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Fixation disparity curve in dyslexic adults

ALICJA BRENK-KRAKOWSKA*, MILENA SZADY, RYSZARD NASKRĘCKI

Laboratory of Vision Science and Optometry, Faculty of Physics, Adam Mickiewicz University, Umultowska 85, 61-614 Poznań, Poland

*Corresponding author: ali_bk@amu.edu.pl

Dyslexia is a worldwide disorder in children and adults. The visual characteristics of dyslexics has been studied with variable results. One area of interest is fixation disparity (FD). This is a measure of alignment of the oculomotor system during binocular fusion. A graphical plot of the FD as it changes as a function of induced prisms before the eyes results in a forced vergence fixation disparity curve (FDC). The associated phoria is defined as the prism needed to return the FD to the ortho position.

We performed FD evaluations and compared FDC characteristics with a group of 50 subjects: 25 dyslexic adults and 25 typically reading adults. The comparisons suggest that exo FD and the absolute amount of associated phoria tend to be higher in dyslexic adults. Moreover, they experience more instability of FD compared to the controls. They also have more limited convergence range and total vergence range. Both instability in motor responses and reduced vergence ranges indicate that binocular instability is likely to occur in dyslexic adults.

Keywords: binocular vision, clinical visual optics, developmental dyslexia, fixation disparity, optometry, Wesson fixation disparity card.

1. Introduction

Fixation disparity (FD) is the condition in which the images of a bifixated object are not imaged exactly on corresponding retinal points but are still within Panum's fusional area. If the eyes are slightly under-converged for an object of regard, the exo FD occurs and conversely when they are over-converged, there is an eso FD. It is influenced by the sensory vision system and changes with the introduction of visual stress factors such as lenses and prism. FD is thought to occur when the fusional system of vision is under stress from a decompensated heterophoria* [1]. Previous studies have shown

* Heterophoria is a deviation of the lines of sight from bifixation of the object of regard when the fusion is eliminated. It is commonly measured with the Maddox rod, von Graefe method or with the objective cover test (measurements under dissociated conditions). Usually heterophoria is compensated (*i.e.* symptom free). When the heterophoria is not overcome by fusional vergence, symptoms appear and heterophoria becomes decompensated.

a lack of relationship between symptoms** and a degree of heterophoria [2, 3] and suggested that FD is a better indicator of a decompensated (symptomatic) heterophoria [4, 5]. The vergence system is more influenced by the motor fusional system. FD can be measured objectively with an eye tracker system, but in clinical practice it is most often measured subjectively by two methods. One is qualitative measuring the amount of FD. These devices can determine the prismatic or spherical power that eliminates the FD (Mallett unit [5, 6]). Other, quantitative devices allow the measure of the angular amount of FD (the Wesson card [7] or disparometer [8]). An advantage of FD measurements over heterophoria-vergence testing is that the data are gathered under fused conditions.

FD changes when fusional vergence demand is altered with base in (BI) and base out (BO) prisms [9]. Usually exo FD increases directly with increasing amounts of BO prism and eso FD tends to be higher with increasing amount of BI prisms [10]. A graphical plot of FD changes as a function of the power of prisms introduced before the eyes produces a forced vergence fixation disparity curve (FDC). The major diagnostic features of FDC are: x-intercept (associated phoria), y-intercept (the actual amount of FD in minutes of arc without any prism), slope of the curve and type of curve, defined from the shape of curve [10, 11]. The associated phoria is most widely used as a descriptive characteristic of FD. In studies that plotted FDCs, the curve (y-intercept, slope and type of curve) has been shown to be a better predictor of symptoms [4, 10, 12]. Some have reported that the y-intercept of FDC [4, 13] and their slope [4, 14, 15] are the best discriminators of patient symptoms. The curve slope shows the ability of the visual system to cope with different visual demands. A flat slope indicates the ability to adapt to visual changes while a steep slope suggests the inability to adapt. FDCs were described and classified into four types from I to IV by OGLE *et al*. [16]. Type I curves are usually associated with asymptomatic patients and are most frequently found. Other types are often associated with high dissociated heterophoria (types II–III) and unstable binocularity (type IV). SHEEDY and SALADIN state the curve type to be one of the main parameters associated with symptoms [4].

The vergence ranges and stability of response are the two parameters which are also possible to be obtained during FD measurements. Through increasing amounts of BI and BO prisms, presented in discrete steps, one estimates the break and recovery ranges of fusional vergence [10]. Stability, another aspect of FD measurement, is found when an individual notes movement or instability of the response during FD measurements. The amplitude of movement, assessed clinically, may be as high as 10 min of arc or more [12].

