Protocol for Visual Intervention of Developmental Dyslexia

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Abstract

Developmental dyslexia is characterized by phonological and visual deficits. Phonological interventions contribute to the correspondence between sound and letter, but not fluent reading. Creating a system of dynamic programming interventions in visual modality is the main goal for promoting the reading-related cognitive skills of children with developmental dyslexia. Visual stimuli for discrimination of direction, speed, and contrast of visual stimuli have been used to improve visual-perceptual performance, information processing, and visual-spatial attention. Other tasks included stimuli with low- and high-spatial frequency illusions that determine the limitations of the visual system were used to urge on the effectiveness of the visual presentations. A children's development program of visual-spatial memory and attention was also included in these interventions. The results showed that visual-perceptual learning with non-verbal visual programs eliminates time deficits in the dorsal stream, in attention and working memory networks, in processing speed and accuracy of performance, and generally promotes cognitive skills and comprehension related to reading. Visual-spatial interventions on memory and attention improved the strategy that the children used during reading and were effective in overcoming the difficulties in children with developmental dyslexia. The application of spectral/colored filters showed also a beneficial effect on the orthography and reading process of children with reading disabilities.

Keywords*:* developmental dyslexia, training, direction discrimination, velocity discrimination, contrast discrimination, visual-spatial attention.

1. Introduction

In developmental dyslexia, the deficient ability in letter decoding, pronunciation, and correctly recognition of polysyllabic words, leads to considerable difficulties in the educational process. Research in the past decades has shown that developmental dyslexia is a heterogeneous disorder in which the reading problems are based on both phonological

(Vellutino et al., 2004) and visual-spatial deficits in attention, as well as anomalies in visual information processing (Badcock et al., 2008; Menghini et al., 2010; Gori et al., 2016; Stein, 2019). Initial proposals suggest the importance of the magnocellular system for the rapid timing of visual events and the coarse structure in the letters during reading and the suppression of the parvocellular system during eye saccades which defined the fine details in the letters and the color discrimination (Breitmeyer, 1993). One of the strongest precursors of reading accuracy is the programs for phonological processing, which successfully correct the reading accuracy of single words and pseudowords for many children, as well as their recognition in the auditory modality (Mann and Wimmer, 2002). However, recent studies show that in one-third of children with dyslexia, such programs are ineffective about speed, accuracy, expression, and comprehension of a reading text (Whiteley et al., 2007). More recently, interventions for reading improvement have shifted to numerous non-phonological procedures focusing on visual-spatial attention deficit and related mechanisms. The directional attentional disorder in developmental dyslexia is related to the inefficiency in the selective extraction and information processing from a specific visual field (Facoetti et al., 2000; Treisman and Gormican, 1988). Such children manifest a more sparse/diffuse form of attention, affected focusing of the spatial attention, visual search, and guide (Facoetti et al., 2000; Franceschini et al., 2013; Liu et al., 2018; Pammer et al., 2004; Vidyasagar and Pammer, 2010). There is significant evidence that for the auditory and the cross-modal information, the temporal processing deficit and this in the attentional shift, routine in the visual modality, are essential (Lallier et al., 2010; Harrar et al., 2014). Dyslexic children show a deficit in visual perception of motion with reduced ability in the sensitivity to speed and direction discrimination of visual stimuli (Boets et al., 2011). The impairments in visual processing comprised higher thresholds in the sensitivity to coherent stimuli (Wang and Yang, 2018), in the contrast visual sensitivity to low-/high-spatial frequency stimuli in external noise (Slaghuis and Lovegrove, 1985), and the slow visual letter-sequencing recognition (Ozernov-Palchik et al., 2017). Eye movements, inefficiently driven by attention, are also observed in dyslexic children during verbal and nonverbal tasks (Dahhan et al., 2016). Illusory motion tasks are an important tool through which indirectly receives information about visual perception of the brain (Peters, 2016). A visual test for short-term memory is the detection of color changes in objects (Phillips, 1974). In dyslexic children, the overcome of dynamic visual attention disorders requires adequate interventions with a maximum load of spatial and/or temporal visual information processing according to the individual's ability. Mainly, the low contrast perceptions are determined by magnocellular retinal ganglion cells, sensitive to the coarse structure of low-spatial frequency sinusoidal gratings flickered at high temporal frequencies. However, a possible neuronal substrate of the deficit in the coherent motion processing could result from an abnormal magnocellular input to the dorsal visual stream related to the optimal movement response (Cornelissen et al., 1995).

The presentations of the above-described tasks on a computer actively engage the attention in space and time (Franceschini et al., 2013), stimulating the improvement of cognitive ability in children under 14 years (Lorusso et al., 2011; Gori et al., 2016). At this age range, these interventions are with the most profit in children due to undergoing rapid changes in the plasticity of attention-related neural networks that are still in the process of maturation (McIntosh et al., 2006; Klaver et al., 2011). Interventions with visual-spatial stimuli are an effective opportunity for correction of attention, improve reading overall in children with developmental dyslexia. They are applied in different orthographies and are more effective than other strategies (Mann and Wimmer, 2002; McIntosh et al., 2006; Whiteley et al., 2007; Lorusso et al., 2011; Koyama et al. 2013; Lobier et al., 2014; Wang and Yang, 2018; Liu et al., 2018). Manipulations that facilitate the magnocellular visual function as the viewing of a coarse text structure with yellow or blue spectral/colored filters (or other color hues) help to decrease the number of skipped reading words (Ray et al., 2005). The amount of light with a longer length of the wave falling on the retina increases by the yellow spectral filters, and due to pupil dilation, stimulates more M-cells. Control filters for the effects of the yellow filters are the blue spectral ones. The blue-sensitive melanopsin-pigment retinal ganglion cells with projection to the suprachiasmatic nucleus of the hypothalamus are responsible for the internal clock and the daily rhythm control (Hankins et al., 2008). The blue filters help more reliably to focus the children's attention and eye movements. According to many authors, the colors of the effective spectral filters, assisting the reading in dyslexic children, are grouped around the yellow and blue spectral filters (Wilkins et al., 1994; Hall et al., 2013).

The goal of the study is to create a training protocol, comprising dynamic computerized tasks in the visual modality, which promotes the cognitive skills related to the reading of children with developmental dyslexia. The main questions are: Can this intervention improves the speech-related brain structures functioning which in turn will help to overcome the writing speech disorder in second-grade and third-grade children with developmental dyslexia? Can spectral/colored filters promote the reading sub-skills (a voice reaction time, duration of word reading, percent of error reading words, percent of omitted words, and speed of reading)?

2. Materials and methods

2.1 Participants

Thirty-seven children with developmental dyslexia (19 boys and 18 girls) diagnosed with appropriate psychometric tests were examined. The age range of children was 8-9 years old. The children were from the 2nd and 3rd-grade of general education. Their parents gave informed consent following the Helsinki Declaration. One dyslexic group from twenty-two children with developmental dyslexia (12 boys and 10 girls) accepted to participate in the current protocol with magnocellular (M-based) and middle temporal (MT-based) visual-motor intervention, described below. While other children were involved in another intervention version in motion perception, visual attention, and goal-directed behavior, described in previous work (Lalova et al., 2019), also stimulated the dorsal stream.

