Chapter

Eye Tracking Using Nonverbal Tasks Could Contribute to Diagnostics of Developmental Dyslexia and Developmental Language Disorder

Zuzana Bilkova, Martin Dobias, Jaromir Dolezal, Vratislav Fabian, Helena Havlisova, Jiri Jost and Olga Malinovska

Abstract

There are not many studies dealing with a comparison of the eye movements of individuals with dyslexia and developmental language disorder (DLD). The aim of this study is to compare the eye movements in the two most common language disorders, dyslexia and DLD and to consider their contribution to diagnostics. In the research the oculomotor test was administered to 60 children with the clinical diagnosis of dyslexia or DLD and 58 typically developing children (controls). The test included a prosaccadic task, antisaccadic task and a nonverbal sequential task with self-regulation of the pace. Controls could be singled out from other two clinical groups by means of the oculomotor imaging. Both of the clinical groups in comparison with the controls were characterized by worse overall performance. Through the employment of the oculomotor it was possible to differentiate between both of the clinical groups. The dyslexics had an overall worse oculomotor performance than the DLD group. The results of the study show that the oculomotor test has the potential to contribute to diagnostics of dyslexia and DLD and the screening of these disorders at pre-school age.

Keywords: saccade, antisaccade, dyslexia, developmental language disorder, orthographic complexity

1. Introduction

Developmental language disorder (DLD, also called specific language impairment or developmental dysphasia) is characterized by difficulties in the acquisition and the use of language with a co-existing absence of any clear etiology – hearing impairment, intellectual disability, neurological or psychiatric findings and insufficient language stimuli. Difficulties include a delayed start and slower acquisition of lexical and grammatical forms, smaller vocabulary as well as difficulties with receptive and expressive language skills. Individuals with DLD acquire the meaning of new words and new meaning of already acquired words with difficulty and they also need more time to identify familiar words. Developmental dyslexia (further dyslexia) is usually associated with problems of writing and reading language. In the diagnostic process, as well with DLD, sense defects, intellectual disability, neurological or psychiatric findings and poor learning opportunities must be excluded [1].

DLD is the most commonly studied disorder of the oral language while dyslexia is the most commonly studied disorder of the literary language. In both cases, these are language disorders that are often associated with each other. Individuals with DLD may also meet the criteria for dyslexia whereas the appearance of dyslexics in DLD population is significantly higher than in the normal, non-DLD population. This is similar with the occurrence of individuals with DLD in the dyslexic population. The comorbid occurrence of both disorders is estimated to be approximately twice as common as isolated occurrence [2]. Researchers therefore ask whether their relationship can be characterized as sisterly or whether one is a mother and the second is the child, or possibly if they are independent of each other. Tallal [3, 4] suggested a simple deficit model, according to which dyslexia and DLD are different manifestations of one and the same disorder. The common cause is the deficiency in phonological processing, accurately in distinguishing of fine acoustic sequences occurring in the order of tens of milliseconds. This deficiency gains a various depth. If it is deep, the individual has problems with reading as well as in the oral language. As a consequence, comorbidity of both disorders appears. If the deficit is not so deep, then the individual has problems in reading and only to a limited extend struggles in oral language. Tallal is aware that not all individuals with DLD have a problem in rapid auditory processing, and further that not all individuals with a deficiency of rapid auditory processing develops DLD. The aforementioned experience is difficult to explain using her model, although the author contends that there are methodological disadvantages regarding the present tests of rapid auditory processing which may not be sensitive enough and may therefore offer false negative results.

Bishop and Snowling [5] made a proposal of a model which expands the phonological aspect by means of the semantic-syntactical aspect. Individuals with dyslexia and DLD have in common problems in phonological processing. Unlike the Tallal's model, the degree of the phonological difficulties is roughly the same in both disorders. Both disorders differ in their respective semantic-syntactic aspect: individuals with DLD, unlike the individuals with dyslexia, have significant semantic-syntactic difficulties. Some individuals are difficult to classify in this model. Hence, the authors mark them as "poor comprehenders." Although they have good phonological abilities and are able to decode written text very well, they have difficulties to fill in its meaning.

Both of the aforesaid models perceive the deficiency in the phonological processing as the main factor contributing to dyslexia. Therefore dyslexia is regarded as a language disorder. Neurobiologically-oriented authors perceive dyslexia also as non-language disorder (for example [6–8]) with nonverbal symptoms as dyschronism, dysbalance, sensorismotor dyscoordination or a disturbance of orientation in place as well as space. Initially, language disorder thus had for this reason a new dimension built into a multidimensional model [9, 10]. The model works at four levels: etiological, neural, cognitive and behavioral. The model recognizes that many factors are involved in the etiopathogenesis of the disorder; some are risky, others protective; some are genetics while others are environmental. Their interaction forms neural structures necessary for cognitive functions, so deviations in cognitive functioning produce behavioral symptoms generating a particular picture of the neurodevelopmental disorder. According to the model for the beginning and the subsequent development of the disorder, a simple etiological factor is insufficient; there are indeed many factors involved on the disorder. If there are etiology and cognitive deficiencies, collectively shared by several disorders, comorbidity is to be expected. The model accesses the dynamic nature of the neurodevelopmental disorders and their development and to the high plasticity of the brain. The model allows for a better understanding of why, for example, in the Bakker's treatment of dyslexia, the change of poles happens of the L-type to the P-type or vice versa [11], and why remedial efforts on the behavioral level can produce structural improvements in neuronal networks associated with phonological processing and reading ([12] for review), and why phonological type of dyslexia ("deep" type) changes in the visual type ("surface" type) [13], as well as why dyslexia is associated with ADHD or DLD.

