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Original Article

Eye movement patterns in Iranian dyslexic children compared to non-dyslexic children

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ABSTRACT

Objective: Dyslexia is the most common learning disorder that affects 5–10% of school aged children. Eye movement abnormalities and visual processing deficits have been reported in some of dyslexic children. Objective of this study is to compare the eye-movement patterns of Iranian dyslexic children with those of non-dyslexic children as they perform the oculomotor tests and to explore the relationship between their eye-movement patterns and their reading ability.
Methods: Binocular eye movements were recorded by oculomotor subtype of videonystagmography (VNG) testing on 30 dyslexic children and 20 non-dyslexic age-matched children (aged 8–12) in both genders. Dyslexic children were diagnosed with DSM-V scale by experts in reading disorder centers. Gain of the pursuit and optokinetic tests and the latency, accuracy and velocity of the saccade test were measured in both groups of dyslexic and non-dyslexic children. The independent samples *t*-test, Chi-square test and linear regression test in SPSS v. 21 were used to analyze behavioral and eye-movement parameters.
Results: Compared to the non-dyslexic group, dyslexic children presented lower gain in pursuit and optokinetic tests, and increased latency with decreased accuracy in saccade test. All behavioral and eye-movement parameters without saccade velocity differed significantly among two groups.
Conclusion: The atypical eye movement patterns observed in dyslexic children suggests a deficiency in the visual information processing and an immaturity of brain structures responsible for oculomotor skills.

1. Introduction

Reading is one of the most important skills that children need to acquire. Its development is reflected in readers' changing eye movement patterns. However, these do not mature completely until age seven to eight; this suggests that the parts of the brain that are involved in the sequential saccadic eye movements required for reading, have to mature for it to develop successfully [1].

The specific reading disorder known as "Developmental Dyslexia" is defined as a selective disability of learning to read despite normal nonverbal intelligence, adequate education, and socio-cultural opportunities, without basic sensory

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defects in vision or hearing and often with a family history of similar problems [2]. It is a complex reading disorder involving genetic and environmental factors [3]. This disorder affects 5–10% of school-aged children [4]. The origin of dyslexia is still controversial. The main hypothesis in this regard is a phonological awareness deficit, that has been supported by several authors [5,6], but literature review showed that the phonological theory cannot explain all deficiencies reported in dyslexia and other theories have been proposed such as visual perception, working memory, auditory and attentional abnormalities [7,8] suggesting that causes of dyslexia could be multiple and interacting rather than only one clear reason.

Some studies show that eye movement patterns in dyslexic patients are different from normal, not only during reading but also in the simple tracking of sequentially moving light targets [9,10]. Pavlidis was the first to report a large number of regressive saccades and unstable fixations in Greek dyslexic children [1]; this was confirmed in Greek children again by Hatzidaki et al. [11]. Rayner likewise reported multiple saccades with short amplitude and longer fixation durations in English dyslexic children [12]; similarly, De Luca et al. observed numerous fixations with long durations in Italian dyslexic children [13]. Besides, Li et al., reported abnormal eye movements in Chinese dyslexic children in an image search task, consisting of increased numbers of long fixations and multiple saccades with short amplitudes [14]. Again recently, Trauzettel-Klosinski et al. reported reduced reading speed and a higher number of saccades and regressive saccades in German dyslexic children [15]. Although Caldani et al. assessed pursuit eye movements in dyslexic children and their results showed catch-up saccades were significantly more frequent in the dyslexic group than in the non-dyslexic group of children, and they suggested a deficit in visual attentional processing [16]. In this regard, our group further explored the effect of oculomotor rehabilitation on eye movement patterns of dyslexic children. Our results showed the positive effects of oculomotor rehabilitation on eye movements of dyslexic children that confirm oculomotor abnormalities in dyslexic children [17]. Finally, the hypothesis of an impairment of the visual system in dyslexia is still under debate given that some recent researchers think that this deficiency could be a consequence and not the cause of dyslexia. Several studies reported visual deficits and oculomotor abnormalities in dyslexic children, supporting the hypothesis of deficiencies in the magnocellular system [7,18] and of a cerebellar impairment [19]. However, some others did not support the hypothesis of deficiencies of the magnocellular system [20,21]. Although these abnormal eye movements are often argued to be a consequence of their difficulties with reading rather than their cause, this could not be the case in the studies where they were recorded in response to sequences of nonverbal targets; rather they suggest that they can be due to defective visual information processing in general [16]. The abnormalities may be related to abnormal development of the oculomotor control systems by which oculomotor coordination and stabilization are achieved [11,17]. In general, all of these findings suggest that abnormal eye movements observed in dyslexic children can be due to poor strategy of visual information processing. Another group of researchers suggested that these defects are related to the lack of maturity of the oculomotor learning mechanisms; the mechanisms through which the oculomotor coordination and stabilization are achieved [22]. Other studies on dyslexic children, with comparison between reading and non-reading tasks, found oculomotor defects only in reading tasks. So they suggest that in dyslexia, defects are found at higher levels of psychological processing [23,24]. Of course, it should be noted that the presence of oculomotor disorder in dyslexic individuals causes higher levels of attention focus on basic oculomotor activity during reading (such as intermittent focusing on words), which reduces the person's ability for word perception [24] .