The Ethics Committee of Institute of Neurobiology, Institute for Population and Human

Studies, BAS, State Logopedic Center, and Ministry of Education and Science approved the study. Bulgarian is the first language spoken by the children. Seventeen of them are right-handed, and five - ambidexters. The handedness was assessed by classification of hand preference (Annett, 1970). Children underwent neuropsychological studies (Raichev et al., 2005). The DDE-2 test battery was used to assess developmental dyslexia and dysortography (Sartori et al., 2007; Matanova and Todorova, 2013). Phonological awareness, as well as reading and writing skills, were assessed with psychometric tests (Kalonkina and Lalova, 2016). Assessment of nonverbal perception and rapid serial naming of color and object was performed with the Girolami-Boulinier test "Different Oriented Marks" (Girolami-Boulinier 1985; Yakimova 2004). Children's nonverbal intelligence was tested with the Raven Progressive Matrix Test (Raven et al., 1998).

The non-verbal intelligence scores of the participants were 98 or higher (Raven et al., 1998). The children had normal hearing after an examination by an audiometer. Their vision was normal/or corrected-to-normal vision. The dyslexic group included children with reading difficulties who showed one standard deviation below-norm performance of standardized control group of either speed or accuracy in subtests of the DDE-2 battery and “Reading abilities” battery. DDE-2 battery included lists of reading words, reading pseudo-words, choosing the correct meaning of a word, looking for spelling mistakes; writing a word/pseudoword in dictation. The Reading Ability battery included identifying the first sound in a heard word and skipping it within a word, fragmenting words into syllables and skipping the last syllable, reading text, dictating sentences, filling in a missing compound word.

2.2 **Procedure**

The training tasks for each child were conducted in an arbitrary order and divided two-weekly into individual sessions of 45 minutes, which was performed over three months. After training intervention, the dyslexic children performed Wechsler test (WISC-4; Wechsler, 2003). The WISC-4 is an individually administered IQ test for assessment of the intellectual and cognitive abilities of six to sixteen-year-old children through intellectual tasks as verbal comprehension, perception, working memory, attention, concentration, and speed of information processing. Ten WISC-4 subtests are most commonly used in intelligence testing. The basic subtests for verbal comprehension are vocabulary, similarities, and comprehension. The main perceptual subtests are the design of blocks, matrix reasoning, and picture concepts. The digit span and the letter/number sequencing are the core working memory subtests, as well as the coding and symbol search is basic processing speed subtests. The child's ability to quick and correct scanning or tracking of visually presented standing out stimuli is indicated by the scale of speed processing. The remaining additional subtests give information about reasoning on words (as a part of verbal comprehension), picture finishing (perceptual reasoning), arithmetic (as a part of working memory), and processing cancellation (as a part of the speed of processing). The indices for all tests provide the overall level of intelligence

IQ. The scale of the success is reported in standard points (sum of the subtests). The reaction times and performance accuracy of pre-training and post-training dyslexic groups were compared for each condition by ANOVA.

2.2. Visual psychophysics tasks

2.3.1. Coherent motion task

The task, stimulating magnocellular (M-based) function, is direction discrimination of a vertical coherent motion (upwards or downwards) of white dots in a patch of randomly moving ones (with 100% contrast of each and a dot size of 0.1°) within a 20° circle on a black screen (Benassi et al., 2010; Boets et al., 2011. The velocity of the moving dots is 4.4°/s. In 12-frame sequences presented the dots with lasting of each frame 16.7 ms. The smallest number of coherently directional moving points, when their direction is still perceived, determines the coherent perceptual threshold. In a previous study (Lalova et al., 2018), the thresholds of the dyslexics were found to be higher than those of the controls, suggesting that the dyslexics have impairments in the magnocellular pathway (M-pathway). The coherent movement threshold is 50% of the arbitrarily moving dots. During the presentation of the stimulus, the red locking cross remains in the center of the screen. The stimuli are presented for 200 ms in the center in the pseudorandom sequence and an interstimulus interval of 1.5-2.5 s (ISI) at a distance of 57 cm. During an upwards dot motion, the instruction is a left button pressing. During an upwards dot motion, the instruction is a right button pressing. Twenty trials of stimuli are with an upward movement and 20 - a downward movement. The correct responses and the reaction time are taken into account.

2.3.2. Contrast discrimination in illusion motion tasks

Discrimination of different contrasts at an illusionary motion of low-spatial frequency sinusoidal grating, embedded in an external noise field, maximally activates the magnocellular pathway (Pammer and Wheatley, 2001; Sperling et al., 2005). Discrimination of different contrast high-spatial frequency gratings is in an illusionary motion task activates a parvocellular pathway (Pammer and Wheatley, 2001; Sperling et al., 2005). The sinusoidal gratings vertically flicking with 15 Hz counter phase in a center of a noise region (11 × 11 cm) on a gray screen with a fixation cross for 200 ms. The refresh rate of the screen of the computer screen was 60 Hz with a pixel resolution of 1920 × 1080. Gabor's oscillating gratings are perceived at twice the spatial frequency of their actual spatial frequency. The stimulus is subtended around a visual angle of 2.7 × 2.7 degrees at a viewing of 210 cm on the screen. The child has to indicate which model has low or high contrast. The contrast thresholds separately for magnocellular and parvocellular tasks are selected in previously performed psychophysical contrast-sensitive tasks (Lalova et al, 2018). In the first discrimination task (2fd), the contrast levels of the stimuli are 6% and 12% of the threshold (Lalova et al., 2018). In the parvocellular discrimination task (10fd), the contrast levels of the high spatial Gratings (10 cpd), with a low-temporal flicking frequency, are 3% and 6% of the predefined contrast threshold (Lalova et al., 2018). Gratings with different contrasts are presented in a pseudo-randomized sequence with an ISI of 1.5-3.5 s. By pressing a button with a left hand, the child discriminates a sinusoidal grating with low contrast, with a right hand - a sinusoidal grating with high contrast. Each series has 20 high-contrast elements and 20 low-contrast elements. The correct answers and the reaction time are taken into account.