** EVANS (2007) classified the symptoms of decompensated heterophoria (symptomatic heterophoria) into three categories: visual symptoms (blur, diplopia, distorted vision); binocular difficulties (difficulty with stereopsis, monocular viewing comfort, difficulty changing focus); and asthenopia (headache, aching eyes, sore eyes, general irritation) [1]. Individuals are able to maintain binocular vision but do so with asthenopia, blur and often with intermittent diplopia.

FDC can characterize the vergence and accommodative interactions under binocular conditions [10] and may provide information on the ability of the visual system to maintain fusion. The FDC can then reveal disturbances in binocular vision and it is also possible that such disturbances may occur more frequently in developmental dyslexia [17–21]. Dyslexia is defined as a specific reading disorder despite normal intelligence and conventional teaching. It affects about 10% of population [22] and is traditionally characterized by specific difficulties in reading and writing that do not result from a mental handicap, damage of sense organs (vision or hearing), emotional and behavioral disorders, or socio-cultural failure [23]. Previous studies have pointed out problems in the convergence-accommodation system including reduced vergence ranges [18, 24], poor convergence [19] and impaired accommodation [18] in dyslexic children. Stein and Fowler have shown inferior binocular vergence control or binocular instability in dyslexic children testing with a synoptophore version of the Dunlop test (DT) to evaluate ocular motor integration [25]. Some researchers believe that the DT assesses the stability of ocular motor dominance and in turn would indicate vergence capabilities to maintain fusion [20, 25, 26]. However, the DT is controversial and some researchers have found it unreliable [27].

Binocular instability, as a separate condition from decompensated heterophoria or strabismus, is characterized by both reduced vergence ranges and unstable heterophoria [1]. It is often associated with symptoms of asthenopia, blurring, symbol reversals and eyes jumping from one line to another when reading [1]. Such symptoms are often reported by dyslexics [20]. Evans *et al*. reported clinically that binocular instability was correlated with dyslexia [18] showing significantly reduced vergence ranges (lower than 20Δ) and exhibited vergence instability under dissociated conditions at near. This instability was defined as a movement of the arrow in the Maddox wing test more than $\pm 2.0\Delta$ [18]. They also have reported no differences in the associated phoria or stability of response (stability of FD) obtained with the Mallett unit between dyslexic children and the control group [18]. However, the literature generally suggests that an unstable heterophoria is usually more evident when it is manifested as an unsteady response on FD testing (*e.g*. the Mallett unit) [1].

Objective measurements of eye movements with eye trackers have shown deteriorated binocular control of saccades and vergence in dyslexics diagnosed both with single targets [28, 29] as well while reading text [30]. This supports the possibility that unstable fusion is correlated with dyslexia. Furthermore, overall FD has been found to show a tendency to be slightly greater for dyslexic children in text reading [30]. Conversely, others found no difference in the amount of FD between dyslexic children and age-matched controls when performing a simple fixation task [31] or single word reading task [26]. Recently, Kirkby *et al*. have shown that the type of task might affect the amount of FD in dyslexic children [32]. Increased FD was observed solely when dyslexics were reading [32].

In conclusion, dyslexics possibly show inferior binocular coordination manifested by a tendency for larger FD [30] as well as variability of the FD [20, 30]. FD measurement is usually considered as ancillary vergence testing if the FDC is plotted.

FDC testing appears a more reliable method for testing binocular function, particularly with those who exhibit problems in reading. We contend that testing under dissociated conditions may not accurately reflect the way the visual system performs under binocular conditions. Thus, FD testing represents a more reliable measure when a participant is reading since it is performed under binocular condition.

The purpose of this study was to evaluate the binocular vision factors under fused conditions by plotting FDC and the fusional range together with stability of response (stability of FD) in the group of dyslexic young adults.

2. Method

Data were collected in one optometric examination in a vision training room at the Laboratory of Vision Science and Optometry (Faculty of Physics, Adam Mickiewicz University, Poland). All data were subjected to a test of normality (the Shapiro–Wilk test). When the results came from a normally distributed population and the variances of the two populations were also equal, the unpaired Student's *t*-test was used. This was assumed for the following variables: rate of non-word reading, time of Spoonerism test and vergence ranges.

