Unstable Binocular Fixation Affects Reaction Times But Not Implicit Motor Learning in Dyslexia

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PURPOSE. Individuals with developmental dyslexia suffer not only from reading problems as more general motor deficits can also be observed in this patient group. Both psychometric clinical tests and objective eyetracking methods suggest that unstable binocular fixation may contribute to reading problems. Because binocular instability may cause poor eye–hand coordination and impair motor control, the primary aim of this study was to explore in dyslexic subjects the influence of unstable binocular fixation on reaction times (RTs) and implicit motor learning (IML), which is one of the fundamental cerebellar functions.

METHODS. Fixation disparity (FD) and instability of FD were assessed subjectively using the Wesson card and a modified Mallett test. A modified version of the Serial Reaction Time Task (SRRT) was used to measure the RTs and IML skills. The results for the dyslexic group (DG), which included 29 adult subjects (15 were tested binocularly, DGbin; 14 were tested monocularly, DGmono), were compared with data from the control group (CG), which consisted of 30 age-matched nondyslexic subjects (15 tested binocularly, CGbin; and the other 15 tested monocularly, CGmono).

RESULTS. The results indicated that the DG showed poorer binocular stability and longer RTs in the groups tested binocularly (RTs: 534 vs. 411 ms for DGbin and CGbin, respectively; P < 0.001) as compared with the groups examined monocularly (RTs: 431 vs. 424 ms for DGmono and CGmono, respectively; P = 0.996). The DG also exhibited impaired IML when compared with the CG (EFIML: 25 vs. 50 ms for DG and CG, respectively; P = 0.012).

CONCLUSIONS. Unstable binocularity in dyslexia may affect RTs but was not related to poor IML skills. Impaired IML in dyslexia was independent of the viewing conditions (monocular versus binocular) and may be related to cerebellar deficits.

Keywords: binocular instability, cerebellum, developmental dyslexia, fixation disparity, implicit motor learning

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developmental dyslexia is a common specific reading disability in individuals, which occurs despite normal intelligence, adequate environment, and educational opportunities. It affects approximately 5% to 10%1 of the population and is considered a life-long disorder. Individuals with dyslexia not only experience reading and writing problems but also more general motor and oculomotor deficits.2–4 The etiology of dyslexia remains unclear.

One of the most influential theories of dyslexia assumes that the disorder is directly and exclusively caused by a cognitive deficit specific to symbolic representations and the processing of speech sounds.5,6 The phonologic hypothesis claims that phonologic deficits (i.e., deficits in how words [printed letters] are uttered [relevant speech sounds]), cause reading difficulties in dyslectic individuals. However, the hypothesis fails to explain other nonlinguistic difficulties occurring in dyslexia, such as problems with postural stability1 or impaired visual processing (e.g., visuospatial attention6 or binocular instability9–11) that are common among dyslexic children and adults.

A contrary magnocellular hypothesis suggests that dyslexia might be caused by visual processing impairment rather than a linguistic problem12–14 and that reading problems arise from abnormal functions of the magnocellular visual pathway.15 This deficit is associated with low contrast sensitivity,16,17 impaired detection of motion,18,19 and poor eye movement coordination.20–23 Unstable binocular fixation and poor vergence control might induce symptoms, such as image blurring and/or unstable letters while reading.

The influence of oculomotor deficits in dyslexia is still under debate. There is growing evidence that indicates that unstable binocular fixation and saccadic disconjugacy may disturb word identification and, in addition to the phonologic deficits, might interfere with fusion and the reading process. In general, studies show that dyslexic children need more fixations and regressions, as well as demonstrate longer saccade amplitudes than nondyslexic controls.21,24 Eden et al.20 demonstrated unstable fixation and impaired vergence control following saccadic eye movements in children with dyslexia. The idea that unstable binocular fixation may at least contribute to reading problems is confirmed by psychometric clinical tests11 and the results of research using objective eyetracking methods.22,23,25,26
It seems that oculomotor deficits in dyslexia could be better explained by a cerebellar hypothesis, which assumes that dyslexic problems may arise from an impaired ability for motor learning and automatization process. The cerebellum is involved in movements executed automatically and implicitly (procedural) motor learning (IML). IML refers to the process of gradual improvement of motor performance through practice without any knowledge of theoretical rules or conscious intention to learn. Studies have shown that cerebellar activity is high at the beginning of the acquisition phase and gradually decreases later in the process of learning a movement sequence. More evidence for the cerebellar involvement in IML comes from studies on subjects with cerebellar damage who demonstrated impaired IML with other types of motor learning skills remaining intact.