1.1 Eye movements of individuals with dyslexia

The oculomotor studies in dyslexics may be divided into two groups: in the first group we include studies on eye movements during reading and in the second group studies concerning eye movements in non-reading tasks. The studies of the first group agree, that while reading the eye movements of individuals with dyslexia differ significantly from the control group ([14]; newer [15, 16]). They are characterized by a larger number of fixations and a longer period of their duration, by larger number of saccades, from which a large part falls on regressions. The regressions of dyslexics are often shorter than by the control group and move within the frame of one word (the so-called innerword regressions) in an attempt to identify it, whereas regressions of the control group are more often between words. Their function is to contribute to the understanding of links between the passages of the text. These findings are independent of language region, for example in English-speaking countries [14], German-speaking countries [17] and China [18]. Any interpretation of these findings in terms of causes and consequences is very difficult, for a difficult question must be addressed. Are the nonfunctional eye movements the cause of the poor reading or is the poor reading the cause of the poor eye movements? To clear up that question, the researchers use non-reading tasks free of language influences which at the same time demanding of the subject under examination the identical or very similar regime of eye movements as occur during a real reading.

Non-reading tasks are possible to classify according to which particular kind of eye movements is stimulated. During so-called fixation task, the subject's duty is to observe a stationary point and for a certain time not to let it go out of eye sight. This task tests the so-called fixation stability that means the ability to keep the picture of a stationary object on command. Pavlidis [19] is one of the first to point out a worsening of the fixation stability by individuals with dyslexia in a non-reading task. Eden et al. [20] also included into their testing battery a fixation task by which they managed to distinguish dyslexics from the control group. More recently this difference was confirmed by Tiadi, et al. [21] and by Vagge et al. [22]. The fixation instability is considered as a sign of distinguishing dyslexics from the control group. However, these findings are not always consistent. The causes may be found in varieties of demands on the subject of the fixation task, differences in the time of its duration and eventually different degrees and types of the dyslexic disorder. Fischer and Hartnegg [23] point out two kinds of fixation instability, which are to some extent independent of each other and whose substitution contributes to the lower consistency of the findings.

In the so-called standard saccadic task the subject is required to move his/her eyes from one fixation position to another. The changes of the positions generally take place in the horizontal plane, in which his/her eyes are also moving according to the lines of the text – therefore we speak of the horizontal saccades. Regarding measurement, the saccadic reaction time is used, also the saccadic velocity and duration, the saccadic amplitude, the main sequence relationship, i.e. peak velocity or duration as a function of amplitude, and accuracy. The majority of studies do not find any difference between individuals with dyslexia and the control group (see review study Rommelse et al. [24]; more recently Vagge et al. [22]). From previous findings it appears that the standard saccadic task (1) has restricted potential to discriminate dyslexics from typically-developing readers and (2) it shows a normal function of cerebral circuits in/by dyslexics, which control reflexive, subcortical level of saccadic eye movements. Its submission in the testing battery corresponds to the exclusive nature of dyslexia diagnostics, i.e. excluding among other ailments neurological disorders.

The so-called antisaccadic task holds a privileged position. While undergoing the test, the subject's duty is again to follow up the changing position of the point to which the subjects fixes his/her eyes. However, in contrast to the standard saccadic task, he/she must transfer to the opposite direction. For example, the point which the subject is supposed to follow up actually appears on the left side of the screen. However, the subject's task is to look exactly at the opposite side. The antisaccadic task tests the voluntary component of the eye movements. His/her reaction to change to the left is based on automatically triggered reflexive mechanisms which must at first be suppressed by his/her will. Not until then it is possible to program a new direction of the movement, in our case, to the right. The antisaccadic task is therefore considered as an inhibitory capability test. It is correspondingly called neurological for the test of the frontal dysfunction [25]. The antisaccades were in case of the dyslexics systematically researched by the team of B. Fischer [26–28] who observed significant escalation in the directional mistakes in contrast with the control group. More recently this finding was confirmed by Bucci et al. [29] or Lukasova et al. [30].

The nonverbal sequential task was applied in dyslexics by Pavlidis [19, 31]. The task of the subject was to watch a set of horizontally arranged lights, which turned on and off in sequence. These lights were turned on and off, always from the left to the right and again when the last light in the line went out, a new cycle of observation began from left to right. There was always one single light on in the line. The subject followed up with a number of such cycles, respectively lines. However, for diagnostics, Pavlidis used only the first cycle, which he considered to be the most valuable. In contrast to the simple fixation task or the standard saccadic task, this task was testing more complex oculomotor behavior, which included fixation stability as well as saccadic movements with an automatic and voluntary component. By means of this task Pavlidis managed to find significant differences between dyslexics and the control group and especially to facilitate the researcher's interest in the relationship between eye movements and dyslexia. However, a number of authors replicated Pavlidis' research with different results. Some authors agreed [32], while others did not confirm his findings [22]. The causes can be understood due to a different methods (differently formulated sophistication of the task, different experimental procedure, different number of parameters used for the evaluation of the eye movements, differently sensitive devices for eye movements registration), in the selection of the participants and the typology of dyslexics and inaccuracies or inconsistencies of their descriptions.