For the rest of variables, the assumptions were not met and non-parametric tests were used (the Mann–Whitney test, corrected for ties or the Mann–Whitney *U* test for small sample size). Moreover, if the variables were categorical (assessed on a nominal scale) then the chi-square test (χ^2) with Yates's correction for continuity was applied.

2.1. Participants

Fifty university students (25 dyslexic and 25 at an adult reading level) were asked to participate in this study. All participants were native speakers of Polish. The dyslexics (11 females and 14 males; 20–25 years of age, $M = 21.9 \pm 1.6$) had a documented history of dyslexia: formal assessment of developmental dyslexia provided by qualified psychologists on the basis of significant discrepancies between literacy skills and other cognitive abilities. Non-dyslexics (12 females and 13 males; 19–29 years of age, $M = 22.9 \pm 2.5$) reported no reading problems. All participants had normal or corrected to normal visual acuity and no suppression at near.

2.2. Cognitive abilities and literacy skills assessment

Besides the documented history of dyslexia, the participants' cognitive abilities and literacy skills were investigated. Characterisation of the participants is presented in Tab. 1. Cognitive abilities were measured by Raven's progressive matrices test [33]. The difference between the two groups in terms of cognitive ability occurred non-significant ($p = 0.370$). However, the participants with dyslexia did make more errors and it took them more time to perform the literacy and phonological tasks

T a b l e 1. Characterisation of the dyslexic and control groups participating in the study.

	Dyslexics ($N = 25$)			Controls ($N = 25$)			Statistics
Variable	Mean	SD	Median	Mean	SD	Median	Z or t
Age (years)	22.9	2.5	23.0	21.9	1.6	22.0	–1.65; NS
Raven test (standard score)	91.8	7.3	93.0	89.2	11.0	93.0	–0.9; NS
Word-chain: time (sec)	124.4	39.2	109.0	71.0	11.3	70.5	-5.83^{***}
Word-chain: errors	0.7	0.9	0.5	0.2	0.2	0.0	-2.57^{*}
Sentences-chain: time (sec)	136.0	28.8	125.5	91.8	17.1	94.0	-5.42^{***}
Sentences-chain: errors	1.4	1.5	1.0	0.4	0.5	0.0	-3.85^{***}
Rate of word reading (mean correct in 30 sec; max = 75)	56.7	8.7	56.0	69.6	4.4	70.5	4.80^{***}
Rate of word reading: errors	0.9	0.7	1.0	0.4	0.5	0.0	-2.62^{**}
Rate of non-word reading (mean correct in 30 sec; max = 69)	29.8	5.7	29.5	40.3	4.9	40.5	6.93^{***}
Rate of non-word reading: errors	2.7	1.8	2.5	1.8	1.2	1.5	-1.97^{*}
Spoonerism: time (sec)	185.3	48.3	182.0	104.4	39.3	98.0	6.49^{***}
Spoonerism: errors	4.6	2.6	5.0	1.8	1.3	1.0	-4.12^{***}
Correct writing: time (sec) (orthographic skills)	215.4	57.2	216.0	117.3	24.5	113.5	-5.49^{***}
Correct writing: errors (orthographic skills)	10.1	4.5	10.0	3.3	1.5	3.0	-5.40^{***}

NS – non-significant; significant differences: $p \leq 0.05$ (*), $p \leq 0.01$ (**), $p \leq 0.001$ (***).

comparing to non-dyslexic adults. Reading and spelling ability were tested using the word-chain, sentence-chain tests [34], the rate of word and non-word reading test. The word-chain test is composed of a list of 44 eleven-letter strings being a combination of two words. Participants were asked to separate them into two words by drawing short vertical lines, as fast and accurately as possible. The sentence-chain test contains 31 sentences written without capitals at the beginning and full stops at the end. Participants were asked to separate the sentences with short vertical lines, as fast and accurately as possible. The rate of word and non-word reading test is the Polish adaptation of the TOWRE test used in Great Britain (test of word reading efficiency) [35]. Moreover, the participants were given Polish adaptation of the Spoonerism task [36] that tests the ability to segment and manipulate phonemes. The dyslexic group performed worse than the controls on all administered tests.