A modified version of the Serial Reaction Time Task (SRTT) is usually employed to evaluate the level of IML skills. During this task, subjects perform movements (e.g., hand or finger movements) in a planned sequential order. The subjects are not aware of any of the sequences used in the tests but their performance will nevertheless improve with practice as a result of automatic motor learning mediated by the cerebellum. At the end of the task, the previously learned sequence of the stimuli/movements turns into a new subconscious order, which leads to an increase in reaction times (RTs) if the subject has implicitly learned the old pattern. When IML occurs, RTs increase with each new sequence of stimuli/movements (for a better understanding of the IML evaluation using SRTT see Ref. 39).

SRTT has been used to test the ability for motor learning in dyslexic adults and children who demonstrated poor IML skills, interpreted as a result of cerebellar deficits. Menghini et al. used functional MRI data to demonstrate different patterns of brain activation in dyslexic subjects during an IML test. The lack of supplementary motor area activity was accompanied by higher parietal and cerebellar activity during the whole motor learning process. High cerebellar activity is necessary during the early phase of learning when associations between a series of spatial locations and adequate motor responses are being formed. With practice, when the error signal arising from the comparison between the actual and the expected position decreases, cerebellar activity gradually declines. Normally, lower cerebellar activity in the late stage of learning shows that an internal model of movement sequences has been created in the cortex. Thus, high cerebellar and parietal activity in dyslexia during the whole learning process, associated with low supplementary motor area arousal, may suggest that dyslexic subjects have problems with building the internal model of movements, possibly due to cerebellar dysfunctions.

However, not all studies on motor learning have confirmed deficits in IML in dyslexic patients. For example, Kelly et al. found IML to be intact in adults with dyslexia. Howard et al. found IML to be intact in children with dyslexia. Menghini et al. used functional MRI data to demonstrate different patterns of brain activation in dyslexic subjects during an IML test. The lack of supplementary motor area activity was accompanied by higher parietal and cerebellar activity during the whole motor learning process. High cerebellar activity is necessary during the early phase of learning when associations between a series of spatial locations and adequate motor responses are being formed. With practice, when the error signal arising from the comparison between the actual and the expected position decreases, cerebellar activity gradually declines. Normally, lower cerebellar activity in the late stage of learning shows that an internal model of movement sequences has been created in the cortex. Thus, high cerebellar and parietal activity in dyslexia during the whole learning process, associated with low supplementary motor area arousal, may suggest that dyslexic subjects have problems with building the internal model of movements, possibly due to cerebellar dysfunctions.

In the present study, SRTT was used for evaluation of the IML skills in young adults with dyslexia and to investigate the influence of unstable binocular fixation on motor performance (RTs). The authors expected that impaired binocular fixation would disturb RTs and IML but only when the test is performed binocularly. If IML was impaired in dyslexics because of cerebellar dysfunction, monocular procedures would not influence IML and/or RTs. Thus, both groups of dyslexic subjects (examined monocularly and binocularly) would demonstrate a lower IML skill than control subjects.

MATERIALS AND METHODS

Optometric Examinations

Each subject was given an eye examination by an optometrist (one of the authors of this paper). The administered tests included: an interview (detailed case history), ocular dominance test (fixating through a hole), refractive error, monocular and binocular visual acuity at distance and near (Snellen’s letter chart) with prescription corresponding to the subject’s refractive error, amplitude of accommodation (push-up test), and monocular/binocular accommodative facility test (accommodative flipper ±2 diopters [DI]). Binocular vision was examined using the following tests: alternating cover test with prism bar (phoria measured for both distance and near), Worth 4-dot test (suppression and the ability to fuse), and a Titmus stereotest (Stereo Optical Company, Inc., Chicago, IL, USA) for stereopsis. If all measurements were within normal limits, further tests for fixation disparity and fixation instability were administered. The study procedure is described further in this article.

Assessment of Literacy Skills and Cognitive Abilities

All dyslexic subjects had a documented history of developmental dyslexia confirmed by psychologists based on significant discrepancies between literacy skills and cognitive abilities. Despite the documented history of developmental dyslexia, cognitive abilities of the study subjects were investigated by the research team using the Raven’s progressive matrices test. Reading and spelling abilities were measured with word-chain and sentence-chain tests as well as the Polish adaptation of the Test of Word Reading Efficiency (the rate of word and nonword reading test). To evaluate the ability to segment and manipulate phonemes the subjects were given a Polish adaptation of the Spoonerism task.

The difference in cognitive ability between the study groups (dyslexic group [DG] versus control group [CG]) was nonsignificant \( (P = 0.454) \). However, the dyslexic subjects needed more time to perform the literacy and phonologic tasks and they made more errors than controls (see Table 1).

Subjects

Young adult volunteers, all native Polish speakers, were recruited among the faculty students of Adam Mickiewicz University in Poznan (68 subjects in total). Based on an interview, all subjects were healthy without any neurological or musculoskeletal disorders. None of the subjects were taking medication, which could affect their attention or RT. Subjects with any ocular pathology or strabismus were not included in the study.