1.2 Eye movements in individuals with DLD

The eye movements in the conditions of non-verbal tasks are rarely studied in individuals with DLD, unlike persons with dyslexia. Children with DLD are given language tasks accompanied with picture illustrations. During that time, eye movements are being scanned (for example, Andreu et al. [33]). In these studies eye movements are understood as a supportive method which should appropriately support the primary language examination, and not be understood as a biological marker of the disorder. Less frequent are oculomotor studies, where individuals with DLD are administered non-language tasks. These include Kelly et al. [34] studies, who administered the fixation task, the standard saccadic task and the antisaccadic task to different groups of children: to high-functional autistic children with language disorder, high-functional autistic children without language disorder, and finally to the individuals with DLD and control group. Persons with language disorder (whether with combination of autism or not) were characterized by fixation instability and by a significantly higher proportion of directional errors in the antisaccadic task. On the other hand, in a standard saccadic task their performance was comparable with the control group. The study showed that the basic level of oculomotor system controlled by the lower cerebral levels is intact for those individuals with DLD as well as in high-functioning individuals with autism. The study also showed that the deficit of the voluntary control of the eye movement is not exclusive for individuals with autism, but is connected to the language status, that means a presence versus an absence of a language disorder. Language is an important mediator of the executive control. For example, language can be helpful in supporting the children to reflect and realize in a clear way the conditions of the task (explicit verbalization of a type "if a point appears on one side of the screen, do not look at it, but on the opposite side"). The voluntary control deficit manifests itself with difficulties to suppress the reflexive reactions and to maintain the fixation stability. A similar finding is mentioned also by Norbury [35].

Studies which were engaged in comparing eye movements in individuals with dyslexia and individuals with DLD, are probably not so numerous. In databases like (PubMed, PsychINFO, ScienceDirect, Scopus, SpringerLink employing such key words as dyslexia, developmental language disorder, eye movement, saccade) we were not successful in finding such any study. Therefore we have decided to research their relationship and to verify the diagnostic contributions of the oculomotor examination of both disorders in non-language tasks.

2. Method

2.1 Participants

The clinical group (N = 60) constituted pupils with diagnosed dyslexia (n = 27) and DLD (n = 33) with an average age of 121 months, a standard deviation of 8 months and a range of 108–140 months. The pupils attended altogether six elementary schools in Prague specializing in children with special educational needs. An official governmental agency handles diagnostics and follow-up care for children with neurodevelopmental disorders in the Czech Republic. The government agency follows this work according to DSM-5 or a similar norm ICD-10. The diagnosis is a result of a team work of a psychologist, a special education teacher, a social worker and further a pediatrician, a speech therapist, a hearing doctor, eventually a child neurologist or another specialist. From standardized testing methods for example for testing IQ the WISC-III is used, re-standardized for the Czech population. For testing reading and writing, tests made and standardized are being used which had been produced by the team of the late Zdenek Matejcek, the vice president of IARLD (International Academy for Research in Learning Disabilities). For testing of the language skills, Heidelberg's test of the language development by J. Grimm and P. Schöler (HSET) is used, re-standardized for the Czech language. Phonological tests (test of the phoneme awareness and spoonerisms and the test of the auditory analysis and synthesis proposed and standardized by Czech authors). For testing of self-esteem of pupils with the special needs, SPAS test (Student's Perception of Ability Scale by F. J. Boersma and J. W. Chapman) is used, again re-standardized for the Czech population. For identification of at-risk children between the age of 6–8 years, children's screening from Kline, Graham, King, and Wringley is used. For checking language and literary deprivation of the child and the stable functioning of its family, the test of the family background from M. J. Herbert is used, re-standardized for the Czech environment, as well as the test ADOR (Adolescent about himself and parents) designed and standardized by the team of the aforementioned Zdenek Matejcek.

The control group (N = 56, average age 119 months, standard deviation 7 months, ranging from 108 to 136 months) is composed of pupils attending elementary school. The criteria for selection were better grades than average in both Czech language as the mother tongue and mathematics, non-problematic behavior without pathological pediatric finding and finally parental agreement with oculomotor examination. For all children, both the clinical and control group intellectual disorders were excluded or any disorders of the autistic spectrum, any psychiatric or neurological disorders, emotional deprivation, sensory defects (eye defects were corrected) or any serious pediatric complications. The pediatric evaluation conclusion was always a healthy condition. The families of children were rated as functional, i.e. none of them was monitored by the social welfare authorities. All children were of Czech nationality and their mother tongue was Czech – as with both their parents. None of the children came from a bilingual family or an immigrant family. The average age difference of both groups was insignificant (t = 1.046, p = 0.297).

2.2 Oculomotor test

The oculomotor test consisted of three tasks: standard saccadic, antisaccadic and non-verbal sequential tasks with self-regulation of the speed. All the tasks tested eye movements in horizontal plane. In the standard or "classic" saccadic task, the examined subject at first always had to fix his/her eyes at the point in the middle of the screen for 1000 ms. Afterwards a saccadic stimulus, the point appeared randomly left or right in a horizontal plane, always at a constant distance of 9 degrees of the visual angle (dva) from the center and always at the time of 700 ms. The point was black on a white background and had a diameter of 5 mm. The examined subject was instructed to move his/her eyes as quickly as possible to the saccadic stimulus. The task contained 20 attempts; 10 attempts oriented to the left, 10 to the right and the order was random. The time interval between the ending of the fixation point and the start of the saccadic stimulus was zero (sometimes called the "null" condition). As to oculomotor measurements, we have used the number of dysmetric saccades in relation with the number of attempts in the test and average size of their amplitude from the target amplitude. Because almost all the dysmetric saccades were hypometric, we have taken into consideration only the hypometric saccades (sometimes called "undershoots"). Both measurements characterize the accuracy of the saccadic movement. Among other things, the accuracy of the saccadic movement is dependent, on the quality of the neural circuits controlling the saccades. Normometry is a sign of the normal, healthy functioning of the saccadic system. One of the possible causes of dysmetria is cerebellum dysfunctions [25]. The value of this finding, i.e. dysmetria, results from a cerebellum theory of dyslexia [6, 8, 36]. This theory operates with a narrow relationship between cerebellum dysfunction and dyslexia. Directional errors in this task were extremely rare and, therefore, are not under consideration.