2.3. Visual function measurements

Changes in the FD with an increasing amount of prism were determined with the Wesson fixation disparity card [7] in its original, English version. It is a commonly used [7, 37–41] device to generate FDCs and it is a modern variant of the Woolf card. The Wesson card consists of a series of color lines separated by 1 mm and an arrow located below these lines. When polarized filters are worn, one eye sees the arrow and the other sees the colored lines. The Wesson card was mounted on a phoropter reading rod. The testing distance was 40 cm from the spectacle plane and the participants wore their habitual corrections (contact lenses or spectacles). An appropriate accommodation response was stimulated by instructing the participants to keep the words at the side of the central, polarized area as clear as possible while the assessment was being made. The participant was told to observe and report the position of the arrow in relation to the red ortho line. Different prisms were then introduced. A scale on the card showed the amount of FD in min of arc in relation to the color line which was indicated by the arrow. FD was determined by introducing prisms from 0 to 15 prism diopters (Δ) in increments of 3Δ, alternating BI prism with BO prism (0, 3Δ BI, 3Δ BO, 6Δ BI, 6Δ BO, *etc*., to 15Δ or until diplopia was reported). The examiner recorded FD for each amount of prism as well as the stability of response (stability of FD) without induced prism (movement of arrow or lines, any fading or flickering of those).

Each participant's results from different FDs were plotted to form a FDC. The four parameters were determined: x-intercept, y-intercept, curve slope and curve type (Fig. 1). The x-intercept or associated phoria was the point where FDC crossed the x-axis or the amount of prism where FD equals zero. Generally, there is no single amount of prism that reduced FD but rather a range of different values [42, 43]. If there were more than one prism setting for which FD was zero, the associated phoria with the lowest prism power was chosen. For one subject (from the dyslexic group) FD curve did not cross the x-axis thus x-intercept was not established. The x-intercept was first analyzed for the magnitude with direction of deviation (BO as positive and BI as negative) and then for the absolute magnitude (without direction). Likewise the y-intercept was the point where FDC crossed the y-axis, as a result of FD in

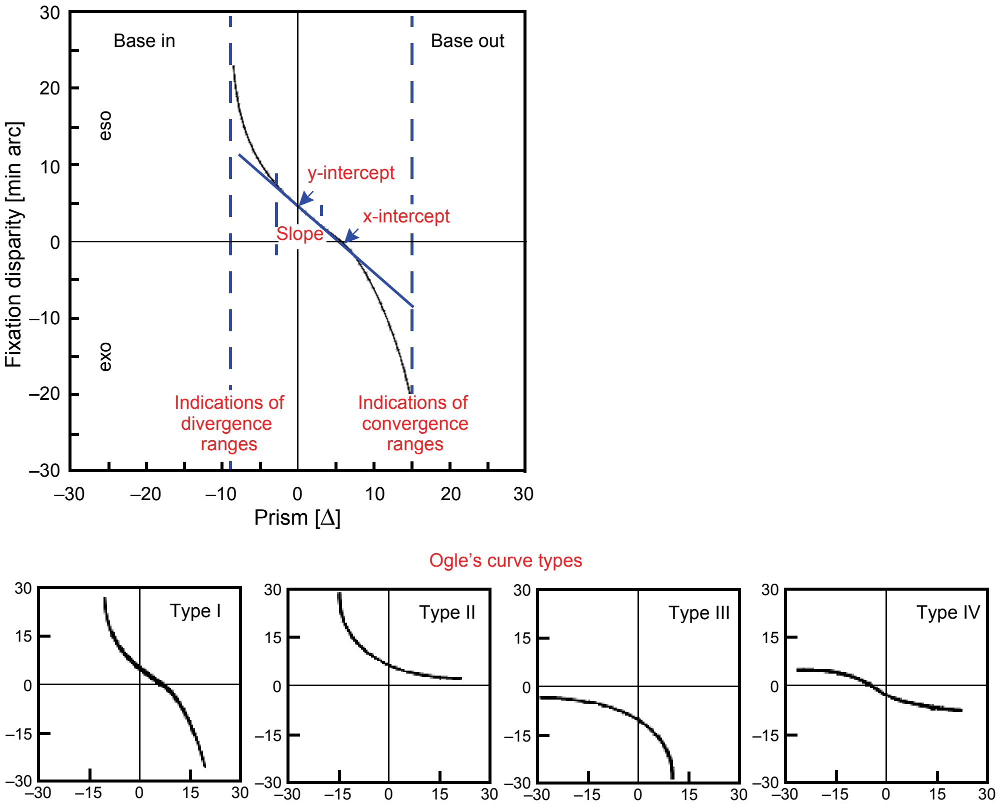

Fig. 1. The major fixation disparity curve features: x-intercept, y-intercept, slope and type of curve.