After the optometric and reading ability tests, subjects were assigned either to the DG or CG. All subjects had at least normal visual acuity (or corrected to normal) at distance and near \( (\log\text{MAR} \leq 0.00) \). None of the subjects exhibited suppression or diplopia at near (Worth 4-dot test) and all measured at least 50 seconds of arc in stereopsis test. The majority of phorias at near for both groups were in the
exodirection (−2 Δ vs. −2.4 Δ, for DG and CG, respectively). Phoria measurement was similar in both (DG and CG) groups (P = 0.480).

Next, the subjects were tested for fixation disparity (FD) and SRTT. To determine the actual IML skill level using SRTT, each subject was allowed to take the test only once in order to avoid detection of the hidden sequence. Thus, DG and CG subjects were randomly assigned to subgroups: either performing the SRTT monocularly with the dominant eye (DGmono and CGmono) or binocularly (DGbin and CGbin). The researcher assigning the subjects to the above subgroups was unaware of the results of the FD test administered earlier. The results obtained from SRTT were analyzed further only if the participant was unable to explicitly detect the order of the sequence hidden in the SRTT. If a participant detected the sequence, he/she was excluded from the analysis and a new participant was recruited. This procedure was repeated until 15 participants in each of group completed the task without explicit detection of the sequence. Overall, nine participants were excluded from the analysis as they detected the sequence explicitly (3 subjects from DG and 6 from CG). As numerous volunteers without reading problems were available, the researchers managed to collect two nondyslexic groups; however, 14 participants were included in one of the dyslexic subgroups. Finally, the data from a total of 59 subjects was assigned the subjects to the above subgroups was unaware of the presence of FD found using the Wesson card. This ensured an appropriate accommodative response. During the modified Mallett test FD was registered "0" when no FD was found or "1" if FD was identified. The amount of FD found using the Wesson card was recorded in minutes of arc. All measurements were repeated three times and averaged.

During FD assessment the subjects were also asked if they had noticed any instability. The instability of FD response was evaluated both with the modified Mallett test and the Wesson card. Each subject was asked to report if the lines/arrow moved and/or the targets faded periodically. Fixation instability was estimated in the same way as in our previous research in three categories: motor instability (targets moved), sensory instability (targets faded away), and sensory–motor instability (targets moved and faded away periodically), as proposed by Evans et al.11

The Main Experiment: Implicit Motor Learning. In order to investigate motor learning ability, the researchers used a variation of the SRTT. The same test was used in the authors’ previous study on strabismic subjects. A detailed description of the stimuli and procedure is discussed later in this paper. In brief, the study subjects were asked to indicate the position of a target (black X; size 0.38°) that could occur in one of four green squares (the size of each square was 1.9° with 0.49° separation between them) presented on a liquid-crystal display screen. The subjects responded by pressing one of four corresponding keys as quickly and accurately as possible with one of four predetermined fingers. The target was displayed in two sequences: (1) sequence 1: 121342314324 (numbers corresponded to the four possible positions on the screen), and (2) sequence 2: 42313241321. Sequence 1 was displayed in blocks 1 to 11

**Table 1.** Characteristics of Study Subjects: Literacy Skills, Phonological Skills, and Cognitive Ability

<table>
<thead>
<tr>
<th>Variable</th>
<th>Dyslexics, N = 29</th>
<th>Controls, N = 30</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raven test (standard score)</td>
<td>92.1 (8.1)</td>
<td>91.4 (7.5)</td>
<td>−0.75; NS</td>
</tr>
<tr>
<td>word-chain: time, s</td>
<td>118.1 (33.6)</td>
<td>75.9 (8.1)</td>
<td>−6.59†</td>
</tr>
<tr>
<td>Word-chain: errors</td>
<td>0.6</td>
<td>0.1</td>
<td>−3.98†</td>
</tr>
<tr>
<td>Sentences-chain: time, s</td>
<td>130.1 (22.0)</td>
<td>93.7 (8.9)</td>
<td>−6.36†</td>
</tr>
<tr>
<td>Sentences-chain: errors</td>
<td>1.3</td>
<td>0.1</td>
<td>−6.30†</td>
</tr>
<tr>
<td>Rate of word reading (mean correct/30 s; max = 75)</td>
<td>56.4 (7.1)</td>
<td>69.4 (3.8)</td>
<td>6.60*</td>
</tr>
<tr>
<td>Rate of word reading: errors</td>
<td>0.5</td>
<td>0.1</td>
<td>−3.79†</td>
</tr>
<tr>
<td>Rate of non-word reading (mean correct/30 s; max = 69)</td>
<td>30.3 (3.1)</td>
<td>44.5 (6.9)</td>
<td>6.58*</td>
</tr>
<tr>
<td>Rate of non-word reading: errors</td>
<td>1.5</td>
<td>0.9</td>
<td>−2.50†</td>
</tr>
<tr>
<td>Spoonerism: time, s</td>
<td>161.6 (48.1)</td>
<td>107.7 (20.2)</td>
<td>−4.35†</td>
</tr>
<tr>
<td>Spoonerism: errors</td>
<td>5.7</td>
<td>2.3</td>
<td>−5.01†</td>
</tr>
<tr>
<td>Correct writing: time, s/orthographic skills/</td>
<td>193.3 (44.7)</td>
<td>121.6 (15.3)</td>
<td>−6.37†</td>
</tr>
<tr>
<td>Correct writing: errors/orthographic skills/</td>
<td>8.7</td>
<td>2.9</td>
<td>−5.96†</td>
</tr>
</tbody>
</table>

NS, nonsignificant.

