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Subjective and objective evaluation of visual functions in dyslexic children with visual perceptual deficiency – before and after ten-weeks of perceptual training

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Abstract

This pilot study investigated perceptual and electrophysiological characteristics of dyslexic children and evaluated the immediate and prolonged effect of 10-weeks visual perceptual training on these characteristics in these children. Seven dyslexic children and seven controls aged 7-8 years completed this study. Results showed significant reduction ($p=0.021$) in visual evoked potentials (VEP) amplitudes in the dyslexic subjects, compared with controls, prior to perceptual training. A significant correlation ($p=0.005$) was found between the VEP amplitude and the total score of Test of Visual Perceptual Skills (non-motor)-revised (TVPS-R). After training, dyslexic subjects scored higher in some of the visual perceptual tasks and these improvements persisted for 3 months. However, the VEP amplitude in the dyslexics showed no significant change after perceptual training.

Keywords: Perception, Visual Evoked Potential, Dyslexics, Visual Perceptual Deficiency, Perceptual Training

Introduction

Dyslexia, according to the World Health Organization (1993), is a specific disorder in reading and writing, despite normal intelligence, adequate education resources and normal visual acuity. The prevalence of dyslexia is 9.7-12.6% in Hong Kong (Chan, Ho, Tsang, Lee, & Chung, 2007) while that in United State is 5-12% (Katusic, Colligan, Barbaresi, Schaid, & Jacobsen, 2001) depending on the inclusion criteria. The common presentations of dyslexic children include omissions, substitutions, distortions, or additions of words or parts of words (World Health Organization, 1993). They may also have long hesitations or "loss of place" in text, inaccurate phrasing and poor comprehension skills (World Health Organization, 1993). Dyslexics suffer from visual perceptual problems which can contribute to their disorder in reading and writing (Ho, Chan, Tsang & Lee, 2002). It was suggested to determine if any visual dysfunction is contributing to the learning difficulties (Allen, Evans & Wilkins, 2009). Evans (2004) illustrated the pathways of reading process shown in Figure 1: When we read, we have to recognize simple words firstly by sight analysis, then followed by phonetic analysis, which is a process to break down complicated words into sound components. Some dyslexics have deficit in one of these two pathways (Evans, 2004). Both pathways start with visual perception and all forms of reading start with visual perception (Evans, 2004), hence visual perceptual deficiency may contribute to the learning difficulties in dyslexics. Visual perception involves visual skills for organizing and extracting visual information from the environment, and the ability to integrate this information with that from other sensory modalities and with that from higher cognitive functions (Scheiman & Rouse, 1994). Good visual perception is essential in most school activities such as writing, reading, copying and remembering letters or words. It has been reported that 75% to 90% of classroom learning is vision-related (Carol, 2005). Therefore, any disorder in visual perception can greatly hinder learning and academic performance in school.