min arc present with no induced prism. The y-intercept was first analyzed for the magnitude with direction of deviation (eso-deviation as positive and exo-deviation as negative) and then for absolute magnitude (without direction). The curve slope was estimated by calculating the change in FD between prisms 3Δ BI and 3Δ BO: the FD at 3Δ BI was subtracted from the value at 3Δ BO and the result was divided by 6Δ. Slopes were not determined for the participants who had diplopia at the 3Δ BI or 3Δ BO (dyslexic group $n = 5$, control group $n = 2$). FDCs were described and subjectively classified as one of the four standard curve types (from I to IV by OGLE *et al*. [16]). There were several cases (dyslexic group $n = 5$, control group $n = 2$) where the curve type could not be classified as one proposed by Ogle. Those curves were classified as unknown type (type U) [41].

The application of increasing amounts of BI and BO prisms in 3Δ steps gave an estimation of limits for fusional ranges. Vergence ranges should be measured to the limits of the fusion when the participants report diplopia (or suppression) [11]. Since a modified method for the curve generation was applied [10, 44], diplopia (or suppression) was not found for each participant (BI: dyslexics $n = 2$ and controls $n = 1$; BO: dyslexics $n = 0$ and controls $n = 5$). It was assumed for analysis that when there was no diplopia or suppression, the next step of prism (18Δ) was taken as the limit of vergence ranges. Thus, the indications of vergence ranges were measured rather than the actual vergence ranges.

In addition, while measuring FD without prisms, the participants were asked if lines or arrow moved and/or if the targets (arrow or lines) ever faded away. Thus the stability of response was assessed in three categories as *motor instability*, *sensory instability* and *sensory-motor instability* [18]. Motor instability was defined as a movement of either the arrow or lines. The sensory instability occurred when the arrow or the lines faded or flickered. Sensory-motor stability was the occurrence of both sensory and motor instabilities. The response was classified as unstable (scored as 1) or stable (scored as 0).

3. Results

3.1. Near fixation disparity curve (FDC)

The three main parameters of FDC (*x*-intercept, *y*-intercept and slope) where analyzed with the Mann–Whitney U test since distributions were not normal. The median value of *x*-intercept (associated phoria) was –2.4Δ (exophoria) in dyslexic group and 0.0Δ in controls. Differences in *x*-intercept were non-significant ($Z = 1.00$, $p = 0.316$), indicating that the associated phoria was similar in both groups. However, there was a tendency ($Z = -1.87$, $p = 0.061$) for the absolute magnitude of near associated phoria to be greater for dyslexics (median 3.0Δ) than for controls (median 1.0Δ). Moreover, there was a non-significant tendency ($Z = 1.71$, $p = 0.087$) for exo FD in dyslexics when compared to controls (–4.3 vs. 0.0 min arc). The median absolute magnitude of *y*-intercept was 4.3 min arc for the dyslexic group and 2.2 min arc for controls, but the differences were not statistically significant ($Z = -1.59$, $p = 0.111$). The descriptive and comparative statistics showed no difference between slopes in the groups (–1.1 vs. –1.1 min arc per prism diopter; $Z = 0.47$, $p = 0.641$). FDC parameters for both groups are presented in Tab. 2.

The distribution of the curve types is given in Table 3. Curves typed I were most common in the control group while the curves of type II, III and IV where almost equally represented in both groups. It was more difficult to classify all curves into the four types according to Ogle for the participants from the dyslexic group than for those from the control group (U curve type: 20% dyslexic vs. 8% non-dyslexics). However, no statistically significant differences were found in the distributions of the curve types in both groups ($\chi^2 = 2.17$, $p = 0.705$; the Pearson χ^2).

3.2. Indications of near vergence ranges

The mean divergence range was 9.7Δ and 10.7Δ in the dyslexics and control group, respectively. This difference was not statistically significant ($Z = 1.51$, $p = 0.132$). The mean value of BO diplopia in the dyslexic group was 9.1Δ while in the control group it was 12.4Δ. The convergence range was significantly different in these two

T a b l e 2. Fixation disparity curve parameters in dyslexic and control group.