† P < 0.001.
and block 13 while sequence 2 was presented in block 12. Each sequence was presented 10 times in each block. RTs and error rates in response to the X position were analyzed. The order of the blocks allowed the researchers to observe the process of IML. If the subject implicitly learned the order of the sequence, then his/her RT’s in blocks with sequence 1 should have gradually decreased with respect to the first block, and should have increased when the block with new sequence was displayed (block 12), with RTs again returning to the earlier level on block 13 with the previous sequence.

To assess IML skills, the effect of implicit motor learning (EFIML) was calculated based on the difference between the RT on block 12 and the average RT on blocks 11 and 13, according to the following equation: EFIML = RTblock12 - RTmean block11&13. The higher EFIML, the better the IML skills.\(^b\) As mentioned earlier, test results were taken further analysis only if the subject had not identified the sequence in the main experiment (he/she had not learned the sequence explicitly/consciously).

SRTT was administered in groups that viewed monocularly using the right eye (with the left eye occluded: DGmono and CGmono) or binocularly (DGbin and CGbin).

### Statistical Analyses

Statistical analyses were performed using Statistica Software (ver. 10; StatSoft Polska, Cracow, Poland). The parameters with normal distribution (RTs, EFIML) were analyzed using parametric tests: ANOVA with repeated measurements within factors: (1) group: DG versus CG, and (2) visual condition: monocular versus binocular. Additionally, EFIML was compared with zero using the Student’s \(t\) test.

Results

#### Fixation Disparity: Amount and Instability

Manifestation of FD on the modified Mallett test and on the Wesson card was presented in Figure 1 and Table 2. FD values in minutes of arc measured with the Wesson card are shown in Figure 2.

FD measured using a strong central fusion lock (modified Mallett test) was found in more than 40% (41%; \(n = 12\)) of dyslexic subjects and only in 20% (\(n = 6\)) of control subjects. Statistical analysis showed that this difference was nonsignificant (\(P = 0.134\)). When comparing groups that viewed monocularly or binocularly, no significant differences in FD were found either between DGmono and DGbin (43% vs. 40%, respectively, \(P = 0.825\)) or between CGmono and CGbin (27% vs. 13%, respectively, \(P = 0.651\)). Also, the researchers did not find statistically significant differences in FD neither between groups DGmono and CGmono (43% vs. 27%, respectively, \(P = 0.450\)) nor DGbin and CGbin (40% vs. 13%, respectively, \(P = 0.215\)).

FD measured with weak central fusion lock (Wesson card) was found in more than 70% (72%; \(n = 21\)) of dyslexic subjects but only in 30% (\(n = 9\)) of control subjects. Statistical analysis showed that this difference was significant (\(Z = 8.98, P = 0.002\)). When comparing groups that viewed monocularly or binocularly, no significant differences in the incidence of FD were identified either between DGmono and DGbin (71% vs. 73%, respectively, \(P > 0.999\)) or between CGmono and CGbin (33% vs. 27%, respectively, \(P > 0.999\)). However, in the mono group the researchers observed a tendency among dyslexic subjects (DGmono) to experience FD more often than controls (CGmono) (71% vs. 35%, respectively, \(P = 0.066\)). In binocular condition groups, FD occurred more often in DGbin than in CGbin (75% vs. 27%, respectively, \(P = 0.027\)).

The median value of FD (Wesson card) was higher in the exodirection in the DG as compared with the CG (−2.2 min of arc, \(SE = 2.2\) vs. 0.0 min of arc, \(SE = 1.5\), for DG and CG, respectively; \(Z = −3.31, P < 0.001\)). Moreover, in the DGbin, the median value of FD was −4.0 min of arc (\(SE = 1.5\)) while in the CGbin it was 0.0 min of arc (\(SE = 0.4\)). The difference was statistically significant (\(Z = −3.13, P = 0.002\)). When comparing DGmono with CGmono, there was a tendency for a higher exo-FD in the DGmono than in the CGmono (−2.2 min of arc, \(SE = 4.3\) vs. 0.0 min of arc, \(SE = 1.5\)).