Our visual system has complementary pathways, the magnocellular pathway (M-pathway), parvocellular pathway (P-pathway) and koniocellular pathway (K pathway), which have different physiological characteristics but with a degree of cross-talk (Merigan & Maunsell, 1993). The M-pathway substrate is the large ganglion cells, which are widely distributed across the retina, and whose axons pass to the ventral lateral geniculate nucleus (LGN); information is then transmitted to the visual cortex. It responds to low contrast stimuli with high temporal frequencies and low spatial frequencies. The M-pathway is responsible for perceiving rapidly flickering or moving stimuli. The P-pathway substrate is cells mainly at the fovea, and whose axons pass to the dorsal LGN; information is then transmitted to the visual cortex. It responds to high contrast stimuli with low to moderate temporal frequencies and high spatial frequencies. The P-pathway is responsible for perceiving colour and fine detail (Merigan & Maunsell, 1993). The K-pathway is the least studied, K cells are very small and form six thin layers in the LCN, not much is known of their receptive field properties(Martinovic, 2016; Sherman 2009). K pathway was through to response to blue/yellow chromatic stimuli; in addition, it contributes to motion processing as K-cells project directly to motion-sensitive cortical area (MT/V5). (Martinovic, 2016; Sherman 2009) It has been suggested that 70-75% of dyslexics have a disorder in the M-pathway (Lovegrove, 1993; Lovegrov, Martin, & Slaghuis, 1986). A histological study has shown a significantly smaller size of magnocellular cells in the brains of dyslexics, but no significant difference in the size of parvocellular cells, when these cells are compared with those of controls (Livingstone, Rosen, Drislane, & Galaburda, 1991). Many studies have suggested abnormality in the M-pathway at the level of the primary visual cortex (V1) or earlier in dyslexics (Greatre & Drasdo, 1995; Maddock, Richardson, & Stein, 1992; Khaliq, Anjana, & Vaney, 2009; Kubová, Kuba, Peregrin, & Nováková, 1996; Romani et al., 2001; Schulte-Körne, Bartling, Deimel, & Remschmidt, 2004; Wang, Gao, & Wydell, 2010; Kobayashi, Inagaki, Yamazaki, Kita, Kaga, & Oka, 2014). Several studies have shown reduced sensitivity and/or increased latency to pattern visual evoked potentials (VEP) stimuli with lower spatial frequencies and/or higher temporal frequencies in dyslexics compared with normal readers (Livingstone, Rosen, Drislane, & Galaburda, 1991; Greatre & Drasdo, 1995; Maddock, Richardson, & Stein, 1992; Kobayashi, Inagaki, Yamazaki, Kita, Kaga, & Oka, 2014). Motion VEP studies have provided further evidence to support the suggestion of a disorder of the M-pathway in dyslexics. Longer latency (Kubová, Kuba, Peregrin, & Nováková, 1996) and lower amplitude in P100 and P200 components (Schulte-Körne, Bartling, Deimel, & Remschmidt, 2004) have been found in dyslexic subjects. Schulte-Körne, Bartling, Deimel, & Remschmidt (2004) have examined dyslexic and controls with a motion-onset VEP at three different velocities (2, 8, and 16 deg/s). They have found lower amplitude in P100 and P200 components in dyslexic subjects, and the differences in amplitude between the dyslexics and the controls were more significant with motion-onset VEP at higher velocity.

Perceptual learning is a process of learning to improve the selection of information available in the world that is relevant to the task (Gibson, 1969). Perceptual training can be used to improve the perceptual performance of an individual, which may allow that individual to be more responsive to educational instruction (Gersten et al., 1975; Rosen, 1966) and may enhance reading performance in dyslexia (Meng, Lin, Wang, Jiang, & Song, 2014). Gori & Facoetti (2014) suggested that perceptual learning selectively improves visual abilities and brings performance improvement through training on tasks not involving reading letters or letter chunks. Gori & Facoetti (2014) also suggested that perceptual learning training reduces the symptoms of dyslexia to make reading easier. However, there is no method to evaluate the improvement quantitatively. Does perceptual training give only symptomatic relieve or does it actually lead to improvement in the visual information processing particularly up to the cortical level? The knowledge about the effect of visual perceptual training at the physiological level (i.e. activity of M-pathway) is limited. Our hypothesis is that visual perceptual training in dyslexics may influence the activity of the M-pathway, which can be reflected by VEP. The aim of this study was to investigate the quantitative measure using VEP on the information processing deficit in the dyslexics as well as on the immediate and prolonged effect of visual perceptual training.

Methods

Subjects

A total of seventeen subjects, including 8 dyslexics and 9 controls aged 7 to 8 years, were recruited in this study. All dyslexic subjects had been diagnosed by a psychologist before this study. All subjects were from Hong Kong mainstream local primary schools and were using Chinese and Cantonese as their primary written and spoken language.

This can ensure that they were in the same education system with similar education background. All of them had normal IQ, best corrected visual acuity of 6/6 or better and good ocular health. Informed consent was obtained from their parents or legal guardians before enrollment. All subjects underwent a battery of visual perceptual assessments, and only those scoring below 50% percentile rank in any of those assessment items were recruited into the dyslexic group. Children with reported emotional or behavioral problems such as attention deficit hyperactivity disorder (ADHD), mental retardation and neuromuscular disabilities were excluded from this study. Children with binocular vision problem were excluded.

All research procedures adhered to the tenets of the Declaration of Helsinki and were approved by the Human Ethics Committee of the School of Optometry, The Hong Kong Polytechnic University.