2.3.3. Velocity discrimination task

Two pairs of radial optical flows (Sun et al., 2014) within the diameter of a 14 ° eccentricity appear one after the other from the center to the periphery of the screen. The speed discrimination task, adopted M-pathway intervention, is induced changes in the MT / V5 brain area and visual areas as V3, V4, and V6. The first element in each pair of stimuli has always been at a constant slow speed (4.5 °/s). The second element in the stimulus pair has a flow velocity of 5.0 °/s or higher 5.5 °/s (Joshi and Falkenberg, 2015). The first element appeared for 300 ms, and after 500 ms, the second item of the stimuli pair appeared for 300 ms in the center of a black screen at a distance of 57 cm. The period of the stimulus pair appearance in a pseudo-randomized subsequence varies from 1.5 to 3.5 s. The total number of stimulus pairs in the session is 40 (20 with a slow speed of the second item; 20 - with a high speed). The instruction is to press a key on the right side of the computer keyboard when the speed of the pairs is slow. While the second stimulus in the pairs has a higher speed than the first one, the children press a left-side key on the keyboard. The correct answers and the reaction time are reported.

i. Visual-spatial attention task

The main requirement is to search for a color change in a cue, focusing on visual-spatial attention and oculomotor control in the center of the visual field (Ross-Sheehy et al., 2011). On a white screen, located on distance of 57 cm, a black frame (a cue) surrounding a color square appears for 300 ms before four differently colored squares (each with a size 3°x3°) around a screen center for 200 ms, one of which is in the frame. The instruction is for the comparison of the color in the frame with the next color that is presented in the cue. The children press a left key on a keyboard when two consecutive colors in the frame are the same, and with a right key – when the colors are different. The stimuli in a session are 40: 20 are with the same consecutive colors (invalid stream) and 20 are with different consecutive colors (valid stream). The invalid and stream valid alternate in pseudo-randomized sequence with ISI = 1.5 - 2.5 s. The correct responses and the reaction times are reported.

2.3.5. Color filters

For each child, separate training sessions conduct with eleven spectral/colored filters, applied for each task in randomized order: 1 – 'aqua', 2 – 'grass', 3 – 'gray', 4 – 'green', 5 – 'jade', 6 – 'magenta', 7 – 'orange', 8 – 'pink', 9 – 'purple', 10 – 'sky', 11 – 'yellow' (Stein, 2019). The correct answers and the reaction time are reported.

2.3.6. Reading tasks

Single words in Microsoft Sans Serif font are presented on a laptop at a distance of 57 cm from the observer. The black letters on a white background have an angular size of about 1 ° each. The age-appropriate words are balanced according to their frequency characteristics - low and high frequency of use and cover different parts of speech: adjectives, verbs, prepositions, numbers, pronouns, conjunctions, and adverbs. The series of multi-syllable words (2/3-syllables) contains 40 words in each block. The word remains on the computer screen for 800 ms. The word replaces another word in a pseudo-random sequence with an interval between the words of 1.5–2.5 s. In a reading task, the behavioral parameters were assessed for each child as a voice reaction time, duration of word reading, percent of error reading words, percent of omitted words, and speed of reading. The voice reaction time is determined from the beginning of the appearance of the visual stimulus (word) to the beginning of its pronunciation. The duration of reading is the difference in time from the beginning of word reading to its end reading. The speed is the number of correctly reading words to their common duration. The percent of dropped words also determines the accuracy of the reading. The success rate is defined by the correct reading words. After the training sessions, the task of reading words is repeated.

2.3.7. Visual verbal tasks

Two types of visual-verbal stimuli consisted of words and pseudowords, are presented in pseudo-random order and stay on the computer screen for 800 ms. Its duration is defined by a reading task. The pseudowords are the same words in sequence but with all replaced vowels. The block contained 40 words and 40 pseudowords. The instruction is to push a right-side button when seeing a word and to push a left-side button when the stimulus is a pseudoword. The correctly identified words/pseudowords and the reaction time are reported.

The reading of words and the visual word/pseudoword discrimination are performed one month after the training ends with the visual nonverbal programs.

Irrespective of the verbal tasks, the experimental group with dyslexia receives an intensive procedure with training visual tasks over three months, performed twice a week into individual 45 min sessions.

2.3.8. Statistics

The psychophysical tasks, performed by the dyslexic group, were analyzed by one-way ANOVA. The factors as correct answers (%) and reaction time to complete the task were reported in the first and last experiences of the training intervention for each child. The parameters of the best performance with the most appropriate filter were also compared with the non-filter session, conducting in the randomized order during the training.

3. Results

3.1. Coherent task

In the coherent motion, the correct responses increased significantly after training $p < 0.001$, $F = 54.6$, while the reaction time was not statistically significant. The children with dyslexia discriminated directions before and after training at one of the same time (Figure 1). Regardless of the direction of upward and downward of the coherent dots, achievements and reaction time did not differ statistically between upward and downward directions in the sessions before and after training.

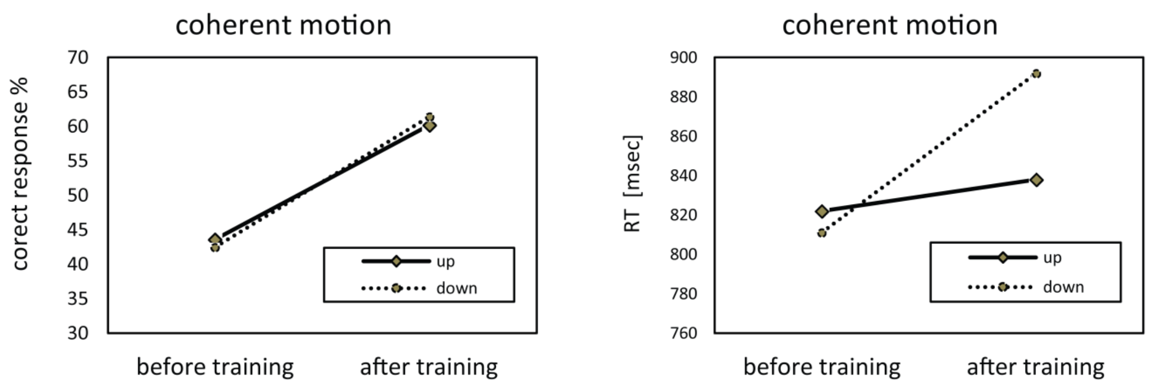

Figure 1. Correct responses and reaction time in coherent motion task before and after training.

Dyslexics make significantly fewer mistakes by distinguishing the downward direction in coherent moving points covered with a color filter. In both conditions, the success rate was significantly higher than that without a filter. In the downwards, the mean (± se) rate with the most suitable filter was 64.04% (± 2.3%) comparing to the non-filter case 54.18% (± 3.53%) ($p < 0.026$, $F = 5.32$). In the upwards, the mean (± se) rate with filter was 65.25% (± 2.22%) comparing to the non-filter case 47.84% (± 2.8%), ($p < 0.0003$, $F = 22.89$). In downward discrimination, the reaction times of 799.54 ms (± 75.92 ms) were faster but not statistically significant ($p > 0.05$, $F < 0.27$) than those in the representation of coherent moving points that are not covered by a filter 860.85 ms (± 85.3). The reaction time to the upward movement does not change during the execution of a coherent motion covered with a filter with an average reaction time of 827.81 ms (± 88.21), compared to the case without a filter with an average time of 890.39 ms (± 82.3). During training, the success rate was significantly better with the most suitable jade spectral filters when dots moving down, and with yellow / sky filters upwards. Sky / yellow spectral filters improved the performance of 36% of children (half of them up). While jade filters (including grass, celery filters) were the most suitable in 41% of dyslexics (more than half of them down direction), the purple filters (including also pink filter) were useful in 23% of dyslexics.