During antisaccadic task, the examined subject was to fix his/her eyes at the point of the center of the screen at first (the time of its duration was constant = 1000 ms) and then, afterwards, when the saccadic stimulus appeared – randomly on the left or right, but always at a constant distance of 9 degrees of the visual angle from the center and always for the time of 1000 ms. According to the instruction a saccadic movement was to be executed (so-called antisaccade) on the opposite side into the spot situated approximately as far as possible from the fixation point. The task consisted of 20 attempts; 10 attempts oriented to the left, 10 to the right, and the order was again performed randomly. The time interval between ending of the fixation point and the start of the saccadic stimulus was zero. For oculomotor measurements, we have employed (1) the number of correct reactions (antisaccades); (2) the number of saccades during the time of the fixation of the central point – this parameter is characterized as the fixation in/stability, the basis of which could be an increased arousal, which the antisaccadic task provoked in the participants and led to an increased saccadic activity; and (3) the ratio of correct antisaccades to prosaccades, i.e. directional errors. The standard saccadic task tested cerebral mechanisms associated with a lower level of control, whereas antisaccadic task tested mechanisms connected with higher, executive level of control [25].

Non-verbal sequential task with self-regulation of the speed (further the "self-pacing task") is submitted to the subject as six lines of dots after six dots in a row. The points were black on a white background and had a diameter of 5 mm. The angular dimensions of the entire picture equaled to ca 12° horizontally and ca 7.7° vertically. The distance between the dots in the line was always constant and equaled to ca 2.4°; between the lines ca 1.5°. The task of the subject was to "jump" with his/her eyes to all dots in every line, always in the direction from left to right and down from the top, thereby keeping to the comparable regime as one does while reading. At the same time, the examined person was not allowed to assist with his/her finger. When the participant reached to the last dot of the last line, he said "stop." It differs from the classical sequential non-reading task that Pavlidis worked with, whereby the subject alone sets the speed of his/her advancement. It also, hypothetically, sets higher demands on voluntary eye motor control than the task of Pavlidis. However, to verify this hypothesis, a neuroimaging study is probably necessary. The self-pacing task was proposed and already used by dyslexics earlier [37], where it has proven itself effective. We have not come across this task by any other authors. We are now upgrading it through an examination of saccades in the standard saccadic task and antisaccadic task. For oculomotor dimensions we have used (1) a number of forward saccades, (2) the number of regressive saccades, (3) the number of transition fixations from going over from one line to the other, and (4) the ratio between the fixation time in the first half and second half of the task. Using these parameters, we measure the fixation stability, voluntary control over saccades, the equability of the oculomotor performance in time and the efficiency of the visual orientation in the surface.

2.3 Registration of the eye movements

We have used a device technically labeled I4Tracking produced by Medicton Group, Ltd., Czech Republic in cooperation with the Technical University in Prague. The device works on the principle of video-oculography and facilitates contactless, distant scanning of eye movements. It offers to the examined subject an examination at a high comfort; the subject sits in front of the screen of the monitor on which the task is projected, without him/her being attached to the device, without the scanning part of the device being attached to the subject's head. We appreciate this attribute especially for children as well as anxious people who are more likely to be reluctant to cooperate. The disadvantage of this otherwise highly valued technology is a difficult on-line control. A chin rest was deployed to minimize head movements and stabilize the viewing distance at approx. 130 cm. Stimuli were visually presented on a 22-inch monitor with a resolution of 1920 x 1080. The sampling frequency equaled to 80 pictures per second.

2.4 Procedure

We motivated the subjects at first by an "astronaut" instruction which had already proved itself to be effective once before. Subjects heard the following: "Just imagine you are an astronaut and on the screen in your spaceship you are watching the universe. There are planets and stars moving and your task is to watch every planet or star and not let your eyes off of it." In the first examination phase, we administered a standard saccadic task. In the second phase we administered anti-saccadic task and in the third phase the self-pacing task. There were short breaks between the phases, when we instructed the subject about the new upcoming task. Each examination phase was preceded by a 9-point calibration. The total examination time approximated 10 minutes.

2.5 Data processing

The oculometric data obtained on-line we have further processed off-line in the Mathlab setting. For processing of the measured data we used the programming packet Eye Movements Signal Analysis (EMSA, further only "toolbox") developed at the Technical University in Prague. Scanned signals representing the view coordinates on the monitor were at first preprocessed, specifically the detection of the biological artifacts was done (blinking, unwilling head movements) and of the technical artifacts (incorrect detection) and their follow-up correction by interpolation. All data records were visually checked and records that were not of a high quality were not included into further processing. Afterwards the aforementioned basic parameters of the eye movements were calculated; in general we can say that the designated parameters are quantifying the temporo-spatial deviations from the ideal course of the eye movements.