#### Fixation Disparity: Amount and Instability

- The median value of FD (Wesson card) was higher in the exodirection in the DG as compared with the CG (−2.2 min of arc, \(SE = 2.2\) vs. 0.0 min of arc, \(SE = 1.5\), for DG and CG, respectively; \(Z = −3.31, P < 0.001\)).
- Moreover, in the DGbin, the median value of FD was −4.0 min of arc (\(SE = 1.5\)) while in the CGbin it was 0.0 min of arc (\(SE = 0.4\)). The difference was statistically significant (\(Z = −3.13, P = 0.002\)). When comparing DGmono with CGmono, there was a tendency for a higher exo-FD in the DGmono than in the CGmono (−2.2 min of arc, \(SE = 4.3\) vs. 0.0 min of arc, \(SE = 1.5\)).
### Table 2. Incidence of Binocular Fixation Problems for Each Group (Separately)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Subject</th>
<th>Modified MALLETT Test</th>
<th>WESSON Test</th>
<th>Occurrence of Binocular Fixation Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S-M Instability</td>
<td>FD</td>
<td>S-M Instability</td>
</tr>
<tr>
<td>MONO</td>
<td>DM1</td>
<td>0 0 1 1 1</td>
<td>6 9 10 11 14</td>
<td>CM1 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM2</td>
<td>1 1 1 1 1</td>
<td>1 1 1 1 1</td>
<td>CM2 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM3</td>
<td>0 1 1 1 1</td>
<td>6 9 10 11 14</td>
<td>CM3 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM4</td>
<td>1 0 1 1 1</td>
<td>1 1 1 1 1</td>
<td>CM4 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM5</td>
<td>0 0 0 0 0</td>
<td>1 1 1 1 1</td>
<td>CM5 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM6</td>
<td>1 1 0 1 1</td>
<td>6 9 10 11 14</td>
<td>CM6 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM7</td>
<td>1 1 1 1 1</td>
<td>6 9 10 11 14</td>
<td>CM7 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM8</td>
<td>0 1 0 1 1</td>
<td>6 9 10 11 14</td>
<td>CM8 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM9</td>
<td>0 0 0 0 0</td>
<td>1 1 1 1 1</td>
<td>CM9 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM10</td>
<td>1 1 1 1 1</td>
<td>1 1 1 1 1</td>
<td>CM10 1 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM11</td>
<td>0 0 0 0 0</td>
<td>1 1 1 1 1</td>
<td>CM11 1 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM12</td>
<td>1 1 0 1 1</td>
<td>1 1 1 1 1</td>
<td>CM12 1 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM13</td>
<td>0 1 0 1 1</td>
<td>6 9 10 11 14</td>
<td>CM13 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM14</td>
<td>0 1 1 1 1</td>
<td>1 1 1 1 1</td>
<td>CM14 0 0 0 0 0</td>
</tr>
<tr>
<td>MONO</td>
<td>DM15</td>
<td>1 1 1 1 1</td>
<td>6 9 10 11 14</td>
<td>CM15 0 0 1 1 1</td>
</tr>
<tr>
<td>MONO</td>
<td>ALL</td>
<td>6 9 10 11 14</td>
<td>1 1 1 1 1</td>
<td>CM16 0 0 0 0 0</td>
</tr>
</tbody>
</table>

S-M, sensory-motor.
0.0 min of arc, SE = 2.7, for DG and CG respectively; $Z = -1.75$, $P = 0.080$).

There was a difference in motor instability (modified Mallett test) between the DG and the CG. Less than 25% of the DG subjects and none of the CG subjects exhibited motor instability (24.1% vs. 0.0%; $P = 0.005$). Sensory instability also occurred more often in the DG than in the CG (55.2% vs. 20.0%; $\chi^2 = 6.36$, $P = 0.012$). Again, there was a difference in sensory-motor instability between the two study groups. Instability response was detected in more than 65% of DG subjects but only in 20% of the CG subjects (65.5% vs. 20.0%; $\chi^2 = 10.72$, $P = 0.001$).

Dyslexic subjects also exhibited unstable response in the Wesson card test. A higher number of dyslexic subjects showed motor instability (69%). Motor instability was also identified among some control subjects (almost 17%) and the difference was significant ($\chi^2 = 14.44$, $P < 0.001$). Sensory instability was similar in both groups as only 6.7% from the DG (2 subjects) and no subject from the CG reported fading of the targets ($P = 0.237$). Sensory-motor instability occurred more often in the DG than in the CG (75.9% vs. 16.7%; $\chi^2 = 18.50$, $P < 0.001$). All of the above data is presented in Figure 3.

**FIGURE 2.** Median value of FD obtained with a Wesson card. The incidence of FD in all dyslexics and all control groups is shown on the left. The incidence of FD is shown in the middle and on the right, separately for the mono and bin group, respectively. The vertical bars indicate the standard error. *$P < 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$.

**FIGURE 3.** Instability of response observed using the modified Mallett test (left) and Wesson card (right). *$P < 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$.