Procedures

Perceptual and physiological characteristics in dyslexic children after visual perceptual training

The procedures of the experiment are showed in Figure 2, which included baseline measurement, intervention and evaluation. All the dyslexic and control subjects received eye examination, VEP measurement and visual perceptual assessment in baseline measurement. Ten-week home training was provided to all dyslexic subjects. Assessments done in baseline measurement were repeated for dyslexic subjects 3 months after the first assessment (Evaluation I) and 6 months after first assessment (Evaluation II).

Demographic information

Demographic information (including age, gender, birth history, personal general and ocular health history, family general and ocular health history, and history of last eye examination) was obtained by the mean of a structured questionnaire.

Eye examination

A battery of vision tests, including subjective refraction, best corrected visual acuity, color vision, binocular alignment revealed by cover test, motility, stereopsis, accommodation (by blur-to-clear method), near point of convergence, anterior and posterior ocular health assessment (including fundus photography, non-dilated fundus examination), were examined. Children with binocular vision problem (including tropia, exophoria of more than 4^{Δ} at distance, phoria of more than 8^{Δ} at near, monocular and/or binocular accommodation amplitude of less than 13D and nystagmus) were excluded.

Visual evoked potential (VEP) measurement

The general procedures and preparation for VEP recording followed ISCEV standards (Odom et al., 2010). Pattern-reversal VEP was recorded with active electrode placed 1 cm above Inion (Oz). The reference electrode was placed on the forehead (Fz) while the ground electrode was placed at the earlobe (A1 or A2). The impedances across the electrodes were less than 5kΩ. Bandpass filter of 1–100 Hz with amplifier gain of x20000 was used. The fully corrected subjects were in a quiet dim room and fixated on a red square in the center of the computer screen with both eyes at 100 cm viewing distance. The visual stimulation pattern was a black and white checkerboard (Figure 3) with checks subtending 180 min of arc. Two conditions of pattern stimulation were used for measurements:

1. 5-Hz reversal frequency at 15% contrast
2. 15-Hz reversal frequency at 15% contrast

The selection of the above protocol was based on the previous study which focused on the evidence illustrated that M-pathway is highly involved in the dyslexia (Greatrex & Drasdo, 1995). In addition, the cortical area MT related to depth perception was also reported to be influenced by dyslexia (Chowdhury & DeAngelis, 2008) and the MTprojecting layer 4B neurons was later found to receive the fast transmission of information from the M pathway (Nassi & Callaway, 2008). It is why the VEP measurement for M-pathway was chosen in this study. The recording time of each measurement was 1000 msec. The testing field size for VEP recording was 15˚. The mean luminance of the checkerboard was kept at $50cdm^{-2}$. Each subject had a 5-sec pre-stimulation adaptation for stabilization of signal before the start of recording.

Visual perceptual skills

Three major areas of visual perceptual skills, including visual spatial skills, visual analysis skills and oculomotor skills, were assessed. Table 1 lists the assessments tools used in this study. After analysis of the results, only those subjects who scored under the 50th percentile rank in more than four assessment items were recruited into the dyslexic group and were eligible to participate the perceptual training afterwards.

Visual spatial skills

Visual spatial skills were tested using the Southern California test of right left discrimination and Gardner reversal frequency test: recognition subtest. The Southern California test of right left discrimination tests an individual's concept of right and left on his own body and on that of another person. The subjects were asked 10 questions about Left/Right differentiation in Cantonese. Performance was scored based on both accuracy and response time. Subjects with higher accuracy and faster responses score higher. Gardner reversal frequency test: the recognition subtest examines whether the child can recognize letters and numbers printed in the correct or reversed direction. The total number of errors was counted to give an error score. The higher the error score, the worse the performance. The Gardner reversal frequency test was administrated to 500 normal children and 343 learning-disabled (LD) children, significant higher error number was obtained from LD children (Gardner 1979). Hence, the author suggested the test can determine whether the patient's reversals frequency is in the normal or abnormal range.

Visual analysis skills

Visual analysis skills were tested with the Test of Visual Perceptual Skills (non-motor) - Revised (TVPS-R). Visual analysis skills are the abilities to discriminate, recognize and analyze visual information, distinguish important features from a background, recall single or sequence of visual information. Test of Visual Perceptual Skills (non-motor) - Revised (TVPS-R) is a reliable and valid test (Chan & Chow, 2005), consists of 7 subtests: Visual Discrimination, Visual Spatial Relationships, Visual Form Constancy, Visual Figure Ground, Visual Closure, Visual Memory and Visual

Sequential Memory.

