemi and Kapoula (2013) also presented high disconjugacy of saccades and postsaccadic drifts during both text reading and letter recognition tasks in the dyslexic group (mean age 11 years). They also found that oculomotor deficits did not change according to depth (i.e., near and far distances). These results clearly demonstrate that binocular coordination deficits are more generalized in this disorder and related to magnocellular and cerebellar deficits independent from reading (Ghassemi & Kapoula, 2013).

On the contrary, task-dependent results were reported in different studies. Heller and Radach (1999) stated that larger disconjugacies were observed during reading. Kirkby et al. (2011) showed increased fixation disparity only in a reading task, not in a dot scanning task in children with dyslexia aged 9–12 years. They concluded that poor binocular coordination could result from attentional processing and/or cognitive performance deficits which manifest as reading difficulties. In other words, reading impairment causes binocular saccadic control disability and fixation instability. Kirkby and colleagues set out an argument against the magnocellular theory, and claimed that a deficiency in high-level cognitive processing could be responsible for dyslexia (Kirkby et al., 2011).

In a developmental study, Bucci and Kapoula (2006) examined saccade and fixation characteristics during single-word reading and target fixation. They found larger disconjugacy of saccades and postsaccadic drifts in children (mean age 7 years) compared to adults during both tasks. In addition, binocular coordination of both groups did not depend on the condition. A more recent study by Seassau and Bucci (2013) also presented important results in the typical population involving children (aged 6 to 15 years) and adults (aged 24 to 39 years). According to this study, there was a significant association between age and disconjugacy of saccades as well as postsaccadic drifts in both reading and visual search tasks, and disconjugacy decreased with age. Older children (after 10 years of age) and adults had different eye movements regarding the two conditions, whereas similar oculomotor patterns were observed among young children. It could be said that because the two tasks required different cognitive processes, eye movement characteristics would differ across the two tasks, in relation to improvements in binocular control. In other words, task-dependent changes were observed among older subjects who had mature binocular function, unlike younger subjects with poor binocular performance (Seassau & Bucci, 2013).

In another study investigating developmental aspects of binocular coordination in typical readers and children with dyslexia aged 8 to 13 years, Seassau et al. (2014) indicated poor saccadic control and vergence capabilities in dyslexia. Disconjugacy during and after the saccades were larger in children with dyslexia than typical children during both reading and visual search tasks. No task and age effects were found in terms of saccade disconjugacy. Age effects on disconjugacy after the saccades were found only in the reading task for both groups; however, no relation was found in the visual search task. Children with dyslexia had smaller amplitudes of convergence and divergence compared to typical readers. There was a correlation between saccade disconjugacy and convergence values in the control group, while no relation was found in the dyslexic group, which could be explained by the immaturity of saccade-vergence interaction in dyslexia (Seassau et al., 2014).

Discussion

The aim of the present review is to provide a comprehensive evaluation of the literature on binocular coordination in children with dyslexia and typically developing children. In this context, studies examining binocular eye movements in linguistic and nonlinguistic tasks in children with dyslexia and developmental aspects of binocular control in children with normal development are discussed, and the arguments, findings, and conclusions are presented in terms of the etiological theories of dyslexia.

Developmental studies have provided a reference for the normal development of binocular control suggesting that binocular coordination improves with age and achieves adult levels by early adolescence (Blythe et al., 2006; Fioravanti et al., 1995; Yang & Kapoula, 2003). With the studies applying oculomotor tasks in mind, it may be assumed that children are incapable of fine binocular coordination due to the poor compensation of mechanical asymmetries of the orbital plants (Fioravanti et al., 1995) or the immature cortical or subcortical control of both saccade and vergence signals in early development (Yang & Kapoula, 2003). On the other hand, investigations in reading suggest that poor binocular control in in children results from the low-level immaturity in their oculomotor control rather than the high-level cortical functions related to reading development (Blythe et al., 2006). Further extended observations reporting poorer coordination in children than in adults during both linguistic and nonlinguistic tasks also show that the lower quality of vision caused by binocular coordination deficits delays linguistic processing (Bucci & Kapoula, 2006; Seassau & Bucci, 2013). As a consequence, it can be assumed that there is a mutual interaction between binocular motor control and linguistic processing involving cortical structures (Bucci & Kapoula, 2006).

An important implication of the studies on children with dyslexia during nonlinguistic tasks is that children with dyslexia have problems with binocular coordination, which reflects an immaturity of the oculomotor system independent of the reading process (Kapoula et al., 2009). The presence of oculomotor abnormalities in children with dyslexia during oculomotor tasks points out that deficient control of eye movements cannot be explained purely by language deficits, but that visuospatial problems also play a crucial role (Bucci et al., 2008a; Eden et al., 1994). With respect to more recent studies indicating poor binocular fixation capability in the vertical plane among children with dyslexia, both impaired attention abilities and immaturity of the cortical areas controlling the fixation system seem to be responsible for visual fixation incapability in dyslexia (Tiadi et al., 2014, 2016).