**FIGURE 4.** Reaction times recorded during SRTT. The results recorded in the monocular condition groups (mono) are shown on the top graph and the results for the binocular condition groups (bin) are shown on the bottom graph. The vertical bars indicate the standard error.

Unstable Binocularity and Motor Learning in Dyslexia

SRTT: Reaction Times

The results of RTs obtained from the SRTT are presented in Figure 4.

Mean RT from blocks 1 to 11, where sequence 1 was displayed, was higher in the DG than in the CG (484 vs. 418 ms, for DG and CG, respectively, see Fig. 5). This was confirmed by a significant main effect of the group ($F_{1,55} = 10.23$, $P = 0.002$, $\chi^2 = 0.16$). RTs were related also to the visual condition (monocular versus binocular). Here, mean RTs were shorter in the group, which viewed monocularly as compared with the binocularly viewing group (427 vs. 472 ms, for monocular and binocular, respectively; $F_{1,55} = 4.95$, $P = 0.030$, $\chi^2 = 0.08$). However, the RTs were related to the visual condition only for DGs but not for CGs, which was suggested
by significant group × visual condition interaction \(F_{1,55} = 8.23, P = 0.006, \chi^2 = 0.13\). This interaction indicated that DGbin demonstrated a large increment in RTs when viewing with both eyes, compared with DGmono (534 vs. 431 ms, for DGbin and DGmono, respectively). This effect was not present in the CG, where sequence 1 was displayed, with similar values in both mono and bin groups (0.02 vs. 0.03 for DG and CG, respectively; \(Z = -1.39, P = 0.165\)) and for both visual conditions (0.03 vs. 0.02 for monocular and binocular, respectively; \(Z = 1.79, P = 0.074\)).

SRTT: Error Rates

As can be seen in Figure 6, error rates for the first 11 blocks, where sequence 1 was displayed, were had similar values in both groups (0.02 vs. 0.03 for DG and CG, respectively; \(Z = -1.39, P = 0.165\)) and for both visual conditions (0.03 vs. 0.02 for monocular and binocular, respectively; \(Z = 1.79, P = 0.074\)).

However, when compared the experimental groups separately, it was found that in the DGbin error rates were higher than in the DGmono (0.04 vs. 0.01, respectively; \(Z = 3.39, P < 0.001\)). The influence of binocular viewing was not observed in the CGs (0.03 for CGmono and 0.04 for CGbin; \(Z = -1.29, P = 0.199\)). Additionally, the difference in error rates between DGbin vs. CGbin, as well as between DGmono versus CGmono, was not statistically significant (\(P > 0.05\)).

SRTT: Implicit Motor Learning

As can be seen in Figure 4, the RTs changed in both study groups when a new sequence (sequence 2) was presented in block 12: mean RTs increased in the CG by 50 ms and by 25 ms in the DG (see Fig. 7). When comparing EIML with zero value, it was noticed that dyslexic and control groups learned the sequence implicitly, which was reflected by EIML being significantly higher than zero for both the DG and the CG (\(t_{28} = 5.29, P < 0.001\) for the DG; \(t_{29} = 6.20, P < 0.001\) for CG). Despite the retained IML ability in both groups, the mean EIML was significantly lower in the DG than in the CG, and was confirmed by the significant effect of the group \(F_{1,55} = 6.78, P = 0.012, \chi^2 = 0.11\). The EIML was not associated with visual condition, as indicated by the nonsignificant mean effect of the visual condition \(F_{1,55} = 0.79, P = 0.377, \chi^2 = 0.01\), as well as the lack of a group × visual condition interaction \(F_{1,55} = 0.18, P = 0.670, \chi^2 < 0.01\).

The EIML was found in RTs but not in error rates but no significant differences between the groups or visual conditions were observed \(\chi^2 = 4.41, P = 0.220\).

Discussion

The purpose of the present study was to investigate the relationship between unstable binocular fixation and motor performance (RT and IML) in dyslexic subjects. Based on the previous research that demonstrated poor binocular coordination and vergence eye movements in subjects with developmental dyslexia,9,23,24,26 the authors assumed that impaired binocular visual skills might disturb the processing of visual information leading to slower motor responses of the hands/fingers. The obtained results showed that subjects with
dyslexia have poorer motor responses, related to both binocular instability and poor IML, which is independent of binocularity. Each aspect will be discussed below.