	Dyslexics				Controls				Statistics
Variable	Mean (SD)	Median	Min	Max	Mean (SD)	Median	Min	Max	*Z*
x-intercept [Δ]	–2.3 (4.1)	–2.4	–9.0	6.0	–1.3 (2.9)	0.0	–8.3	3.0	1.00; NS
x-intercept absolute [Δ]	3.6 (3.1)	3.0	0.0	9.0	2.0 (2.4)	1.0	0.0	8.3	–1.87†
y-intercept [min arc]	–8.3 (11.7)	–4.3	–34.4	4.3	–3.0 (9.1)	0.0	–34.4	17.2	1.71†
y-intercept absolute [min arc]	9.4 (10.8)	4.3	0.0	34.4	5.2 (8.0)	2.2	0.0	34.4	–1.59; NS
Slope [min arc/Δ]	–1.2 (1.2)	–1.1	–4.3	0.7	–1.1(0.9)	–1.1	–2.9	0.0	0.47; NS

Signs for *x*-intercept are negative for base-in and positive for base-out. Signs for *y*-intercept are negative for exo fixation disparity and positive for eso fixation disparity. The comparative statistic: the Mann–Whitney U test, corrected for ties. Non-significant (NS); non-significant tendency (†).

T a b l e 3. Distribution of curve types obtained with the Wesson card for dyslexic and control group.

Curve type	Dyslexics $N = 25$ (*n* [%])	Controls $N = 25$ (*n* [%])	All $N = 50$ (*n* [%])
I	32.0 (8)	44.0 (11)	38.0 (19)
II	28.0 (7)	24.0 (6)	26.0 (13)
III	16.0 (4)	16.0 (4)	16.0 (8)
IV	4.0 (1)	8.0 (2)	6.0 (3)
U	20.0 (5)	8.0 (2)	14.0 (7)

T a b l e 4. Indications of vergence ranges in dyslexic and control groups.

	Dyslexics				Controls				Statistics
Variable	Mean (SD)	Median	Min	Max	Mean (SD)	Median	Min	Max	*Z* or *t*
BI diplopia [Δ]	9.7 (3.9)	9.0	6.0	18.0	10.7 (3.2)	12.0	3.0	18.0	1.51; NS
BO diplopia [Δ]	9.1 (4.4)	12.0	3.0	15.0	12.4 (3.9)	12.0	6.0	18.0	2.34*
Ranges [Δ]	18.8 (4.5)	21.0	12.0	30.0	23.0 (5.7)	24.0	12.0	36.0	2.89**

The comparative statistic: the Mann–Whitney *U* test, corrected for ties (diplopia BI and BO) and the Student's *t*-test (ranges). Non-significant (NS); significant differences: $p \le 0.05$ (*), $p \le 0.01$ (**).

groups ($Z = 2.34$, $p = 0.019$). Moreover, statistical analysis (unpaired *t*-test) demonstrated that the vergence ranges were significantly reduced in the dyslexic group (18.8 vs. 23.0Δ; $t = 2.89$, $p = 0.006$). These data are presented in Tab. 4.

3.3. Stability of response

According to the χ^2 test results (with Yates's correction), there was a difference between groups in motor stability: 64% of dyslexics and only 16% of subjects from the control group exhibited motor instability ($\chi^2 = 10.08$, $p = 0.002$). The sensory stability was similar in two groups (stable for 92% dyslexics vs. 100% for controls ($\chi^2 = 0.52$, $p = 0.470$). The sensory-motor stability was different in the groups studied and instability was detected in a larger number of the dyslexic group members (72 vs. 16%; $\chi^2 = 13.72$, $p = 0.000$). These data are presented in Tab. 5.

3.4. Additional analysis

Comparison of stability of motor response and amount of FD (absolute magnitude of *y*-intercept) showed that the absolute FD were statistically greater in dyslexics who had unstable motor response (8.6 vs. 2.2 min arc; $Z = -2{,}50$, $p = 0.012$) and this relationship was also significant when both dyslexic and non-dyslexic groups were combined (8.6 vs. 0.0 min arc; $Z = -3.04$, $p = 0.002$). Most of the controls did not demonstrate motor instability and the comparison in this group did not reach significance (6.3 vs. 0.0 min arc; $U = 29.50$, $p = 0.369$). Comparative analysis between stability of motor response and relative FD (the magnitude of *y*-intercept with direction of deviation) showed a larger exo FD in the dyslexic group who had unstable motor response (–8.6 vs. 0.00 min arc; $Z = -2.64$, $p = 0.008$). This was also true when dyslexics and controls were combined (–8.6 vs. 0.00 min arc; $Z = 2.12$, $p = 0.034$). Most of the controls did not demonstrate motor instability and the comparison in this group did not reach significance (3.3 vs. 0.0 min arc; $U = 24.50$, $p = 0.203$). These data are presented in Tab. 6.