We linked together all subjects in the first phase of the analysis into one group characterized by a "general" disorder (see further **Table 1**). We will refer to this group as "clinical". In the second phase we attempted to differentiate the clinical group more clearly for one part with the prevalence of dyslexia and part with prevalence of DLD (see **Table 2**).

		Classification of participants according to eye movements		
Classification of participants according to clinical diagnosis		**CL**	**TD**	**N**
	CL	55 (91.67%)	5 (8.33%)	60
	TD	5 (8.62%)	53 (91.38%)	58
				118

Note. TD = typically developing group; CL = clinical group (participants with dyslexia, DLD or comorbidity). Percent correctly classified: (55 + 53) / 118 → 91.53%.

Table 1.
Discriminant analysis, whereby the clinical group was not differentiated any further.

		Classification of participants according to eye movements		
		DD	**DLD**	**N**
Classification of participants according to clinical diagnosis	DD	23 (85.19%)	4 (14.84%)	27
	DLD	4 (12.12%)	29 (87.88%)	33
				60

Note. DD = developmental dyslexia group; DLD = developmental language disorder group; Percent correctly classified: (23 + 29) / 60 → 86.67%.

Table 2.
Discriminant analysis, whereby the clinical group was differentiated according to the prevalence of dyslexia or DLD.

We processed the data with the help of discriminant analysis, into which we inserted the oculomotor measures of the participants and their membership to a group of typically developing, clinical group or group of participants with dyslexia or DLD. The question was whether the oculomotor measures would be discriminating the sample of participants satisfyingly with regard to their membership in groups. Furthermore, we condensed the oculomotor measurements using factor analysis (varimax rotation), in order to construct profiles of the eye movements from the extracted factors for individual groups.

3. Results

Table 3 presents the descriptive statistics of the oculomotor measures. The typically developing group had a tendency to achieve a better oculomotor performance than others; the group of individuals with dyslexia had a tendency to achieve a worse oculomotor performance than others.

By rotating (varimax method) we found a total of 3 factors which explained approximately 65% of the total variance.

The Factor F1 had its Eigenvalue 3.452 and explained 38.4% of the total variance. F1 is the factor of the oculomotor stability, characterized by confidence from going from one line to the other (this certainty was indexed by the number of transition fixations) and by the certainty of the movement in the line characterized through minimal regressions. The subject perfectly adapts to the conditions of the task and is able to move flawlessly in the task. The growth of the factor signals a worsening oculomotor performance in the self-pacing task, i.e. the number of transition fixations increases as well as the number of regressions in the lines and the number of forward saccades decreases.

Factor F2 had its Eigenvalue of 1.297 and explained 14.4% of the total variance. F2 is the factor of the basic dynamics of the saccades. As F2 grows, the proportion of undershoots in the prosaccadic task increases, the size of the undershoots increases, and the proportion of corrected errors in the antisaccadic task decreases. As the factor increases, it may be concluded that the subject has an impaired ability to focus on the target, its distance and accordingly determine the magnitude of the saccadic movement. Because it also correlates with the antisaccadic task, frontal dysfunction may be inferred, specifically the impaired ability to correct erroneous prepotent responses.

Factor F3 had its Eigenvalue of 1.097 and explained 12.2% of the total variance. Growth of F3 indicates a decreasing proportion of correct antisaccades and an increasing proportion of prosaccadic errors, an increasing proportion of saccadic

Oculomotor measure	Mean			Contrast		
	TD[a]	DD[b]	DLD[c]	TDxDD	TDxDLD	DDxDLD
Prosac: The number of hypometric saccades[d]/ number of attempts	0.560	0.856	0.741	*ns*	*ns*	*ns*
Prosac: the size of difference between normometric saccade and hypometric saccade (px)	37.225	73.438	62.457	*	*	*
Antisac: the number of correct antisaccades	11.706	6.888	6.878	*	*	*ns*
Antisac: the number of saccades at the time of fixations of the central point	4.603	8.185	5.363	*	*ns*	*ns*
Antisac: the ratio of correct antisaccades to prosaccades (directional errors)	2.70	2.17	1.95	*ns*	*ns*	*ns*
Self-pacing: the number of progressive saccades falling on the saccadic stimulus on average	0.763	0.665	0.716	*ns*	*ns*	*ns*
Self-pacing: the number of regressive saccades falling on the saccadic stimulus on average	0.078	0.171	0.111	*ns*	*ns*	*ns*
Self-pacing: the number of transition fixations falling on movement from one line to the next on average	1.310	3.0	2.545	*ns*	*ns*	*ns*
Self-pacing: time in the first half/time in the second half	0.506	0.514	0.523	*ns*	*ns*	*ns*

Note. Prosac = prosaccadic task; Antisac = antisaccadic task; Self-pacing = nonverbal sequential task with self-pacing; TD = typically developing group; DD = developmental dyslexia group; DLD = developmental language disorder group.
*ns = not statistically significant; *denotes a statistically significant difference (ANOVA: F = 204.6, Df = 1061, p = .000).*
[a]n = 58.
[b]n = 27.
[c]n = 33
[d]Difference between target amplitude and saccadic amplitude >20 px.

Table 3.
Descriptive Statistics.

intrusions at the time of central point fixation, and an increasing imbalance between the time the subject goes through the first vs. the second half of the self-pacing task. Frontal dysfunction may be inferred; specifically debilitated inhibition and a lowered ability to suppress prepotent responses.

Based on these factors, we have generated profiles of the oculomotor performances for the individual groups (see **Figure 1**).