The present study aims to evaluate the eye movements of Iranian dyslexic children as one of the possible causes of dyslexia in these children. In this study, these patterns were evaluated using a valid electrophysiological test, namely, video-nystagmography (VNG). In the present study, it is assumed that there is a dysfunction at the level of oculomotor responses in children with dyslexia, and the assessment of eye movements can be a useful tool to assess visual attention skills in these children. Given the very close relationship between the mechanism of production and control of oculomotor responses and the ability to read, it is assumed that the oculomotor tests can be a very useful test in the evaluation and diagnosis of reading disorders.

2. Materials and methods

2.1. Participants

This study is a comparative study. Fifty children between 8–12 years old consisted of thirty Dyslexic children (mean age 9.1 ± 1.24 years), including 6 girls and 24 boys and twenty age-matched non-dyslexic children (mean age: 9.55 ± 0.94 years), including 6 girls and 14 boys participated in this study. The ratio of boys to girls was more than three times (76% vs. 24%). Non-dyslexic children were selected among primary school students and dyslexic children were recruited from learning disabilities centers in Tehran based on inclusion criteria. Sampling was done randomly. It should be noted that dyslexia is recognized based on DSM-V criteria in learning disability centers by the relevant group of experts (including a psychiatrist, general psychologist, exceptional psychologist, clinical psychologist, and counselor).

Inclusion criteria for participants include aged 8–12 years, diagnosis of dyslexia based on DSM-V criteria in learning disability centers and the opinion of the expert group in this area, normal hearing in both ears (less than 25 dB HL at frequency octaves of 250–8000 Hz), with normal or corrected vision, normal IQ of children based on using the Wechsler Intelligence Scale for Children- Fourth Edition, WISC-IV), namely above 85,available in the medical files (129), monolinguals and fluency in Persian as a mother tongue and right-handedness based on the Edinburgh handedness test and they did not have any physical or emotional handicaps.

Exclusion criteria include the requirement for the use of Ritalin and other medications during the test in dyslexic children, associated neurological disorders, history of ear diseases, head trauma or accident, brain surgery or epilepsy according to parents' and medical records, and the possibility of the emotional or behavioral problems based on psychiatry and psychology records. Note that, about 26% of ADHD had a comorbid reading disability [25], so in the present study any hyperactivity deficit was excluded using psychiatric diagnosis. This study was approved by the research assistant department and the Ethics committee of Iran University of Medical Sciences (code number: 95-01-32-27836).

2.2. Study design

This study was conducted in two parts. In the first part after obtaining written consent from the parents and case history; basic hearing assessments (including audiometry and tympanometry tests) were performed to ensure the health of the middle ear and the normal hearing of all participants. The second step was eye movement assessment. At this point, eye movements were evaluated with spontaneous nystagmus test and four oculomotor tests (Including gaze, saccade, tracking, and optokinetic tests). In the spontaneous nystagmus test, the eyes are covered and the child is asked to look ahead and numbering two-by-two. The presence or absence of nystagmus was evaluated. In the gaze test, the child will be asked to sit on a chair at a distance of one meter from the screen. Then the child should star to gaze to a yellow circular target at the center, 20º left and right, and 20º up and down target without moving the head. The parameter measured in this test was the presence or absence of the nystagmus. In the tracking test, the visual target is moving slowly at a velocity of 0.2º per second and the child should smoothly track the target with his/her eyes without moving of her/his head. A yellow circular target was initially placed at the center position (0º) and then moved horizontally to one side until reached ±20° location, and then reversed to the opposite side. The parameters measured in this test were the gain and symmetry of response. In the saccade test, the child should follow the target moving randomly at the velocity of 5–30 º per second. The parameters measured in this test were latency, velocity, and accuracy. In the optokinetic test, colored stripes are moving at velocities of 20, 35, and 50º per second to the left and right. The child will be asked to look at the middle of the screen and count the number of stripes passing. The parameters evaluated in this test were the gain and symmetry of response between two sides.