**Unstable Binocular Fixation**

First, the discussed study confirmed the previous observation (i.e., a higher prevalence of unstable binocular fixation in dyslexic subjects). Studies have shown that dyslexic children show a more unstable coordination of both eyes (higher variability of fixation disparity) when measured with both subjective and objective methods. Jaschinski et al. reported an increased variability of FD in children with reading disability and writing impairment when using psychophysical methods. In the study by Brenk-Krakowska et al., unstable fixation was found in dyslexic adults using the Wesson card. Dyslexic subjects exhibited higher motor instability but showed no difference in sensory instability. Similar findings were obtained in this study, that is, higher motor instability in dyslexic subjects (almost 70% of dyslexics) and no sensory instability. Probably the lack of central fusion lock in the Wesson card creates a difficulty in maintaining vergence stability and provokes higher motor instability. In our study, no more than 17% of controls showed motor instability with the Wesson card. However, the instability may not reflect the actual condition during reading. Devices with a good central fusion lock, such as the modified Mallett test, are better indicators of the actual binocular condition when fixing the target. In our study, while detecting fixation disparity with the modified Mallett test, more than half of the dyslexic subjects exhibited sensory instability, yet only less than 25% of dyslexics detected some motor instability. Due to problems with oculomotor adjustments (reflected in motor instability during Wesson card measurements), sensory instability occurred during measurements using the device with a good central fusion lock (modified Mallett test). This fusion lock might reflect a higher demand on the dyslexic’s sensory fusion processes during a reading task. Variability in FD has also been observed in children using objective measurement methods but conversely, Evans et al. did not find any differences in the subjects' sensory or motor responses. The procedure of instability assessment (motor—movement of dichoptic nontext targets or sensory—fading away of the one of the dichoptic nontext targets) relies on the subject's subjective response. As these changes are quite discrete and dynamic, this procedure might be a challenge considering children's attention, because they may not be aware of them. Further studies are necessary in order to compare the variability of FD obtained with psychometric clinical tests and objective eyetracking methods. It is known that FD measured objectively (eyetracking systems) and subjectively (dichoptic nontext lines) differs.

The lack of a central fusion lock may also influence the extent of FD. Some authors suggest that dyslexic adults have at least some tendency toward exo-FD in the Wesson card test. We also found that the mean FD values in dyslexic subjects were higher and shifted in the exo-direction. We suspect that the weak fusion lock may have caused a difficulty in maintaining vergence stability, and thus a greater amount of exo-FD could occur.

Poor binocular coordination should not be treated as a major cause of reading problems because FD and/or vergences were observed mainly in saccadic tasks performed with a text stimuli, but not in the simple dot scanning. One can argue that poor binocular coordination during reading was caused by a phonologic disorder (i.e., problems with symbol decoding could have impaired the control of eye movements and vergences). As was mentioned by Kirkby et al., it is possible that some differences in visual characteristics between a sentence and a dot stimuli could cause fusional difficulties, resulting in more difficult ocular scanning during text reading as compared with dot scanning. In our study, a simple nontext target scanning and slower RTs were observed in dyslexic subjects under binocular viewing conditions. This observation demonstrates that unstable binocular fixation in dyslexia may disturb motor and oculomotor performance, not only while reading a text but also in a simpler nontext task.

How can one explain the lack of FD in dyslexic subjects during simple fixation or dot scanning found by some researchers? One possibility may be a compensatory mechanism where motor disabilities are compensated by attentional resources. Similar compensation was found in subjects with dyslexia during body balance measurements. Their body balance was worse when an additional concurrent task was employed during quiet standing. It is possible that dyslexic individuals' oculomotor deficits could be difficult to detect in simple scanning paradigm because of the aforementioned compensation. However, when a more complex task involving attentional resources is required, the actual oculomotor deficits could be detected. In our study, eye movements were simple but the subjects had to show an additional motor response adequate to the location of the stimulus in space. Thus, the paradigm used in the current study was more complex and it is possible that oculomotor deficits were well compensated.

**Unstable Binocular Fixation and Motor Performance (RT and IML)**

Most importantly, the researchers have observed poor motor performance in dyslexic subjects (slow RTs) during SRTT but only when the test was performed binocularly. Longer RTs in dyslexic subjects compared with controls were observed also in the studies by Nicolson et al., Kelly et al., Vicari et al., Menghini et al., and Stoodley et al., and were explained by the deficits in paired-associate learning. A significant increase in RTs in this study occurred only when viewing with both eyes (534 vs. 411 ms for DG and CG, respectively) but not when viewing with one eye (431 vs. 424 ms for DG and CG, respectively). It suggests that poor motor performance was associated with unstable binocularity during a motor task. This finding supports the view that poor binocular coordination in dyslexia may affect fusion and motor performance. In everyday tasks, unstable binocular coordination may also affect reading skills (decoding of the stimuli required in order to read) as well as motor performance and poor eye-hand coordination, as reported in other studies.

Viewing condition affected RTs, but also partially error rates in the way that DGbin performed less errors than DGmono. One could argue, that longer RTs were a cost of fewer errors. If this were the case, statistically significant differences between DGbin and CGbin should also occur then, but it was not found. It is rather doubtful that small difference in error rates (3%) could influence huge difference in RTs (24% of response speed). Lower error rates could arise also from the possibility that when the DGbin performs the task binocularly it is more difficult and requires more concentration.