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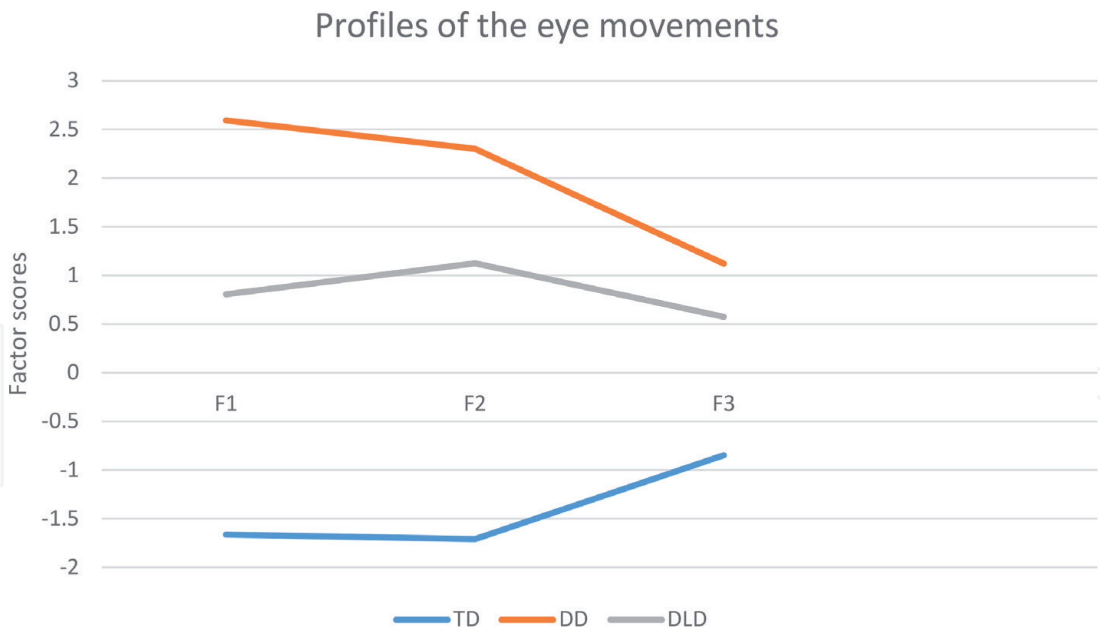

Figure 1.
Profiles of the eye movements. On the horizontal axis factors F1 up to F3 are marked, and on the vertical axis the averages of the factor scores are marked for individual groups. TD = typically developing, DD = developmental dyslexia, DLD = developmental language disorder.

ANOVA (F = 37.43, df = 353, p = 0.000) showed significant differences between the control group and both clinical groups (dyslexic and DLD) in all three factors. Compared to the control group, both clinical groups showed an overall poorer oculomotor performance; in the self-pacing task they did more transitional fixations, more regressions, and less regular saccades; in the prosaccadic task they made more undershots; in the antisaccadic task they made more directional mistakes. The difference between the dyslexic and DLD group was significant for factors F1 and F2; for F3 factor it did not reach statistical significance, although for dyslexics it was leading towards worse performance. The dyslexic group had an overall worse oculomotor performance than the DLD group.

4. Discussion

The conformity of the classification according to eye movements with the classification according to the clinical diagnosis reached 91%, see **Table 1**. This may be partially comparable with the study of Benfatto et al. [15]. However, its authors employed eye tracking while reading a short natural passage of text. Their participants were – when compared with ours – pupils of the third grade of elementary school (age 9–10 years) and were assessed as poor readers or as typically developing readers. Using statistical cross-validation techniques, they achieved a classification accuracy of nearly 96%. Benfatto et al. concluded that eye tracking has the potential to become an objective and accurate screening method useful for identifying school children at risk of dyslexia. A comparable conclusion was also reached by Smyrnakis et al. [16] in a similar study. Our finding supports the screening assumption of Benfatto et al. and also Smyrnakis et al. related to dyslexia but our finding further extends it to DLD. Additionally, we have used non-reading tasks in our study, in contrast to Benfatto et al. and Smyrnakis et al. Therefore, we can transfer the issue regarding screening to the pre-school age. Hypothetically, eye tracking has the potential to contribute to an early identification of children who may be at risk of dyslexia and/or DLD before the child even enters school.

4.1 Discrepancies between oculomotor and clinical classification

The agreement of the classification according to the oculomotor test with the classification according to the clinical finding depended on the type of clinical diagnosis, i.e. dyslexia or DLD. More often, DLD problems of dyslexics were more frequently ignored in the clinical trial from the point of view of the oculomotor test than dyslexic problems of DLD patients (14.84% vs. 12.12%, **Table 2**). Specifically, in 4 subjects with clinically-diagnosed dyslexia, the oculomotor test showed DLD symptoms. The DLD symptoms in those children were most probably secondary in the clinical picture of the disorder and therefore were left without notice by the clinician. In clinical practice, we have encountered individuals diagnosed with DLD in their pre-school age, with whom the DLD disorder had faded out but then while attending school, dyslexic difficulties had come to the forefront. Obviously dyslexic difficulties are evaluated as more serious so the child was examined with the diagnosis "dyslexia." In fact, these 4 participants could be classified as a mixed disorder/comorbidity of dyslexia and DLD.

The 23 participants with the diagnosis of dyslexia (**Table 2**), in which the oculomotor test did not indicate other DLD-type problems, represented on the other hand "pure" dyslexics. In the DLD group (see **Table 2**), the oculomotor test showed 4 participants with a clinical diagnosis of DLD whose difficulties could also have been caused by dyslexia. These individuals could be classified as a mixed disorder of DLD and dyslexia with the dominance of DLD. In those 29 participants where the conformity between the oculomotor finding and the clinical was attained, the so-called "pure DLD" was substantiated.