Oculomotor skills

Oculomotor skill was tested with Developmental eye movement (DEM) test (Bernell, Indiana USA). It involves a vertical test and a horizontal test which consists of numbers to be read vertically and horizontally respectively. In the vertical test card, single digit numbers are arranged into two vertical columns. In the horizontal test card, same numbers are arranged in horizontal array with 5 numbers in each row. In both tests, the participants were asked to call out the numbers as fast and as accurately as possible. The time which the participants used to complete each test and the errors made were recorded. Furthermore, the horizontal to vertical ratio was obtained by dividing the time used for the horizontal test by that of the vertical test. The DEM test has good reliability for all four of its scores (including vertical time, horizontal time, number of error, horizontal/vertical ratio) when it is administered in an office setting (Tassinari & DeLand, 2005). In the vertical test, the subject has to visualize, recognize and then verbalize visually presented materials. Thereby the test is designed mainly to assess the subject’s visual-verbal automaticity. Besides visual-verbal automaticity, the horizontal test is also affected by the subject’s saccadic eye movement. Therefore, a higher horizontal to vertical ratio indicates that the subject’s reading speed is affected more by eye movement than by visual-verbal automaticity, and vice versa. While Error score is a measure of the number of error they made during testing. The between-session intraclass correlation coefficients were fair to good for both the vertical and horizontal score.

Perceptual training

Ten-weeks of home training was provided to all subjects in the dyslexic group. All subjects and parents attended lessons every 2 weeks. During each lesson, the home training exercises were demonstrated and their understanding of training was then evaluated. They were not allowed to proceed to the next training session until they passed the evaluation. A log sheet, printed home training exercises worksheets and detailed instructions were given at each lesson. To ensure their compliance, they were required to return the completed Log sheet and worksheets. All subjects were required to do the home training exercise for 30 minutes every day. Subjects showing low compliance were not allowed to proceed to the next training sessions. The training schedules and the information of the exercises are shown in Appendix I.

Results

Seven dyslexics aged 7.7 $\pm$ 0.6 years and 7 controls aged 8.1 $\pm$ 0.4 years, met our inclusion criteria to participate in this experiment and they completed all assessments. There was no significant difference in age between the groups ($p = 0.118$) All dyslexic subjects were able to pass our evaluations and completed all training sessions.

Difference in visual perceptual skills between dyslexics and controls

The comparison of the visual perceptual assessments between the dyslexics and control groups before training are shown in Figures 4 to 6. All data were normally distributed (by Kolmogorov-Simirnov test). Independent t-test was used in the statistical analysis. The dyslexic children performed worse than the controls in all of these assessments. However, statistically significant differences were found only on the Southern California test ($p = 0.014$), visual discrimination ($p = 0.025$), visual form constancy ($p = 0.029$), visual figure ground ($p < 0.001$) and the total score in TVPS-R ($p = 0.001$) (Figure 4). In Gardner reversal frequency test, the dyslexic group showed inferior performance, which did not reach statistical significance. In the DEM test, the dyslexic subjects took significantly more time to complete the vertical test ($p = 0.002$) and horizontal tests ($p < 0.001$) than did the controls (Figure 5). The dyslexic subjects made significantly more errors in the DEM test ($p = 0.013$), while the DEM ratios of the two groups were similar (Figure 6). Visual perceptual skill performance of each individual subject was showed in Table 2.

Difference of VEP response between dyslexics and controls

There was a reduction in VEP amplitudes in the dyslexic subjects in response to 15 Hz reversal stimulation, but no obvious reduction in amplitude in response to 5 Hz reversal stimulation. Figure 7 is to show typical VEP waveforms obtained from one of the dyslexic subjects to illustrate the remarkable reduction in VEP amplitude in response to 15 Hz reversal stimulation. The amplitude of the VEP response was significantly lower in the dyslexic group than in the control group ($p=0.021$) (Figure 8). The correlation between VEP amplitude and different visual perceptual test scores was also analyzed. A statistically significant correlation (Pearson correlation: $r = 0.705$, $p = 0.005$) was found between the VEP amplitude and the TVPS total score. The lower the VEP amplitude, the lower the TVPS total score was (Figure 9)