4. Discussion

There is an evidence of sensorimotor deficits in dyslexics, including auditory processing [45], visual processing [46] and motor (cerebellar) control [47] impairments. If these deficits include ocular motor problems is still an open question [48]. Much research has been reported on the visual function of dyslexic children [18–21, 29, 49], little is known about the visual parameters in young dyslexic adults.

Most of the authors have suggested problems in convergence-accommodation system of dyslexic children, including reduced vergence ranges, poor convergence (or divergence), impaired accommodation and inferior binocular vergence control [18, 20, 21, 24, 25]. JANITA and KAPOULA have shown that while reading a text, dyslexic chil-

T a b l e 5. Stability of response during the Wesson FD test in dyslexic and control groups.

	Dyslexics $N = 25$		Controls $N = 25$		Statistics
Variable	Stable (n [%])	Unstable (n [%])	Stable (n [%])	Unstable (n [%])	χ^2
Motor stability	36 (9)	64 (16)	84 (21)	16 (4)	10.08*
Sensory stability	92 (23)	8 (2)	100 (25)	0 (0)	0.52; NS
Sensory-motor stability	28 (7)	72 (18)	84 (21)	16 (4)	13.72**

The comparative statistic: the Yates's χ^2 test, $p \le 0.05$ bolded.
Non-significant (NS), significant differences: $p \le 0.01$ (*), $p \le 0.001$ (**).

T a b l e 6. Relationship between the variables.

		Unstable motor response				Stable motor response				Statistics
	Variable	Mean (SD)	Median	Min	Max	Mean (SD)	Median	Min	Max	Z or U
y-intercept absolute [min arc]	All $N_1 = 20; N_0 = 30$	12.1 (11.1)	8.6	0.0	34.4	4.1 (7.0)	1.1	0.0	34.4	–3.04**
	Dyslexics $N_1 = 16; N_0 = 9$	13.3 (11.8)	8.6	0.0	34.4	2.4 (2.5)	2.2	0.0	6.5	–2.50*
	Controls $N_1 = 4; N_0 = 21$	7.5 (7.3)	6.3	0.0	17.2	4.8 (8.2)	0.0	0.0	34.4	29.50; NS
y-intercept [min arc]	All $N_1 = 20; N_0 = 30$	–9.6 (13.5)	–8.6	–34.4	17.2	–3.1 (7.5)	0.0	–34.4	4.3	2.12*
	Dyslexics $N_1 = 16; N_0 = 9$	–12.8 (12.4)	–8.6	–34.4	4.3	–0.5 (3,5)	0.0	–6.5	4.3	–2.64**
	Controls $N_1 = 4; N_0 = 21$	3.3 (10.6)	2.2	–8.3	17.2	–4.2 (8.5)	0.0	–34.4	4.3	24.50; NS

The comparative statistic: the Mann–Whitney U test, and the Mann–Whitney test, corrected for ties.
Non-significant (NS); significant differences: $p \le 0.05$ (*), $p \le 0.01$ (**).

dren have a slight non-significant tendency to greater absolute amounts of FD [30]. They suggested that dyslexic children must deal with slightly larger disparities when fusing images of text and this might cause fatigue or more load on fusional capacities during the reading task [30]. In contrast, CORNELISSEN *et al*. reported no difference in the amount of FD in children with reading difficulties and controls as they read a paragraph containing single words [26]. These discrepant results are probably due to a type of task: more comprehensive vs. simple tasks, respectively. Our clinical results have showed that although the absolute amount of FD in dyslexic adults is greater, these differences in FD are statistically non-significant between the groups. To control accommodation, we required the participants to keep the words clear on the card. Since these words were written in English and the Polish students participated in the research, thus the task might have been more difficult for them to follow than for native English speakers. Recent studies have shown that the type of task might affect the amount of FD in dyslexic children. Increased FD was observed solely when dyslexics were participating in the reading task [32]. KIRKBY *et al*. speculate that the reason for an increased FD in dyslexics during reading task might be the allocation of attentional and/or cognitive resources to the reading process or suboptimal linguistic processing per se [32]. Conversely, others suggested that changes in FD and associated phoria are the result of visual stress and are not produced by reading itself [50].