Despite the significant influence of unstable binocularity on the RTs, no such relationship exists in our study between binocular viewing and sequential implicit motor learning. Dyslexics, similar to controls, gradually decreased their RTs from block to block and increased RTs when new sequence
appeared in block 12. It showed that all experimental groups were able to learn a sequence of the stimuli in the implicit way. However, what was important, dyslexics increased their RTs less from trial 11 to trial 12 than controls: an average 25 ms for DG compared with 50 ms for CG. Weaker IML skills for dyslexic individuals compared with controls were observed for a monocular group as well as binocular viewing group, suggesting that motor learning was not related to any binocular instability. Impaired IML in dyslexia is in agreement with previous findings where weak\(^{40}\) or even absent\(^{61}\) IML was found in dyslexia. In previously mentioned studies, all the tests were performed binocularly and long RTs were explained by inability for proper IML.\(^{2,40,61}\) For example, in the study by Vicari et al.,\(^{61}\) the dyslexics demonstrated longer RTs compared with controls and the difference increased with time. Larger differences in RTs between groups (90 ms in block 5) found in that study was explained by faster responses with practice in the control group by IML, with no improvement in dyslexics because of the lack of IML. It is possible however that the long RTs in the Vicari et al. study,\(^{61}\) as well as in other papers,\(^{40,44}\) was the effect of unstable binocularity and required the necessity for separating their attention between the task and keeping stable clear single vision.

One could argue that weak ability for IML was the effect of the unstable viewing, not learning deficits per se. Thus, in our study SRTT was carried out monocularly and compared with groups, which viewed the test binocularly, to exclude any possible visual influence on the IML skill. The obtained results demonstrated that dyslexics suffer from poor IML skills what was not related to visual condition, so it might be a consequence of a deficit in the cortico-cerebellar pathway, not but pure visual problems.

Cerebellar deficits in dyslexia were demonstrated not only in SRTT task but also in the other neuroimaging studies. For example, Rae et al.\(^{65}\) observed biochemical asymmetry in the cerebellum of dyslexic individuals, Nicolson et al.\(^{60}\) found abnormal cerebellar activity in a positron emission tomography study, and Leonard et al.\(^{64}\) and Eckert\(^{27}\) have shown a reduced region in the right anterior lobe in the cerebellum of dyslexic individuals. Finally, cerebellar dysfunctions were observed also during posturography, where subjects with dyslexia showed impaired body balance in quiet stance.\(^{28-30,59,65}\)

All studies mentioned above, together with the results obtained from the current study, confirm the hypothesis that dyslexia may be accompanied with cerebellar deficits. Bucci et al.\(^{25,66}\) claim that immaturity in neural pathway is related to motor learning and the cerebellum and magnocellular visual stream may be responsible for poor oculomotor behavior. Our results are in agreement with that statement showing that cerebellar network dysfunction may be associated with movement automaticity problems, related not only to gross motility but also to binocular coordination.

**Limitation of the Study and Future Direction**

In the present study, the researchers did not monitor eye movements objectively but based their observations on subjectively reported FD and its instability. In the future, it might be worth considering eye-tracking measurements both during psychometric (subjective) FD test and IML experiment. One should be aware that measuring FD and its stability by eye trackers is a great challenge. Appropriate measurement protocol should therefore be developed.

Because binocular instability seems to occur more often in dyslexic than nondyslexic individuals, the above findings should be taken into consideration in future oculomotor and motor studies. Further investigation of dyslexic subjects’ performance should exclude unstable binocular vision. Visuo-motor test performed with dyslexic subjects performed in monocular viewing conditions should ensure that motor dysfunctions are not caused by unstable binocular vision but by actual central nervous system dysfunctions. In the future studies, it would also be interesting to look at a dyslexic population without any binocular instability and compare their motor and visuomotor coordination with a population with binocular instability problems.

The above study was also limited by gender differences within the groups. As the previous research suggests that the sex factor might influence visuospatial abilities, it seems justified to take it into consideration in future studies.

Also, it seems worth researching whether monocular occlusion technique (as suggested by Stein and Fowler\(^{67}\)) or vergence training (orthoptic or optometric visual therapy), commonly used in case of heterophoria and/or other vergence anomalies,\(^{48,69}\) may significantly improve fixation and motor control in dyslexia. The positive effect of vergence rehabilitation on saccades and fixation during reading was recently examined by Daniel et al.,\(^{50}\) but further studies in that area are necessary.

**Summary**

In order to investigate the specific impact of unstable binocular fixation on motor performance in dyslexic subjects, the present study included a monocular reference condition without binocular demands. The dyslexic group, who viewed the test binocularly, showed longer RTs compared with DG that performed the SRTT monocularly as well as compared with the CG that performed the SRTT binocularly. However, both dyslexic groups (monocular and binocular) showed an impaired IML. Poor IML skills and instability of FD in dyslexia may reflect deficits in the cerebellum area.

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**References**

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