3.2. Contrast discrimination in illusion motion tasks

After training under both conditions of contrast discrimination of the low-spatial frequency (2fd) and high-spatial frequency sinusoidal gratings (10fd) there was a significant increase in the correct responses in 2fd ($p < 0.001$, $F = 24.4$) and 10fd ($p < 0.001$, $F = 25.6$; Figure 2). In addition, the reaction time improved under both conditions at 2fd ($p < 0.05$, $F = 9.7$) and 10fd ($p < 0.05$, $F = 6.6$; Figure 2).

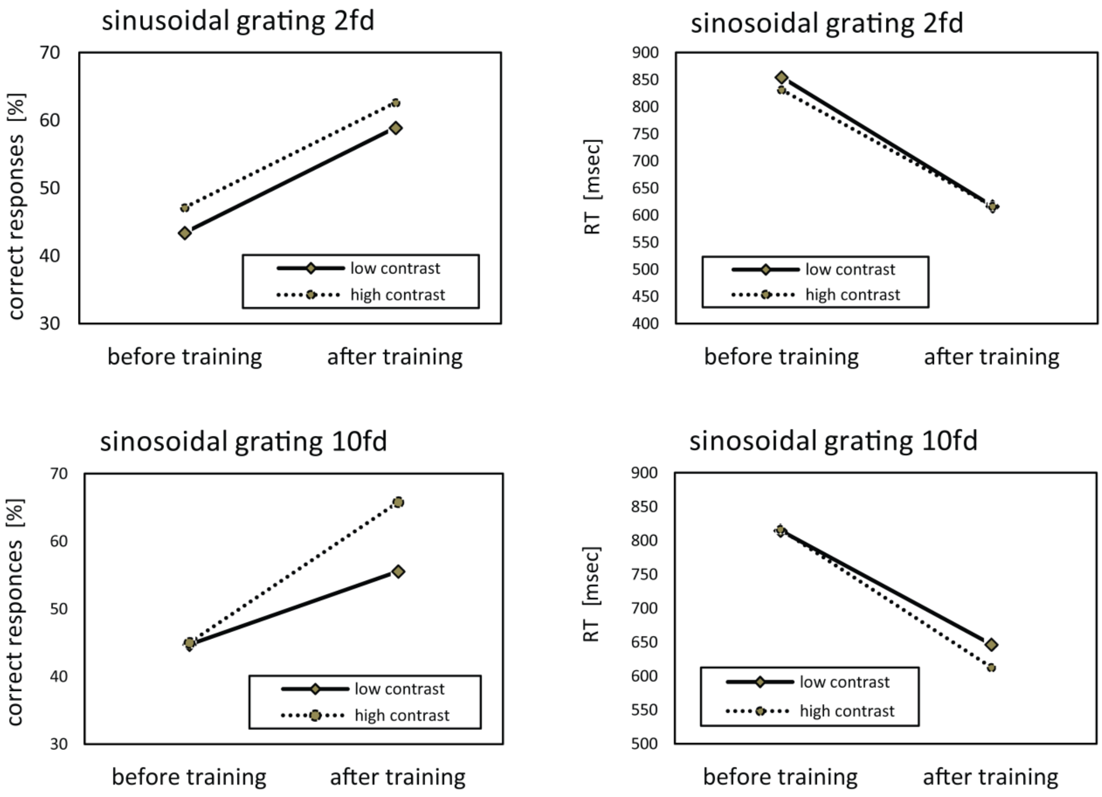

Figure 2. Achievement of the best execution of the 2fd and 10fd task and reaction times before and after training.

The achievement of each child with the best effective color filter is statistically higher than that without a filter in the conditions of higher contrast of the doubling illusion of the low spatial frequency (2fd: 71.14 ± 2.94% with filter; 58.42 ± 3.48% without a filter; ($p < 0.01$, $F > 8.15$), as well as in the doubling illusion of the high spatial frequency (10fd: 68.75 ± 2.53% with filter, 53.00 ± 5.36%)unfiltered state ($p < 0.01$, $F > 7.05$). There is no statistically significant difference between the best success rate with the corresponding color filter and without a filter in the conditions of low contrast in illusions with low spatial frequency 2fd (with filter: 64.77 ± 2.52 %; non-filter: 56.32 ± 3.90 %) and high spatial frequency 10fd (with filter: 64.75 ± 3.29%; non-filter: 56.00 ± 5.67 %; $p > 0.08$, $F < 3.17$). The reaction times did not improve significantly during low contrast (2fd; with filter: 771.80.71 ± 74.62 ms; non-filter: 696.54 ± 69.14 ms) in both doubling illusions with the corresponding color filter imposed on the screen 10fd: with filter: 739.68 ± 77.75 ms; non-filter: 703.18 ± 75.17 ms; p > 0.35, F < 0.87), as well as during a high contrast in both doubling illusions with the corresponding color filter on the screen. The sky (aqua, magenta) and yellow (orange) spectral filters improved the performance of both low and high spatial frequency illusions in more than 60% of dyslexics, while spectral filters with grass (celery) - an average of 30% of children both for tasks as well as for contrast conditions.

3.3. Velocity discrimination task

After training, the children with dyslexia performed significantly more correctly the task of discriminating the speed of optical flows (p < 0.001, F > 47.8; Figure 3). The improvement in performance at a faster speed of the second stimulus than the first in the pair was due to the prolongation of the reaction time (p < 0.05, F > 4.08; Figure 3). In the case of the stimuli with a slow speed, the time for discrimination did not change significantly at the beginning and end of the training.

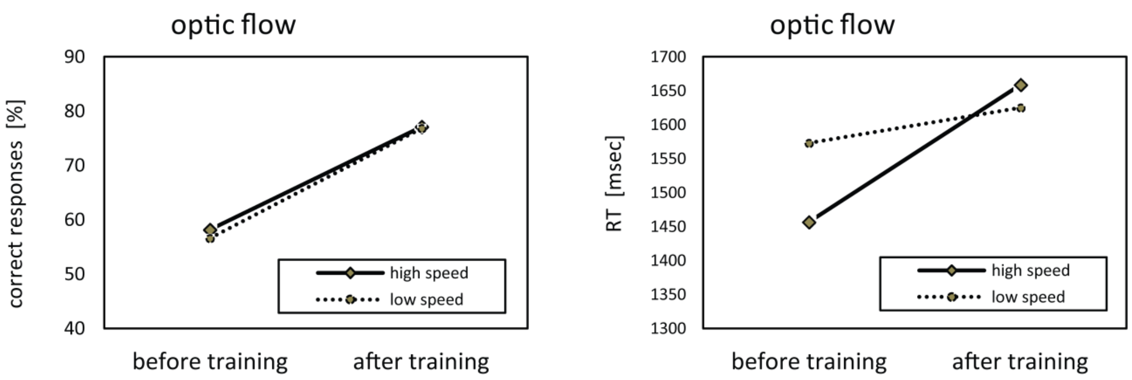

Figure 3. Achievement of the best execution of the radial optic flow and reaction time before and after training.