4.2 Influence of language milieu

Just like English, Czech is also a morphophonemic language. The spelling system utilizes sound units (phonemes) and semantic units (morphemes). Although English is characterized as a non-transparent language which places high phonological demands on the reader, Czech with its high consistency is "phonologically friendly" – the letter corresponds to the sound, which is written as it is pronounced. While English is said to be morphologically simple, Czech is the opposite. Thanks to phonological transparency, Czech 1st graders read coherent texts fluently and with comprehension in the first half of the 1st grade. Owing to the nature of the Czech language and the relatively rapid development of reading skills in a typically developing child, reading tests are not just lists of words, but coherent texts that are administered in the first half of the 1st grade [38]. Because of the grammatical (morphological, syntactic) complexity of Czech language, Czech pupils acquire Czech grammar throughout their schooling, i.e. for 9 years, and even then many of them do not master it perfectly. In the described linguistic environment of the Czech language, reading difficulties become eminent much more easily, while language difficulties (morphological, syntactic) recede into the background. DLD-type difficulties, especially of a milder degree, are easy to become less noticeable among the widespread grammatical difficulties of Czech pupils and can be more easily overlooked diagnostically, in contrast to dyslexic difficulties. Within the grammatically demanding environment of the Czech language, DLD-type difficulties seem to be masked, while reading difficulties are highlighted. With this effect of the Czech language environment, we explain why in the observed confusions the clinical approach preferred the diagnosis of dyslexia and neglected the DLD-type difficulties of the dyslexic group.

4.3 Dual-stream model

Johansson [39] and more recently Specht [40, 41] or Rastle [42] in their studies present the growing evidence for the validity of the dual-stream model of the speech perception and speech comprehension. The ventral stream serves speech comprehension (semantic-syntactic function). It closely interacts with the dorsal stream which plays the strategic role in speech production and likewise serves the auditory-motor integration. The model structurally includes the areas of the temporal, parietal and frontal cortex and probably also other brain areas which were not included in the model at the time. According to Specht, it belongs to other areas which do not have specific language functions, but also serves other non-language functions. For our purpose, motor functions and relevant motor areas of the cortex are interesting. Hypothetically, the dysfunction of the dorsal path could adversely affect oculomotor behavior. This fits in well for children with dyslexia and DLD, where we observed corresponding clinical and oculomotor findings. With just a smaller number of children with dyslexia or DLD (N = 5, **Table 1**) where we found standard eye movements, we may assume, according to the dual modal, a normal function of the dorsal path and a malfunction of the ventral path, which clinical examinations have determined. In contrast, we found subnormal eye movements in five typically-developing children (**Table 1**). Hypothetically, we could infer a malfunction of the dorsal path and the normal function of the ventral path. In both of these groups of children, a comparison of clinical and oculomotor findings could suggest an isolated occurrence of the disorder (either in one or the other path). The reasoning behind this interpretation is merely hypothetical and a confirmation would demand an application of neuro-imaging methods.

4.4 Antisaccadic task and executive functions

The antisaccadic task is widely regarded to be one of the tests of executive functions [43]. Executive functions represent a broader construct, to which planning, generativity, inhibition, set-shifting, working memory and attentional control are usually integrated [44]. The antisaccadic task is used to investigate especially cognitive flexibility and response inhibition [25].

Our study showed deterioration of antisaccadic performance in both clinical groups, dyslexic and DLD group. Both clinical groups made fewer correct antisaccadic reactions and more directional errors than the control group. At the same time, the differences between the two clinical groups were insignificant (**Table 3**). The antisaccadic task did not require language/reading skills. Poor performance in the antisaccadic task in our clinical groups can therefore not be explained by a deficit in language/reading, but by a deficit in executive processing. There is no doubt that in our antisaccadic task, inner speech as a language tool could help facilitate the antisaccadic performance, but it was probably not the sole source of antisaccadic difficulties because the antisaccadic task did not require inner speech to perform well. The problems of dyslexic and DLD subjects in the antisaccadic task were also observed by other authors, cited in the Introduction (subchapters 1.2 and 1.3). We found fewer published studies of eye movements in DLD subjects in the antisaccadic task – most likely because language is perceived as a qualitatively different function from sensorimotor functions, which include eye movements. Dyslexics need visuo-spacial processing for reading with which eye movements correlate. However, mutual comparisons of antisaccadic performance of subjects with dyslexia and DLD are probably rare; hence we cannot verify the results of our study from studies by other authors.

4.5 Oculomotor tasks vs. differential diagnostics

Based on our finding that both language disorders (dyslexia, DLD) were reflected in the non-linguistic oculomotor tasks, we conclude that brain networks, which are the basis of all language functions, are connected to the networks that control eye movements. Because antisaccades specifically activate the dorsolateral prefrontal cortex [25], the antisaccadic task is a useful tool for investigating frontal dysfunction and volitional processes. However, the antisaccadic task is unlikely to be useful for any differential diagnostics between dyslexia and DLD, because the same mistakes in the antisaccadic task are made by schizophrenics or neurological patients [25]. A more specific test for language/reading in comparison with the antisaccadic task seems to us to be the self-pacing task. In addition to volitional processes, this task also requires hierarchical sequencing which is the core component of syntactic processing. The task is not limited only to language stimuli and is not demanding on the working memory. In line with the review fMRI studies of language [45, 46] we believe that the performance in the self-pacing task will be more connected with the involvement of the left dorsal pars opercularis, which also serves non-linguistic syntax, and that the performance of the self-pacing task is less connected with the involvement of the left ventral pars opercularis, which serves working memory and sequencing of articulatory events. The left ventral pars opercularis is therefore a more specific language area than dorsal pars opercularis.