Changes of visual perceptual skills and VEP responses after visual perceptual training

Repeated-measured ANOVA with post-hoc test (LSD) was used to analyze the effect of visual perceptual training in dyslexics on the perceptual assessment results and VEP findings among the baseline, 3 months after the first assessment (Evaluation I) and 6 months after first assessment (Evaluation II). In Southern California test of Right Left discrimination, dyslexic subjects scored slightly higher after training but it there was no significant change (p = 0.572). Similarly, the score of Southern California test of Right Left discrimination was almost the same after a further 3 months. In the Gardner Reversal Frequency Test, dyslexic subjects made significantly fewer errors after the training (p = 0.026). This improvement still persisted 3 months after cessation of training. In the TVPS-R results, dyslexic subjects obtained a higher score in all subtests after training, with statistically significant improvement found in visual discrimination (p = 0.019), visual memory (p = 0.018), visual closure (p = 0.010) and the total score (p = 0.007). No significant difference was seen in any individual score or the total score in TVPS-R after further 3 months. In the DEM test, dyslexic subjects used significantly less time to complete the vertical test (p = 0.014) and the horizontal test (p = 0.017) after training. Subjects also made significantly fewer errors in the DEM tests after training (p = 0.047). No significant change in the results of vertical test, horizontal test and error was found 3-months after cessation of training (evaluation I vs Evaluation II). The DEM ratio in the dyslexic was maintained at similar level throughout the study. In the VEP measurements, the amplitudes of VEP in response to the 15 Hz reversal stimulus and 5 Hz reversal stimulus at 15% contrast in the dyslexics showed no significant change throughout the whole study (Figure 10).

Discussion

Lower amplitude VEP responses in the dyslexic group were found in response to the 15 Hz reversal stimulus at 15% contrast level as compared to the controls. The changes of the transient visual evoked response is believed to be an abnormality in the M-pathway which is responsible to transmit information of low contrast rapidly flickering or moving stimuli from the retina to the visual cortex. This finding is similar to May and co-workers' study reviewed by Greatrex and Drasdo (1995), showed reduced VEP amplitude to sine wave gratings at 15% contrast in poor readers. Maddock, Richardson, & Stein (1992) also observed reduced VEP response to pattern reversal stimulation at 8% contrast in dyslexia. No reduction of response to the low contrast 5 Hz reversal stimulus was shown in our dyslexic group. It implies that the relatively low temporal frequency of stimulation is not able to trigger activity of the M-pathway. Livingstone and co-workers (Livingston, Rosen, Drislane, & Galaburda, 1991) investigated the VEP of 5 dyslexic and 7 normal adults to checkerboards of 1%, 2% and 15% contrast reversing at 5 Hz, 10 Hz and 15 Hz frequencies, and the VEP responses were found to be significantly lower in dyslexia, and the most significant reduction was observed at 15 Hz reversal frequency at the lowest contrast.

There was a significant positive correlation between VEP amplitude in response to the 15 Hz reversal stimulus and the TVPS-R total score. As TVPS-R is closely related to visual analysis performance, our finding implies that the weaker VEP response in dyslexia related to the abnormality in the M-pathway may relate to visual analysis performance. Besides poor visual spatial skills and visual analysis skills, dyslexic subjects also performed poorly on the vertical and horizontal sections of the DEM test. These results indicate that they have problems in visual-verbal automaticity, but have relatively normal eye movements. We surmise that there may be a relationship between this automaticity and the M-pathway. This may be explained by the "Transient-on-sustained inhibition" proposed by Breitmeyer. (1980). It was hypothesized that an image is formed on the retina during fixation when one is reading; this stimulus is then transmitted to the visual cortex through the P-pathway (i.e. sustained system), and the image will fade slowly after the fixation has ended. During the next saccadic movement, the M-pathway (i.e. transient system) is activated and this inhibits the P-pathway causing the previous image to be 'erased', ready for the next image to be input. This "Transient-on-sustained inhibition" process gives a clear image in reading (Breitmeyer, 1980). If the M-pathway fails to inhibit the P-pathway in the saccade, the image of the last fixation persists, leading to the superimposition of images, thus causing confusion in reading (Breitmeyer, 1980). This provides the rationale for the greater number of mistakes by dyslexics in the DEM test. Various recent studies showed that there was an impairment of the P-pathway in dyslexic children (Ahmadi et al., 2015; Bonfiglio et al., 2017). Bonfiglio et al. (2017) found delayed evoked responses to both achromatic stimuli and isoluminant red/green chromatic stimuli in dyslexia compared with age-matched normal readers. Hence, they supported the hypothesis of M-pathway deficit in dyslexia and further hypothesized that the combined impairment of both P- and M-pathway in dyslexia may be the explanation of the visual deficit. It is also the new direction in the future study.