The achievement with the most effective individually selected filter (75.25 ± 2.55 %) of each child with dyslexia is statistically higher than those without a filter in a condition of slow speed 60.75 ± 3.88% (p = 0.004, F = 9.36), as well as in the high-velocity condition of the radial flow (with filter: 78.25 ± 2.77%; non-filter: 61 ± 3.84%; p = 0.0007, F = 13.80). The performance was faster at slow speeds with the corresponding filter imposed on the screen, but not significantly different with the task without a filter on the screen (filter: 1636.7 ± 47.83 ms; non-filter: 1661.9 ± 77.72 ms; p > 0.05, F > 0.1). The sky / yellow spectral filters improved the performance of 41% of children. They were more than half of the appropriate filters in high-speed condition and 30% of them in the low-speed condition. The most suitable color filters were purple filters (including pink) in 36% of dyslexics and grass (covering celery and jade) in 23% of dyslexics, which were more than 50% of useful filters at low-speed conditions.

3.4. Visual-spatial attention task

Before training, the children performed the task of visual-spatial attention relatively well. After training, their results were significantly improved and many of them gave almost 98% correct answers ($p < 0.001$, $F = 30.5$; Figure 4), as well as and significantly faster response time ($p < 0.001$, $F = 19.3$; Figure 4).

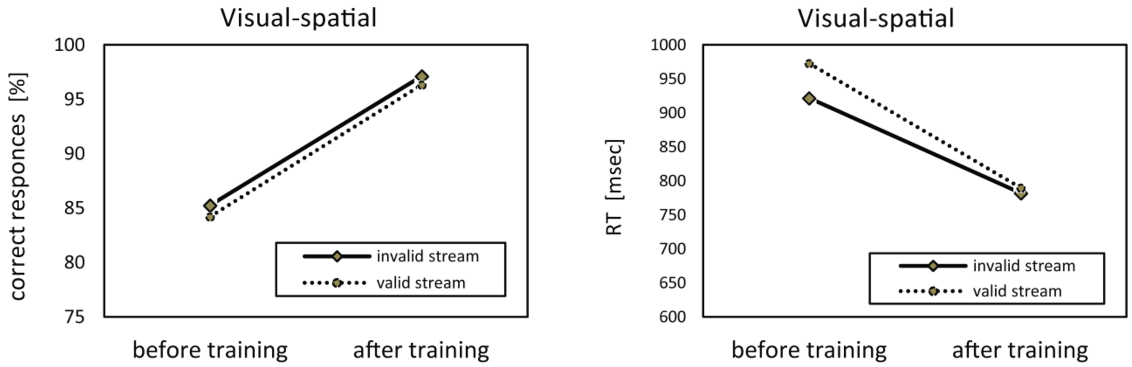

Figure 4. Success rate (%) and reaction time (RT, ms) for a valid (different colors of the squares) and invalid stream (with the same colors of the squares) before and after training.

The achievement of the dyslexics with the best effective filter was statistically higher than those without filter under both conditions (valid stream: with filter, 98.2 ± 0.57 %, non-filter, 87.75 ± 1.93 %; $p < 0.0001$, $F > 26.51$; invalid stream: with filter, 98.0 ± 0.76 %, non-filter, 91.25 ± 1.62 %; $p < 0.0001$, $F > 13.66$). The reaction times were faster in the valid and invalid streams, but not significantly different between filter and non-filter overlaid task (823.38 ± 27.96 ms; 854.78 ± 37.22 ms, $p > 0.05$, $F < 0.53$). The sky/yellow filters improved the achievement in the 50% of the dyslexics, while the grass (jade, celery) filters - in 36% of the experimental group.

3.5. Wechsler test (WISC-4)

The overall indicator of IQ of the dyslexic children was average for the same age, but there were scales whose parameters differ significantly between the dyslexics and the typically reading children. Such an indicator was the scale for the speed of visual information, especially the "coding" and "symbol search" subtests.

The dyslexic children showed a pronounced deficit compared тo the age-matched normolexics concerning the information for the short-term memory, the visual attention, the visual-motor coordination, and the visual processing speed of coding and symbol search ($p < 0.001$, $F > 20.98$). This was a sensitive indicator of learning difficulties and cognitive impairments.

3.6. Reading achievement

Before training, the dyslexics showed a slower voice response time (1497.96 ± 30.5) during the reading of words compared to post-training (1266.16 ± 27.9 ms). After training, there was a significant improvement in voice response compared to pre-training ($p < 0.0001$, $\chi 2 = 30.4$; Table 1).

The children with dyslexia decreased the error rates and missing words from 11% with non-filter conditions to 5% with filter conditions. The reading speed of the trained dyslexics was about twice as high. The duration of the reading word also improved after training ($p = 0.001$). Their performance significantly improved in the visual tasks with filters, reducing reading time and correct reading of words. The untrained dyslexic group showed a higher success rate and slower reaction time compared to both words and pseudowords conditions after training ($p < 0.03$, $\chi 2 = 4.51$ for words; $p = 0.02$, $\chi 2 = 5.29$ for pseudo-words). Their reaction time did not change significantly.

Table 1.

Nonparametric statistical comparison of the behavioral parameters (mean ± se)

tasks	pre-training dyslexics	post-training dyslexics	statistics p	χ^2
Reading				
duration of Reading word	786.87 ± 16.83	657.16 ±14.67	**0.001**	9.48
Voice RT (ms)	1497.96 ± 30.5	1266.16 ± 27.9	**1.7e-06**	30.4
Success rate (%)	77.41 ± 3.8	90.05 ± 4.1	**0.0002**	16.39
Error (%)	11.3 ± 3.30	4.67 ± 3.58	**0.0032**	9.81
Omitted words (%)	11.3 ± 3.8	4.83 ± 4.1	**0.02**	5.26
Speed(N/20 sec)	10 ± 2	21 ± 2.3	**0.01**	6.54
Visual discrimination word/pseudoword			statistics p	χ^2
word condition				
Success rate (%)	69.83 ± 2.75	78.6 ± 2.99	**0.03**	4.51
RT time (ms)	1333.8 ± 18.52	1369.3 ± 19.82	0.08	2.87
pseudoword condition				
Success rate (%)	55.58 ± 3.71	69.5 ± 5.04	**0.02**	5.29
RT time (ms)	1543.3 ± 22.6	1537.8 ± 22.2	0.70	0.07

4. Discussions

It should be noted that the tasks testing the partially magnocellular sub-cortical nuclei (2fd) and the dorsal path passing through the lateral parietal regions (optical flow discrimination problem) ending in the inferior temporal cortex (coherent task) are strongly influenced from the prefrontal areas (Merigan and Maunsell, 1993). These cortical areas control the selective attention (Corbetta and Shulman, 2011; Koyama et al., 2013; Ronconi et al., 2016), which in our study is reflected mainly in the results of short-term memory task (color tracking within a cue). The abnormal magnocellular input to the dorsal pathway, established by the contrast-sensitive low-spatial frequency illusion (2fd), leads to a spatial and temporal attentional deficit of the dyslexic children (Lobier et al., 2014; Vidyasagar and Pammer, 2010).