Upon review of research on binocular viewing during linguistic tasks in children with dyslexia, it is fair to say that fixation instability arising from oculomotor deficits may result in reading problems supporting the magnocellular hypothesis (Jainta & Kapoula, 2011). Moreover, impaired vertical systems while reading reported in dyslexia may have arisen from deficiency in the cerebellum which is involved in binocular yoking during saccades and postsaccadic fixations (Goulème et al., 2018). However, there is a study failing to find larger fixational disparity in children with dyslexia (Cornelissen et al., 1993). These conflicting results could be resulted from the fact that children with dyslexia have to handle slightly larger residual disparities when actually fusing the images of the text rather than single words.

Recent investigations of binocular control among dyslexic groups in both linguistic and nonlinguistic tasks have yielded conflicting results. Greater fixation disparity during reading compared with oculomotor condition supports the conclusion that attentional and/or cognitive processes seem to be affected in dyslexia, pointing out an impairment of high-level functions, in contrast to the magnocellular theory (Kirkby et al., 2011). Many studies highlighted important findings on the interactions between visual crowding and high-level linguistic processes involved in reading (Paterson & Jordan, 2010; Slattery & Rayner, 2013). Nevertheless, other studies of task-independent poor binocular coordination in dyslexia have indicated a deficiency in visual attentional processing as well as an impairment of the magnocellular visual system (Bucci et al., 2008b; Ghassemi & Kapoula, 2013). This can be explained by the strong relationship between the programming of saccadic eye movements and shifts of visual attention (Hoffman & Subramaniam, 1995). Attentional shifts towards saccade target locations are triggered during saccade preparation and that affects reading in dyslexia (Facoetti et al., 2003). Additionally, poor-quality binocular coordination may be related to the impairment of structures involved in ocular motor learning such as the cerebellum or the parietal cortex (Bucci et al., 2012; Seassau et al., 2014). According to these results, reading difficulties could be defined as consequences of oculomotor deficits, supporting the magnocellular deficit hypothesis (Bucci et al., 2012).

As concerns the interventions for reading improvement related to binocular viewing, previous works stating that unstable binocular control might contribute to children's reading difficulties recommended monocular occlusion as a treatment for children with dyslexia (Cornelissen et al., 1992; Stein et al., 2000). Later researchers suggested that orthoptic training involving improvement of vergence capabilities and extraocular muscle abilities could provide increased saccade performance and help children with dyslexia to improve reading skills

(Tiadi et al., 2014). In addition, visuo-attentional training could also be beneficial to increase the capacity of the focus of their attention and, therefore, enhance reading performance (Tiadi et al., 2016).

The bulk of research examining binocular coordination has focused almost exclusively on children with dyslexia and typical populations providing a developmental perspective. Even though most of the studies have employed few subjects and there is a discrepancy between some results, it is clear that typically developing young children and children with dyslexia are more likely to have poor quality of binocular coordination that improves throughout the developmental process. Coordination disabilities during early developmental stages may be considered to be due to the immaturity of visual processing and oculomotor control at both subcortical and cortical levels (Yang & Kapoula, 2003), besides oculomotor learning system impairments, involving the cerebellum and/or parietal cortex (Yang & Kapoula, 2004). As regards binocular eye movement research in children with dyslexia, accumulated evidence appears broadly to support the magnocellular theory which claims that impairment in the magnocellular visual pathway involving the cortical and subcortical structures and the cerebellum causes dyslexia (Bucci et al., 2008b, 2012; Jainta & Kapoula, 2011; J. Stein, 2001). On the other hand, there are also studies in the literature stressing the role of immaturity and/or deficiency of the visuo-spatial attention process as well as the magnocellular pathway in dyslexia (Bednarek et al., 2006; Biscaldi et al., 1994; Bucci et al., 2008a). It can be also argued that binocular control deficits in children with dyslexia could be related to the impaired or/and immature oculomotor learning systems, which supports the Cerebellar Theory (Bucci & Seassau, 2014; Ghassemi & Kapoula, 2013). Finally, poor binocular coordination could be resulted from the deficiency in high-level cognitive processing related to linguistic skills, proving the Phonological Theory (Kirkby et al., 2011). These findings cast light on the theoretical and clinical implications of dyslexia which is a complex disorder related to widespread impairment of brain structures.

Limitations

This review has presented an overview of binocular coordination capability in children with dyslexia and typically developing children from a developmental perspective. However, several limitations were noted. Firstly, many of the studies had small sample sizes and did not include the community sample, which limits the generalizability of the results to the broader population. Secondly, there are few reports of longitudinal outcomes for the development of binocular control among nondyslexic and dyslexic population. As a consequence, the relation between binocular coordination deficits and reading difficulties has not been fully clarified. Furthermore, whether binocular coordination of eye movements differs in languages with deep and opaque orthography in dyslexia was not investigated. Finally, with respect to the theories of dyslexia, these studies do not show convincing evidence in favor of its etiology. Further studies combining neuroimaging and eye-tracking techniques will be necessary to test the hypothesis on the origin of dyslexia.

Conclusion

Investigations on binocular coordination abilities in children with dyslexia and typically developing children appear to be crucial in identifying evidential support for still-debated etiological theories of dyslexia. This systematic review provides a deeper understanding of binocular oculomotor control of eye movements in children with dyslexia which diverge from the normal developmental pattern. Further research is needed that examines the neural correlates of binocular coordination in children with dyslexia, using longitudinal and developmental trajectory samples. Expanding research with large community samples should provide more precise indicators for the underlying processes of the etiology of dyslexia, which are of great importance for the investigation and treatment of children with dyslexia.

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Declarations

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