The variables that have been evaluated in this study are the gain of the tracking and optokinetic tests (which is expressed as a percentage), the saccade latency (which is expressed as a millisecond), the saccade accuracy (which is expressed as a percentage), and the saccade velocity (which is expressed as degrees per second). The qualitative variables include the presence or absence of the spontaneous nystagmus, the presence or absence of the nystagmus in the gaze test, and the symmetry of response between two sides in the tracking and optokinetic tests. All of these variables were measured for all participants.

2.3. Instrumentations

2.3.1. Eye movement recording

Eye movements were recorded with a non-invasive system named videonystagmography (VNG).This system consisted of a laptop, a monitor, and a goggle with two infrared cameras placed above the goggle to record horizontal and vertical eye movements independently and simultaneously. Calibration of the eye positions was done at the beginning of each eye movement recording.

2.3.2. Procedure

Children were seated on a chair in a dark room, in front of the flat monitor in the distance of 1 m. The targets stimulating eye movements were displayed on the 40-in monitor. The head of the child should be held straight to the front and recording was done binocularly.

2.4. Data analysis

Kolmogorov–Smirnov (K–S) test was applied to evaluate the distribution of data. K–S test showed all variables have a normal distribution. Descriptive statistics were used for the calculation of mean and standard deviations of data and participants' demographics. The software Eclipse (provided by VO425 VNG) was used to extract eye movement's information from the data. Pursuit gain was obtained by dividing eye movement velocity by target velocity for each trial. Gain 1 means that eye movement velocity is as same as the target velocity. Scores of pursuit gain and symmetry of response between two eyes were averaged for all participants. Statistical analysis was performed using SPSS 21. For comparison of dyslexic and non-dyslexic children, we used independent samples *t*-test, in which the dependent variable was gain of pursuit and optokinetic responses; latency, velocity and accuracy of the saccades; nystagmus in gaze and spontaneous nystagmus test; and symmetry of the tracking and optokinetic responses and the independent variable was the group. *P*-values less than 0.05 were considered significant in all analyses. For comparison of qualitative variables of oculomotor responses, we used Chi-square test in study population. Also, linear regression model was used for eye movements' parameters (gain value of tracking and optokinetic tests and saccade variables including latency, velocity and accuracy) with the predictor variable being the chronological age in order to investigate the influence of chronological age on eye movements' performances (significant-value below 0.05).

3. Results

Before performing statistical tests, the consistency distribution of data in different variables of the pursuit and optokinetic tests were studied in two groups of dyslexic and non-dyslexic children with the Kolmogorov–Smirnov (KS) test.

Table 1
Comparison of the oculomotor evaluations between dyslexic and non-dyslexic children.

Oculomotor variables	Normal children (Number = 20)	Dyslexic children (Number = 30)	Significance level
Tracking gain (%)			
Mean (SD)	90.20 (2.87)	73.03 (7.72)	0.00
Maximum	95.75	89	
Minimum	84.5	61	
Saccade latency (milliseconds)			
Mean (SD)	205.46 (25.68)	264.82 (25.64)	0.00
Maximum	272.25	333.2	
Minimum	166	221	
Saccade velocity (Degree / Sec)			
Mean (SD)	461.03 (85.07)	475.25 (89.61)	0.72
Maximum	612.75	676.75	
Minimum	291.5	310	
Saccade accuracy (%)			
Mean (SD)	91.30 (8.13)	70.66 (7.33)	0.00
Maximum	103.5	87.25	
Minimum	66	58.5	
Optokinetic gain (%)			
Mean (SD)	90.72 (11.33)	78.57 (20.10)	0.02
Maximum	110.18	141.38	
Minimum	64.93	51.35	

Results showed a normal distribution of data for all variables except the saccade velocity variable. Therefore, for analyzing the results of this variable in all groups, a nonparametric statistical test was used.

3.1. Oculomotor results

Table 1 shows the oculomotor test results for both groups of children examined. The independent samples t-test reported a significant group effect between the dyslexic and non-dyslexic children. According to the results, in the saccade test, in the dyslexic children compared to the non-dyslexic children, saccade latency are increased and saccade accuracy is decreased, but there is no significant difference between groups in saccade velocity (see Table 1).This means that in dyslexic children the eyes were reached to the target later and with lower accuracy, so the target image does not completely fall on the retina and the resulting image will be dark and fade. Although, in the tracking and optokinetic tests, the response gain in dyslexic children was lower than the non-dyslexic children and the response between two sides was non-symmetric and in all of these parameters, there is a significant difference between two groups (see Table 1). These results indicate that in dyslexic children, eye movement velocity is lower than the target's velocity, so the child is not able to correctly follow the target. These results showed central malfunction in dyslexics, namely oculomotor malfunction.