Our studies confirm the hypothesis, that the temporal processing deficit related to the impaired phonological decoding in dyslexia, occurring also in the processing of visual and auditory dynamic stimuli, was influenced positively after training in the visual modality (Lallier et al., 2010; Harrar et al., 2014). At the magnocellular and parvocellular tasks during the contrast discrimination, the number of errors significantly decreased in the dyslexics after training, as well as the reaction time was better especially in the high contrast condition of the parvocellular-sensitive task (see Figure 2). An important factor for improvement of the results in visual discrimination tasks was the spectral/colored filters. The reaction time was faster, using filters. Children with dyslexia discriminated more difficult the low contrast M- and P-stimuli than those with the high-contrast. The benefit of using blue spectral filters was more for some children than using yellow filters. The improvement in dyslexic children is due to the diminution of the “eye stress” or the "Meares-Irlen syndrome", associated with color and shape distortion or motion illusion while reading. The use of yellow or blue spectral filters can stimulate the activity of the magnocellular pathway (Hall et al., 2013; Stein, 2014).

According to recent studies, the speed of visual information processing is dynamically linked to the mental capacity, the reading and its development, the thinking, the preservation of cognitive resources, and the efficient use of working memory (Fry and Hale, 2000), sensitive to the learning disabilities (Mayes at al., 2000). Faster processing of information can reduce the requirements for working memory and facilitate thinking. The dyslexic group processes significantly less amount of information than the normolexics do.

In alphabetic languages and Chinese (Qian, and Bi, 2015), children with dyslexia show deficits in phonological awareness and rapid naming, which play important role in the development of reading and closely related to M-function. The intervention on the M-pathway function stimulates more strongly the changes in the plasticity of the visual areas of the brain than in the motor regions. The intervention with the direction discrimination task is important for dyslexics with pronunciation and/or spelling problems, who show impaired ability to distinguish motion direction due to a deficit in the development of their inhibitory circuits (Lawton and Shelley-Tremblay, 2017). The discrimination of optic flow speed directly influences motion perception by affecting the neural activities in the middle temporal (MT/V5) area that according to some studies probably enhances phonological awareness (Olulade et al., 2013). The visual search/ tracking intervention, focusing on visual-spatial attention controlling eye movements, stronger stimulates the plasticity in the motor cortical areas than in the visual ones. The motion discrimination training (motion direction, motion speed) increases the synchronization between the neurons in the magnocellular and the parvocellular pathways, overcoming early the sluggish magnocellular neurons along the dorsal stream. Thereby the temporal dynamics and the activity of inhibitory circuits improve in the frontoparietal attention networks, in the anterior cortical areas, activated by saccades (frontal eye fields), and in the prefrontal language system, included in the reading network. Therefrom through the visual motion-discrimination training, the convergence of auditory and visual inputs in the posterior parietal cortex leads to the improvement of the auditory phonological processing and auditory working memory (Lawton, 2016).

When reading words aloud is required, the duration of their reading varies, depending on the frequency of use of the word in the language (Davies et al., 2013). The prolonged voice reaction time in children with dyslexia before training became shorter after training, as well as the number of incorrectly reading words reduced. This shows that the information processing continues from the decoding phase (voice reaction time) to the execution phase and indicates continuity between the reaction time and the articulation. When pauses and articulation time are recorded simultaneously, both are strongly related to reading speed and accuracy (Georgiou et al., 2008). Reading requires the effectiveness of several cognitive processes, including fast and effective visual scanning, visual selective attention, rapid lexical retrieval, short-term memory, and performance. The question is whether it is possible to have a stable interpretation of the deficit of children with dyslexia when working with the many components of reading. The most likely cause that children with dyslexia have a predominant deficit is impaired word decoding. This deficiency occurs under experimentally isolated conditions (e. g., voice reaction time for individual words). The voice reaction time is related to the process of decoding information (Georgiou et al., 2008). In our study, the longer decoding time improves the process of reading and understanding the individual words. The training with non-verbal visual tasks has a beneficial effect on orthography as well as improves the reading process. The color filters in education are a factor in improving the results of visual discrimination tasks. Visual-perceptual training favors reading and comprehension, as it improves speed and accuracy in general. Visual-spatial interventions on memory and attention lead to a better and more effective strategy that children use when reading to overcome the difficulties in developmental dyslexia.

5. Conclusions

The visual-perceptual non-verbal intervention remediates the timing deficits in the dorsal stream, in the executive functions, related to attention, working memory, processing speed, and accuracy of action generally, that could promote the reading strategy, reading-related cognitive skills, and reading comprehension. The noninvasive intervention with appropriate spectral/colored filters relieves any abnormality in low-level visual perception or in ocular motor skills of children with visual stress, which promotes their reading performance.

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Conflict of interests

The authors declare no conflict of interest.

References

Annett, M. (1970) A classification of hand preference by association analysis. *Br J Psychol*, 61, pp. 303-321. doi: 10.1111/j.2044-8295.1970.tb01248.x

Badcock, N. A., Hogben, J. H., Fletcher, J. F. (2008). No differential attentional blink in dyslexia after controlling for baseline sensitivity. *Vision Res*. 48(13), pp. 1497-1502. https://doi.org/10.1016/j.visres.2008.03.008.

Benassi, M., Simonelli, L., Giovagnoli, S. and Bolzani, R. (2010) Coherence motion perception in developmental dyslexia: A meta-analysis of behavioral studies. *Dyslexia* 16, pp. 341-357. doi: 10.1002/dys.412

Boets, B., Vandermosten, M., Cornelissen, P., Wouters, J. and Ghesquière,P. (2011) Coherent motion sensitivity and reading development in the transition from prereading to reading stage. *Child Development* 82(3), pp. 854-869. https://doi.org/10.1111/jM467-8624.2010.01527.x.

Breitmeyer, B. G. (1993). The roles of sustained (P) and transient (M) channels in reading and reading disability. In S. F. Wright & R. Groner (Eds.), Studies in visual information processing, Vol. 3. Facets of dyslexia and its remediation (p. 13–31). North-Holland/Elsevier Science Publishers. https://doi.org/10.1016/B978-0-444-89949-1.50008-0.

Corbetta, M., & Shulman, G. L. (2011). Spatial neglect and attention networks. *Annu. Rev. Neurosci*. 34, pp. 569–599. https://doi.org/10.1146/annurev-neuro-061010-113731

Cornelissen, P., Richardson, A., Mason, A., Fowler, S., Stein, J. (1995). Contrast sensitivity and coherent motion detection measured at photopic luminance levels in dyslexics and controls. *Vision Res*. 35(10), pp. 1483-94. https://doi:10.1016/0042-6989(95)98728-r.