An obvious improvement in visual perceptual skill was seen in the dyslexic group after their 10-weeks of training. This was in accordance with the findings of Fusco, German, & Capellini (2015) that dyslexics had significantly higher scores on the Test of Visual-Perceptual Skills (TVPS-3) after visual perceptual training. One may presume learning effect on the visual assessment exist and cause the improvement. Hence an age-matched control group was recruited to assess the learning effect on visual perceptual assessments in 3-month interval. There should be minimal learning effect as no statistically significant change in most assessments except for TVPS-R total score. The data were shown in the Appendix II.

Improvement in visual perceptual skill was found in the dyslexic group after training, however, we did not obtain any change in VEP amplitude in our dyslexic group after training. In usual practice, patients work on perceptual learning task with individualized adaptive paradigm. We usually design exercises for each perceptual skill, which should be able to train their weakness in different aspects. Therefore, it may be the possibility why our study showed a significant increase on the total score of TVPS-R after training. Our findings, however, also showed a significant correlation between the VEP amplitude and the TVPS total score, but not the improvement. Hence, we speculated that non-individualized training adaptive paradigm may contribute to the possibility that the current study did not show training induced VEP change.

Perhaps perceptual training influences behavioral activity but not the physiological activity at the primary visual cortex (V1), hence does not leading to change in VEP. Previous studies have applied fMRI or EEG recording to measure human cortical activity change in V1 after perceptual training. However, the results are inconsistent and seem to be specific to the nature of training task (Schwartz, Maquet, & Frith C, 2002; Pourtois, Rauss, Vuilleumier, & Schwartz, 2008; Jehee, Ling, Swisher, van Bergen, & Tong, 2012; Hamamé, Cosmelli, Henriquez, & Aboitiz, 2011). Some have reported specific improvement in V1 activity after training. These studies provided training in orientation detection at a particular region of the visual field. Greater fMRI

(Schwartz, Maquet, & Frith C, 2002; Jehee, Ling, Swisher, van Bergen, & Tong, 2012) or EEG (Pourtois, Rauss, Vuilleumier, & Schwartz, 2008) response at V1 was detected when the stimulation pattern with the same orientation as in training was presented to the subject. However, Hamamé, Cosmelli, Henriquez, & Aboitiz (2011) failed to show any improvement in V1 EEG response after training with a non-orientation specific target search task. This may suggest that orientation specific stimulation rather than non-orientation specific stimulation may trigger an activity change in V1 area after perceptual training. In our study, a non-orientation specific stimulus, the checkerboard, was used which may not be able to detect the change, if any, in V1 after training.

Apart from the above, the brain locus where perceptual training exerts its effect may be another factor. Stimulus orientation has been found to be encoded in both early processing regions of the visual cortex and higher cortical regions, which suggests that both areas are involved in visual perception (Kahnt, Grueschow, Speck, & Haynes, 2011). When the eye receives an image, a signal is firstly transmitted to the primary visual cortex (V1), and the signal is then projected to association areas (such as V4) or higher cortical regions (such as middle temporal area (MT)), and further to the decision-making regions (such as lateral intraparietal area (LIP)) (Sasaki, Nanez , & Watanabe, 2010). Perceptual training is likely to alter the activity of neurons in cortical regions other than V1. Ghose, Yang & Maunsell (2002) failed to demonstrate any effect on V1 after visual perceptual training in monkeys, but changes were found in V4 instead (Yang &Maunsell, 2004). Activities in both early visual cortex and higher cortical regions, such as lateral parietal cortex and anterior cingulate cortex (ACC), in human brain have been detected when the subjects are encoding stimulus orientation (Kahnt, Grueschow, Speck, & Haynes, 2011). However, changes have only been found in higher cortical regions after training on orientation discrimination tasks; this supports the idea that behavioral improvement on orientation specific tasks is highly associated with higher order changes in the brain (Kahnt, Grueschow, Speck, & Haynes, 2011). On the other hand, perceptual learning has been suggested to modify the connections between the neurons and decision processing (Chowdhury & DeAngelis, 2008; Law & Gold J, 2008). As perceptual training is likely to influence cortical area(s) other than V1, the performance in visual perception may not be reflected in the neurophysiological activity shown in our VEP results.