4.6 Are dyslexia and DLD being distinctive disorders?

Researchers ask whether their relationship can be characterized as sisterly or whether one is a mother and the second is the child, or possibly if they are independent of each other [44]. Various models have been proposed to address this issue, and we regard the multidimensional model to be the most appropriate one [9, 10], see Introduction. We would classify the oculomotor finding at the behavioral level. Therefore, we do not expect the oculomotor examination to provide a comprehensive answer to this question. However, it can enrich it with a new aspect. In our oculomotor test, the profiles of DLD subjects were similar and differed only in the degree of deviation; in dyslexics, the deviations from the controls were greater, see **Figure 1**. Oculomotorically, both disorders appear to us to be close. Although they are studied under the classification of linguistic disorders, we can also characterize them with a common non-linguistic symptomatology, specifically the oculomotor. According to our study, the oculomotor (non-linguistic) accompaniment of both disorders is the rule rather than the exception and makes them, at the symptomatology level, to a large extent also non-linguistic disorders. From our study's perspective, the causal relationship between the linguistic nature of both disorders and eye movements remains unclear: is a language disorder the cause of the deviant eye movements or are the deviant eye movements the cause of a language disorder? Or do both deviations, linguistic and oculomotor, have a common cause?

4.7 Implications of the study

We currently see the benefits of our study in the research dimension. It would be premature to talk about the transfer of this method based on the measurement of eye movements into the clinical practice of child psychologists, special needs teachers/speech therapists, pedopsychiatrists or others. The study showed the promising potencies of this method for the diagnostics of dyslexia and developmental language disorder. However, it pointed out a number of issues that will need to be resolved before the method can be transferred to the field. First, eye movements as a manifestation of brain activity contain a lot of information about various mental functions; we can now register by far not all the information and that we can register is difficult to differentiate diagnostically. Second, the oculomotor tasks used in the examination of eye movements are, in fact, the questions we ask the examined subject-a child in oculomotor language. The child answers us, again in oculomotor language. To get a valid and reliable answer, we must also ask a high quality question. This area of oculomotor tasks therefore requires further research efforts. Third: the child is highly teachable and their brain is highly plastic and dynamically evolving. This characteristic is reflected in the oculomotor performance. When, at what stage of development is it possible to identify impending pathological dispositions, such as dyslexic or DLD-dispositions or schizophrenic dispositions, and to differentiate them from developmentally normal fluctuations and also from each other? How can all these peculiarities, developmentally normal and developmentally abnormal, be embodied in the standards of oculomotor performance? What will we consider in oculomotor performance defined by different tasks as a norm, as a broader norm, as a borderline finding, as a pathology? Fourth: in the diagnostic use of eye movements, we work with measurement parameters at the level of units of milliseconds and angular minutes. Is this a sufficient sensitivity or will it be necessary to register finer differences?

5. Conclusion

Both language disorders, dyslexia and DLD, are also characterized by non-linguistic manifestations, specifically by eye movements that have been tested using non-linguistic tasks. Oculomotorically, we were able to differentiate (a) a group of children with dyslexia and/or DLD from a group of children typically developing; (b) a group of children with dyslexia from a group of children with DLD. According to our results, the cognitive basis of these differences is a result of an altered executive processing, the neural substrate of which is regarded to be the prefrontal cortex. Executive processing in dyslexics seems to us to be worse in comparison with DLD subjects in the conditions of the employed oculomotor tasks.

We interpret the discrepancies between the clinical and oculomotor classification by the peculiarities of the language environment. The morphologically demanding Czech environment conceals the milder degrees of DLD, while the dyslexic difficulties penetrate more easily to the forefront of clinical attention. Hypothetically, the location of the disorder may also be involved in the discrepancies. According to the dual model, the dorsal stream is suspected to induce oculomotor problems as well as ventral stream semantic problems.

From these findings we conclude that the oculomotor examination in the conditions of non-verbal tasks may contribute to (a) the diagnostics of the neurodevelopmental disorders of the linguistic type, dyslexia and DLD; (b) the differential diagnostics of these disorders. The oculomotor examination under the conditions of non-verbal tasks appears to us as a screening method with good prospects for these disorders in the pre-school population.

The study indicated that the oculomotor examination under the conditions of non-verbal tasks has a promising potential for diagnostics. However, much research effort is likely to be required before this method, as sufficiently valid and reliable, can be transferred into the clinical practice.

Conflict of interest

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Ethical Standards and informed consent

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revized in 2000. Informed consent was obtained from all participants for being included in the study.

Author details

Zuzana Bilkova[1], Martin Dobias[2], Jaromir Dolezal[3], Vratislav Fabian[2], Helena Havlisova[1], Jiri Jost[1] and Olga Malinovska[1]*

1 Faculty of Education, University of South Bohemia, Czech Republic

2 Faculty of Electrical Engineering, Czech Technical University in Prague, Prague, Czech Republic

3 Czech Institute of Informatics, Robotics and Cybernetics, Czech Technical University in Prague, Czech Republic

*Address all correspondence to: omalinovska@pf.jcu.cz

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