Also, we analyzed the qualitative variables including the presence or absence of the spontaneous nystagmus and gaze test, and the symmetry of response between two sides in the tracking and optokinetic tests in all participants by the Chi-Square test. The results are shown in Table 2.

Concerning Table 2, the findings showed that out of the 20 non-dyslexic children participating in the study, 17 children in the spontaneous nystagmus test had nystagmus and 3 children had no nystagmus and out of the 30 dyslexic children participating in the study, 25 children had nystagmus and 5 children had no nystagmus. A comparison of responses showed significant difference between two groups of children ($p = 0.00$). In the gaze test, 22 dyslexic children and 3 non-dyslexic children had nystagmus, and a comparison of the results showed that there was significant difference between two groups ($p = 0.00$). In the tracking test, 5 dyslexic and 3 non-dyslexic children had non-sympathetic responses. A comparison of the results showed that there is no significant difference between two groups ($p = 0.25$). Finally, in the optokinetic test, 12 dyslexic and 3 non-dyslexic children had non-sympathetic responses. A comparison of the results showed that there is no significant difference between two groups ($p = 0.059$).

Furthermore, linear regression analysis showed that there is not significant correlation between oculomotorresponses (dependent variables) and chronological age (independent variable). Results are shown in Table 3.In other words, linear regression did not show any improvement in the oculomotor responses by increasing of age in dyslexic and non-dyslexic children.

4. Discussion

The main results reported in this study were: 1) Dyslexic children showed a lower gain in pursuit and optokinetic tests and increased latency and decreased accuracy in saccade test compared to non-dyslexic age-matched children.2)Children did not show any improvement in oculomotor parameters with age. These findings are discussed below.

A comparison of the ratio of boys to girls in the study population showed that the ratio in boys is more than three times. Evaluation sex effect on dyslexia in studies showed that the prevalence of this disease in boys is probably more than

Table 2
Comparison of qualitative variables between dyslexic and non-dyslexic children.

Variable		Group		Pearson Chi-Square	*P*-Value
		Dyslexic Children ($n = 30$)	Non-Dyslexic children ($n = 20$)		
Spontaneous	presence of Nystagmus	25	3	22.74	0.00
Nystagmus	Absent of Nystagmus	5	17		
Gaze	presence of Nystagmus	22	3	16.33	0.00
	Absent of Nystagmus	8	17		
Tracking	Systematic	25	17	0.025	0.87
	Nonsystematic	5	3		
Optokinetic	Systematic	18	17	3.57	0.059
	Nonsystematic	12	3		

Table 3
Linear regression analysis of oculomotor variables with age.

Variable	B	SE	Beta	T	*P*-Value
Tracking Gain	3.18	1.24	0.34	2.5	0.14
Saccade latency	-3.90	4.84	-1.16	-80	0.42
Saccade velocity	6.00	9.35	0.69	0.64	0.52
Saccade Accuracy	3.05	1.54	0.27	1.98	0.06
Optokinetic gain	4.25	1.93	0.30	2.20	0.06

girls [26,27], however, in another study was concluded that there is probably no difference in the incidence of dyslexia between two sexes [28]. Although the relationship between sex and the prevalence of dyslexia is not the aim of the present study, but the higher number of male to female in this study, as well as most other studies, reinforces this hypothesis.

In spontaneous nystagmus examination, nystagmus was recorded in dyslexic children. Based on the "consensus document of the committee for the international classification of vestibular disorders of the Barany Society", the presence of nystagmus in dyslexic children in dark space can be attributed to particular attention problems, especially the spatial attention in these children, compared with normal children [29].In the gaze test, nystagmus was induced with fixation in dyslexic children, which was seen as Nystagmus Square Wave Jerk and related to fixing neurons disorder's in the middle layers of the upper part of the superior colliculus (SC), which is according to the findings of Karatekin study. He observed fixation disorders in people with reading disorders [30].