Dahhan, A. N., Kirby, J. R., Brien, D., Munoz, D. (2016). Eye movements and articulations during a letter naming speed task: children with and without dyslexia. *J. Learn. Disabil*. 50(3), pp. 275-285. https://doi.org/10.1177/0022219415618502.

Davies R., Barbón A., Cuetos F. Lexical and semantic age-of-acquisition effects on word naming in Spanish. Mem Cogn (2013) 41, pp. 297–311. https://doi.org/10.3758/s13421-012-0263-8

Facoetti, A., Paganoni, P., Turatto, M., Marzola, V., Mascetti, G. G. (2000). Visual-spatial attention in developmental dyslexia. *Cortex* 36(1), pp. 109-123. https://doi.org/10.1016/ S0010-9452(08)70840-2.

Franceschini, S., Gori, S., Ruffino, M., Viola, S., Molteni, M., Facoetti, A. (2013). Action video games make dyslexic children read better. *Curr. Biol*. 23(6), pp. 462-466. https://doi.org/10.1016/j.cub.2013.01.044.

Fry, A. F., & Hale, S. (2000). Relationships among processing speed, working memory, and fluid intelligence in children. *Biological Psychology* 54(1–3), pp. 1-34. https://doi.org/10.1016/ S0301-0511(00)00051-X.

Girolami-Boulinier A. (1985). Contrôle des Aptitudes à la Lecture et à l'Ecriture (CALE). Delachaux et Niestlé, Neuchâtel, 1974.

Georgiou, G. K., Parrila, R., & Papadopoulos T. C. Predictors of Word Decoding and Reading Fluency Across Languages Varying in Orthographic Consistency. *Journal of Educational Psychology*. 2008, 100 (3), pp. 566–580. https://doi.org/10.1037/0022-0663.100.3.566

Gori, S., Seitz, A., Ronconi, L., Franceschini, S., Facoetti, A. (2016). Multiple causal links between magnocellular-dorsal pathway deficit and developmental dyslexia. *Cereb. Cortex* 26(11), pp. 4356-4369. https://doi.org/10.1093/cercor/bhv206.

Hall, R., Ray, N., Harries, P., Stein, J. (2013). A comparison of two-coloured filter systems for treating visual reading difficulties. Randomized Controlled Trial. *Disabil Rehabil*, 35(26), pp. 2221-6. doi: 10.3109/09638288.2013.774440.

Hankins, M. W., Peirson S. N, Foster R. G. (2008). Melanopsin: An exciting photopigment. *Trends Neurosci*. 31(1), pp. 27-36. https://doi: 10.1016/j.tins.2007.11.002.

Harrar, V., Tammam, J., Pérez-Bellido, A., Pitt, A., Stein, J., Spence, C. (2014). Multisensory integration and attention in developmental dyslexia. *Curr. Biol*. 24, pp. 531–535. https://doi.org/10.1016/j.cub.2014.01.029

Joshi, M. R., & Falkenberg, H. K. (2015). Development of radial optic flow pattern sensitivity at different speeds. *Vision Res*. 110(Pt A), pp. 68-75. doi: 10.1016/j.visres.2015.03.006.

Kalonkina, A., & Lalova, J. (2016) Normative indicators for the test battery for a written speech assessment. *Logopedic Centre Romel*, pp. 30-38. (in Bulgarian) ISBN 978-954-9458-23-7

Klaver, P., Marcar, V., Martin, E. (2011). Neurodevelopment of the visual system in typically developing children. *Prog. Brain Res*. 189, pp. 113-136. https://doi.org/10.1016/b978-0-444-53884-0.00021-x.

Koyama, M. S., Di Martino, A., Kelly, C., Jutagir, D. R., Sunshine, J., Schwartz, S. J., Castellanos, F. X., Milham, M. P. (2013). Cortical signatures of dyslexia and remediation: an intrinsic functional connectivity approach. *PLoS ONE*, 8, e55454. https://doi.org/10.1371/journal.pone.0055454

Kristen, P., Lavis, R., Hansen, P., Cornelissen, P. L. (2004). Symbol-string sensitivity and children's reading. *Brain Lang*, 89(3), pp. 601-10. doi:10.1016/j.bandl.2004.01.009.

Lallier, M., Tainturier, M. J., Dering, B., Donnadieu, S., Valdois, S., Thierry, G. (2010). Behavioral and ERP evidence for amodal sluggish attentional shifting in developmental dyslexia. *Neuropsychologia*, 48, pp. 4125–4135. https://doi.org/10.1016/j.neuropsychologia.2010.09.027

Lalova, J., Dushanova, J., Kalonkina, A., Tsokov, S., Hristov, I., Totev, T., Stefanova, M. (2018). Vision and visual attention of children with developmental dyslexia. *Psychological*

Research 21(2), pp. 247-261. ISSN 2367-9174 (Online).

Lalova J., Dushanova J, Kalonkina A., Tsokov S. (2019). Application of specialised psychometric tests and training practices in children with developmental dyslexia. *Psychological Research*, 22(1), pp. 271-283.

Liu, S., Liu, D., Pan, Z., Xu, Z. (2018). The association between reading abilities and visual-spatial attention in Hong Kong Chinese children. *Dyslexia* 24(3), pp. 263-275. https://doi.org/10.1002/dys.1584.

Lobier, M. A., Peyrin, C., Pichat, C., LeBas, J. F., Valdois, S. (2014). Visual processing of multiple elements in the dyslexic brain: evidence for a superior parietal dysfunction. *Front. Hum. Neurosci*, 7, pp. 479. https://doi.org/10.3389/fnhum.2014.00479

Lorusso, M.L., Facoetti, A., Bakker, D.J. (2011). Neuropsychological treatment of dyslexia: Does type of treatment matter? *J. Learn. Disabil*, 44(2), pp. 136-149. https://doi.org/10.1177/0022219410391186.

Lawton, T., & Shelley-Tremblay, J. (2017) Training on movement figure-ground discrimination remediates low-level visual timing deficits in the dorsal stream, improving high-level cognitive functioning, including attention, reading fluency, and working memory. *Front Hum Neurosci*, 11, pp. 236. doi: 10.3389/fnhum.2017.00236

Lawton, T. (2016) Improving dorsal stream function in dyslexics by training figure/ground motion discrimination improves attention, reading fluency, and working memory. *Frontiers in Human Neurosci*, 10, pp. 397. doi: 10.3389/fnhum.2016.00397

Mann, V., Wimmer, H. (2002). Phoneme awareness and pathways into literacy: a comparison of German and American children. *Read. Writing Interdiscip. J*, 15, pp. 653-682. https://doi.org/10.1023/A:1020984704781

Matanova, V., & Todorova, E. (2013) DDE-2 Test Battery for evaluation of dyslexia of development - Bulgarian adaptation; OS Bulgaria Ltd.