Both objective [30] and subjective studies [31] have demonstrated that dyslexic children have a higher variability of FD. Increased variability of FD in dyslexics was shown during fixation to single non-linguistic targets [31] and during real text reading [30]. Conversely, EVANS *et al*. did not find any differences in motor response (thus variability of FD) during Mallett unit test in dyslexic children and controls [18]. Our study showed that the motor responses of dyslexic adults were statistically more unstable than those of the controls, while there was no difference in the sensory responses. Additional analysis of the relationships between the stability of motor response and the amount of FD showed that the absolute FD was statistically greater in dyslexics who had unstable motor responses and this relationship was also significant when both groups were combined. Most of the controls did not demonstrate motor instability.

One can argue that the Wesson card does not have a good foveal fusion lock and may provoke higher motor instability or that it does not reflect the actual condition during reading (good central fusion lock) [5]. The lack of central fusion lock in the Wesson card probably made it more difficult to maintain vergence stability and therefore may be a reason why the amounts of FDs obtained were greater and more variable [1]. Further investigation is needed to check if devices with good central fusion lock (*e.g*., the Mallett unit test) give similar responses in dyslexic adults as obtained in this study [55]. Some authors have previously suggested that unstable amounts of FD are associated with fluctuations of accommodative convergence [12]. Usually, there is an exo FD in these cases, since the accommodative lag (measured during dynamic retinoscopy, *e.g*., MEM Retinoscopy) is often large [12]. We also found a tendency toward exo FD in dyslexic adults. Moreover, a greater amount of exo FD was also associated with the occurrence of motor instability. Some other studies have shown an increase in exo FD after reading at very close distances [50–52]. It may be that increased exo FD is associated with vision fatigue [53, 54] and that dyslexic adults may experience this fatigue. We also found a slight tendency to a greater amount of associated phoria in dyslexics, while EVANS *et al*. did not find differences between dyslexic and non-dyslexic children [18]. This discrepancies may have resulted from the differences in the age groups (adults vs. children, respectively) and/or the testing devices (Wesson card vs. Mallett unit).

Dyslexic adults tendency to exo FD and higher amount of absolute associated phoria might be also the result of poorer vergence adjustments in dyslexic adults. Analysis of near divergence capabilities (BI vergence range) showed equality in both groups but convergence capacity (BO vergence range) was reduced in dyslexic adults. This caused the overall fusional capabilities (fusion ranges) to be less in dyslexic adults. These findings follow the data from the fusional ranges in dyslexic children, measured with the Risley prisms [18] and isolated prisms [49]. Conversely, KAPOULA *et al*. found that dyslexic children had reduced divergence capability, while the convergence fusional ranges were the same in both groups [21]. Their study did however report a near point of convergence significantly more remote in dyslexics. Those discrepancies in fusional ranges measured in children prompted deeper investigation into the actual vergence capability of dyslexic adults [55].

As reading distance is decreased, the demand on fusional processes increases [52] and, as shown in this study, dyslexic adults have tendency toward exo FD and reduced convergence capability. This condition might require more demand on their fusional processes [30]. This increased demand may also be a factor in the unstable motor and sensory-motor responses. The difference in the vergence ranges and more variable FD may provide a cue for clinical diagnosis of impaired vergence control in dyslexia. The absolute amount of associated phoria as well as the exo FD might be indicators for the diagnosis. Other FDC parameters (slope and type of curve) do not seem useful to assess vergence control of dyslexic adults.

Above-mentioned binocular problems of the dyslexics could be caused by a general senso-motor deficit [26, 56], impacting both the fusional processes and impaired control of vergence fusional processes. Thus, research that will provide accurate binocular eye movement data regarding FD during real text reading is needed. This research should focus on the hypothesis that visual abnormalities are correlated to dyslexia, or that they cause dyslexia.

5. Concluding remarks

Our results indicate that the associated phoria (x-intercept) in dyslexics is slightly greater when compared to those for non-dyslexic adults when measured with Wesson fixation disparity card. Dyslexic adults also show a tendency to more exo FD (y-intercept) than controls, but the absolute amount of FD was similar for both groups. Both the slope of the curves and the distribution of curve types did not differ in the two groups studied. It was difficult to classify all curves of the dyslexic group into the four types according to Ogle. Further analysis of the fusional vergence ranges suggest that the positive range of vergence (convergence) in dyslexics is reduced and that they might have problems with vergence control (motor and sensory-motor instability).

Therefore our results suggest that dyslexic adults have a tendency toward binocular instability.

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