After cessation of training for 3 months, there was no significant regression in visual perceptual performance. A further longitudinal study is necessary to investigate if there is any regression for a longer beaching period, moreover, literacy test can be included in future study to determine any transfer effect of the perceptual training to reading performance. The VEP measurement was limited to the V1 area and further study with EEG or fMRI would help to assess the brain activity changes in higher cortical regions after perceptual training. Moreover, the sample size in this pilot study was small and the duration of the follow up was only 3 months. A longitudinal study of longer duration and with a large sample size would further strengthen the findings.

Conclusion

Dyslexics showed lower VEP amplitude under low contrast fast reversal stimulation, which may be related to an abnormality of M-pathway. Visual perceptual training can enhance perceptual performance and these enhancements have been shown to be persistent for at least 3 months. However, no observed visual cortical activity change in V1 was noticed after perceptual training, although behavioral improvement was found.

Potential conflicts of interest

The manuscript has been presented in public as posters:

1. Changes of transient visual evoked potentials in dyslexic children, 15-18 July 2011, The Asia-Pacific Conference on Vision 2011, Hong Kong
2. Pilot study on the effect of a ten-week home-based perceptual training programme. 24-26 Nov 2011, Asia Pacific Council of Optometry, Singapore

3. Visual Evoked Potentials in dyslexics with visual perceptual deficiency-before and after perceptual training. 15-18 May 2014, European Academy of Optometry and Optics Conference, Warsaw, Poland.

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Table 1. Assessments tools for assessing visual perceptual skills

Diagnostic Category	*Sub-Classification*	*Test*
Visual Spatial Skills	Laterality	Southern California Left Right Awareness test
	Directionality	Gardner Reversal Frequency Test: recognition subtest
Visual Analysis Skills	Visual Discrimination	TVPS: Visual Discrimination
	Visual Spatial Relationships	TVPS: Visual Spatial Relationships
	Visual Form Constancy	TVPS: Visual Form Constancy
	Visual Figure Ground	TVPS: Visual Figure Ground
	Visual Closure	TVPS: Visual Closure
	Visual Memory	TVPS: Visual Memory TVPS: Visual Sequential Memory
Eye Movement Disorders	Eyes Tracking	Developmental eye movement test (DEM)

Table 2. Visual perceptual skill performance of each subject before and after 10-weeks home based visual perceptual training.

Subject	Age* (year/ Month/ Gender)	Refractive Error*, best corrected VA (Decimal)	Southern California test of Right Left discrimination (Percentile Rank)		Gardner Reversal Frequency Test (Percentile Rank)	
			Pre	**Post**	**Pre**	**Post**
1	8/6/F	OD -1.75/-1.75 x 005 (1.0) OS -2.50/-1.25 x 176 (1.0)	50	50	1	72
2	8/2/F	OD +1.00 (1.0) OS +1.75/-0.75 x 173 (1.0)	20	69	45	82
3	7/1/M	OD +0.75 (1.0) OS +0.50/-0.25 x 090 (1.0)	37	78	1	1
4	7/6/M	OD +0.75/-0.50 x 180 (1.0) OS +1.00/-0.75 x 180 (1.0)	63	73	30	78
5	7/1/F	OD +1.00/-0.75 x 175 (1.0) OS +0.50/ -1.00 x 100 (1.0)	19	58	53	71
6	7/2/F	OD pl/-0.25 x 008 (1.0) OS pl (1.0)	72	3	70	76
7	8/2/F	OD +0.75 (1.0) OS -0.75/-0.25 x 180 (1.0)	26	55	72	82

*The first visit

Table 2 (Cont'd). Visual perceptual skill performance of each subject before and after 10-weeks home based visual perceptual training.