4.1. *Poor tracking and optokinetic performance in dyslexic children*

A reduced gain in the tracking test can be a reason for the risk of central vestibular disorders in the dyslexic children. [31], But in some studies, authors cannot find any difference maybe because of methodology differences [32,33]. Research has suggested that lower gain in tracking is because of reduced eye velocity compared to the target velocity [34]. In literature review has been shown that the cerebellum and parietal area are responsible for tracking eye movements [35]. Based on these findings it is hypothesized that there is a dysfunction at the cerebellar area in dyslexic children, but to confirm our hypothesis neuroimaging studies will be necessary. Furthermore reduced gain in tracking response could be related to decreased visual information processing velocity in dyslexic children. Although any deficiency in attention could disturb eye movements and visual attention that have been shown in some studies [36,37]. . Moreover, Jafarlou et al (2017, 2020) showed that oculomotor rehabilitation improved eye movements and visuospatial attention processing in dyslexic children [17,38]. According to these studies, we could hypothesize that poor eye movement performance in dyslexic children could be due to the immaturity of cerebral areas controlling attention capabilities spatially in tracking of the task.

In the optokinetic test, the gain in the assessed velocities was significantly lower in dyslexic children than non-dyslexic children. Because optokinetic function usually requires the normal performance of the brain stem in the pons region [30], reduced gain in dyslexic children can be another reason for the dysfunction of the oculomotor system at the brain stem level in these children.

4.2. *Poor saccadic eye movements in dyslexic children*

Since one of the important structures of the midbrain involved in the production of the saccade is superior colliculus; saccade abnormalities observed in dyslexic children can be attributed to central dysfunction of the vestibular system in these children. Also, decreased saccade accuracy can be attributed to cerebellar and brain stem disorders in dyslexic patients. [39].

Various studies have shown that eye movements during reading are abnormal in both developmental dyslexia and acquired dyslexia [1,40]. It seems that the cause of oculomotor defects and excessive fixations with long duration during reading and visual search tasks in dyslexic children is due to lack of maturity of visual attention strategies, thus reduces visual information processing velocity; and this leads to an increase of saccade latency and decrease of the response gain and thus reduce the number of letters to be processed simultaneously. This limitation leads to an increase in the number and duration of fixation, so the child reads the text analytically [24,41].

The presence of poor visuospatial function in dyslexia has been identified for years and the abnormal eye movements observed in dyslexic children can be due to a weak visual information processing strategy and is not related to language performance [42,43]. Articles show that attention plays an important role at the beginning of saccade, so that increasing the attention can reduce the latency of saccade and increase its accuracy. Increasing attention in saccade has positive effects in the representation of the environment, accurate target selection in the visual memory, and reduction of internal visual noise [44]. Although, in dyslexic children, weak binocular coordination during prolonged fixations [45], visual illusion during reading [46], and poor eye alignment during fixation [18] have been shown. Iles et al. also reported visual search impairment in a group of dyslexic adults with motor deficits, confirming the magnocellular hypothesis [47]. Similarly, the results of the present study indicate that there is a dysfunction at the brain stem level and vestibular nuclei and in the level of oculomotor responses in children with dyslexia and this oculomotor dysfunction causes problems in reading ability in dyslexic children in Bottom-up mode. On the other hand, given the role of Top-down processes, it seems that visual attention processes also play a role. Overall, the findings show that probably both of Bottom-up and Top-down processes play a role in creating dyslexia.

4.3. Absence of eye movement improvement with age in study population

Analysis of our results showed that the oculomotor parameters including tracking and optokinetic gain and saccade latency, velocity and accuracy did not improve by age in dyslexic and non-dyslexic children.Some studiesrevealed oculomotor responses are immature in the first years of life and reach to adult range with increasing age. These studies reported this improvement in oculomotor skills with age is because of myelination of neurons, maturation of gray matter and development of cortical and sub-cortical regions correlated with eye movements [38,48]., The other study investigated the effect of age on saccadicfunction and they reported that saccade velocity or accuracy was unaffected by age [49].We did not find anyimprovement, maybe because of narrower age range evaluation. Also, the absence of eye movement improvement with age in dyslexic children it's may be because of immaturity of cortical and sub-cortical areas responsible for these movements.Also, Literature showed that there is a cognitive-vestibular interaction and attentional processing is a cognitive factor that influences smooth pursuit response. Also, there are abnormalities in attentional processing in dyslexic children [38]. So, absence of eye movement improvement in dyslexic children could be due to visual information processing deficiency in these children.

5. Conclusion

Our data suggest that dyslexic children have abnormal eye movement patterns (reduced gain of pursuit and optokinetic response and increased latency and decreased accuracy in saccade test) compared to non-dyslexic age-matched children, probably due to immaturity or dysfunction of brain and brain stem structures responsible for oculomotor eye movement. It should be considered that the relationship between dyslexia and oculomotor abnormality offers an objective diagnostic test for dyslexia. Since oculomotor tests are not depending on the reading, it offers the possibility of early diagnosis even before entering school. Therefore, we suggest that oculomotor assessments be performed for all dyslexic children.

Declaration of Competing Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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