Mayes S. D., Calhoun S. L., Crowell E. W. (2000). Learning disabilities and ADHD: overlapping spectrumn disorders. *Journal of Learning Disabilities*, 33(5), pp. 417-424. https://doi: 10.1177/002221940003300502.

McIntosh, K., Horner, R. H., Chard, D. J., Boland, J. B., Good, R. H. (2006). The use of reading and behavior screening measures to predict non-response to school-wide positive behavior support: a longitudinal analysis. *School Psych. Rev*, 35 (2), pp. 275-291. https://doi.org/10.1080/02796015.2006.12087992

Menghini, D., Finzi, A., Benassi, M., Bolzani, R., Facoetti, A., Giovagnoli, S., et al., (2010). Different underlying neurocognitive deficits in developmental dyslexia: a comparative study. *Neuropsychologia* 48 (4), pp. 863-872. https://doi.org/10.1016/].neuropsychologia.2009.11.003.

Merigan, W. H., & Maunsell, J. H. (1993). How parallel are the primate visual pathways? *Annu. Rev. Neurosci*. 16, pp. 369–402. https://doi.org/10.1146/annurev.ne.16.030193.002101

Olulade,O. A., Napoliello, E. M., Eden, G. F. (2013). Abnormal visual motion processing is not a cause of dyslexia. *Neuron* 79, pp. 180–190. doi:10.1016/j.neuron.2013.05.002.

Ozernov-Palchik, O., Norton, E. S., Sideridis, G., Beach, S. D., Wolf, M., Gabrieli, J. D. E., Gaab, N. (2017). Longitudinal stability of pre-reading skill profiles of kindergarten children: implications for early screening and theories of reading. *Dev. Sci,* 20(5), pp. e12471. doi:10.1111/desc.12471.

Pammer, K. and Wheatley, C. (2001) Isolating the M(y)-cell response in dyslexia using the spatial frequency doubling illusion. *Vision Res* 41, pp. 2139-2147. doi: 10.1016/s0042-6989(01)00092-x

Pammer, K., Hansen, P., Krigelbach, M., Holliday, I., Barnes, G., Hillebrand, A., Singh, K. D., Cornelissen, P. (2004). Visual word recognition: the first half-second. *Neuroimage* 22(4), pp. 1819–1825. doi: 10.1016/j.neuroimage.2004.05.004.

Peters, L., Polspoel, B., de Beeck, H. O., De Smedt, B. (2016). Brain activity during arithmetic in symbolic and non-symbolic formats in 9-12 year old children. *Neuropsychologia* 86, pp. 19-28. doi:10.1016/j.neuropsychologia.2016.04.001.

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Perception & Psychophysics, 16*(2), pp.283–290. https://doi.org/10.3758/BF03203943

Raichev, P., Geleva, T., Valcheva, M., Rasheva, M., Raicheva, M. (2005) Protocol on neurological and neuropsychological studies of children with specific learning disabilities. In the "Integrated Learning and Resource Teacher" journal; Ed. “Dr. Ivan Bogorov” - Sofia. (in Bulgarian)

Raven, J., Raven, J. C., Court, J. H. (1998) Manual for Raven’s progressive matrices and vocabulary scales. Section 2: The coloured progressive matrices. *Oxford, UK: Oxford Psychologists Press;* San Antonio, TX: The Psychological Corporation.

Ray, N. J., Fowler, S., Stein, J. F., (2005). Yellow spectral/colored filters can improve magnocellular function: motion sensitivity, convergence, accommodation, and reading. *Ann N Y Acad Sci*, 1039, pp. 283-93. doi:10.1196/ annals.1325.027.

Ross-Sheehy, S., Oakes, L. M. and Luck, S. J. (2011) Exogenous attention influences visual short-term memory in infants. *Developmental Science* 14, pp. 490-501. doi: 10.1111/j.1467-7687.2010.00992.x

Ronconi, L., Franchin, L., Valenza, E., Gori, S., Facoetti, A. (2016). The attentional ’zoom-lens’ in 8-month-old infants. Dev. Sci. 19, pp. 145–154. https://doi.org/10.1111/desc.12288

Sartori G, Job R, Tressoldi, PE (2007) DDE-2: Battery for the assessment of developmental dyslexia and dysorthographia – 2. *Florence: Giunti O.S.*

Slaghuis, W.L., & Lovegrove, W. (1985). Spatial-frequency-dependent visible persistence and specific reading disability. *Brain Cogn*, 4(2), pp. 219-240. https://doi.org/10.1016/0278-2626(85)90071-5.

Sperling, A. J., Lu, Z. L., Manis, F. R. and Seidenberg, M. S. (2005) Deficits in perceptual noise exclusion in developmental dyslexia. *Nature Neuroscience* 8, pp. 862-863. doi: 10.1038/nn1474

Stein, J. (2014). Dyslexia: the role of vision and visual attention. *Curr. Dev. Disord. Rep,* 1(4), pp. 267-280. https://doi.org/10.1007/s40474-014-0030-6.

Stein, J. (2019). The current status of the magnocellular theory of developmental dyslexia.

Neuropsychologia, 130, pp. 66-77. https://doi.org/10.1016/j.neuropsychologia.2018.03.022.

Sun D., Roth S., Black M. J. (2014) A quantitative analysis of current practices in optical flow estimation and the principles behind them. *Int J Comput Vis*, 106, pp. 115–137 doi 10.1007/s11263-013-0644-x

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review, 95*(1), pp. 15–48. https://doi.org/10.1037/0033-295X.95.1.15.

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., Scanlon, D. M. (2004). Specific reading disability (dyslexia): what have we learned in the past four decades? *J. Child Psychol. Psychiatry*, 45 (1), pp. 2-40. https://doi.org/10.1046/ j.0021-9630.2003.00305.x.

Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: a deficit in visuo-spatial attention, not in phonological processing. *Trends Cogn. Sci*, 14, pp. 57–63.https://doi.org/10.1016/j.tics.2009.12.003

Wang, L., & Yang, H. (2018). Temporal processing development in Chinese primary school-aged children with dyslexia. *J. Learn. Disabil*, 51(3), pp. 302-312. https://doi.org/10.1177/0022219416680798.

Wechsler, D. (2003). Wechsler intelligence scale for children, 4th Edn. San Antonia, TX: Psych Corp.

Whiteley, H.E., Smith, C.D., Connors, L. (2007). Young children at risk of literacy difficulties: factors predicting recovery from risk following phonologically based interventions. *J. Res. Read*, 30, pp. 249-269. https://doi.org/10.1080/13682820600806680.

Yakimova, R. (2004) Abnormalities of written speech, Rommel Publishing House. (in Bulgarian).

Qian, Y., & Bi, H.Y. (2015) The effect of magnocellular-based visual-motor intervention on Chinese children with developmental dyslexia. *Front Psychol*, 6, pp. 1529. https://doi.org/10.3389/fpsyg.2015.01529.