Subject	VD (Percentile Rank)		VM (Percentile Rank)		VSR (Percentile Rank)		VFC (Percentile Rank)		VSM (Percentile Rank)		VFG (Percentile Rank)		VC (Percentile Rank)		Total Score (Percentile Rank)	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
1	42	50	2	73	70	82	1	77	68	84	5	84	1	39	6	79
2	19	75	84	97	77	92	39	53	73	91	23	77	9	37	42	87
3	14	79	88	97	88	97	70	97	98	87	18	94	37	97	68	99
4	79	82	84	95	93	90	79	58	87	98	37	73	61	87	82	94
5	25	50	61	73	55	34	39	5	6	30	18	3	1	1	13	15
6	55	79	27	84	95	93	90	97	81	94	55	23	37	86	72	92
7	90	87	53	47	61	70	8	88	86	68	37	77	2	66	42	80

Test of Visual-Perceptual Skill (non-motor) – Revised

VD: Visual Discrimination; VM: Visual Memory; VSR: Visual Spatial Relationships; VFC: Visual Form Constancy; VSM: Visual Sequential Memory; VFG: Visual Figure Ground; VC: Visual Closure.

Table 2 (Cont'd). Visual perceptual skill performance of each subject before and after 10-weeks home based visual perceptual training.

Subject	DEM vertical test (Second)		DEM horizontal test (Second)		DEM error (Number of error)		DEM ratio	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
1	53.0	53.4	73.3	62.3	5	1	1.38	1.15
2	48.0	41.7	52.4	51.1	8	2	1.09	1.23
3	48.4	47.9	63.4	60.6	18	9	1.31	1.27
4	72.7	64.5	83.1	73.0	2	2	1.14	1.13
5	59.9	48.1	80.0	63.7	7	6	1.34	1.32
6	64.9	53.2	86.4	70.7	7	6	1.33	1.33
7	62.8	48.4	91.3	59.3	4	3	1.45	1.22

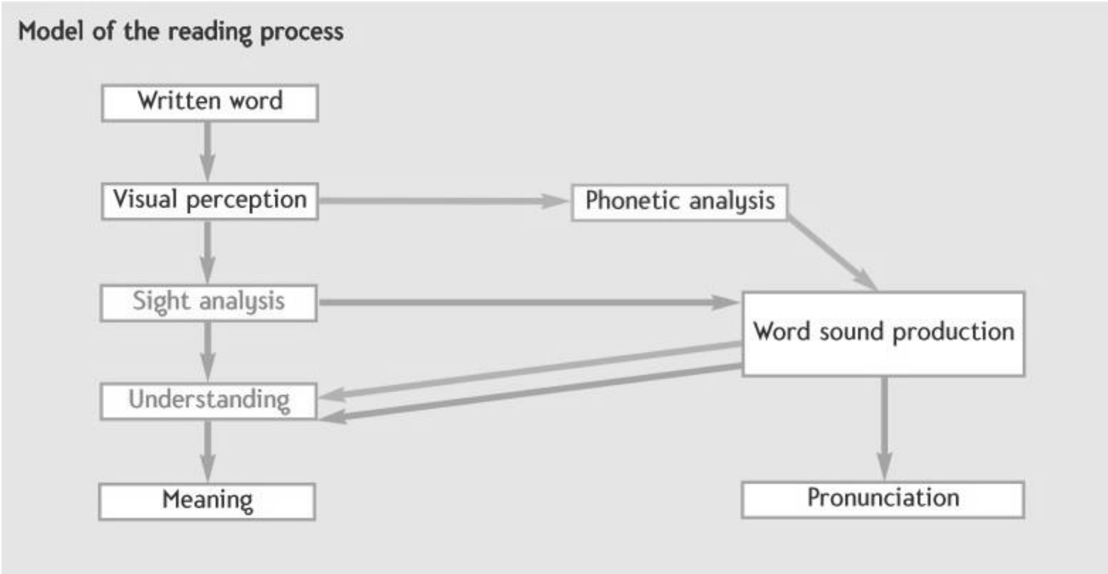

Fig. 1. Different pathways for reading process

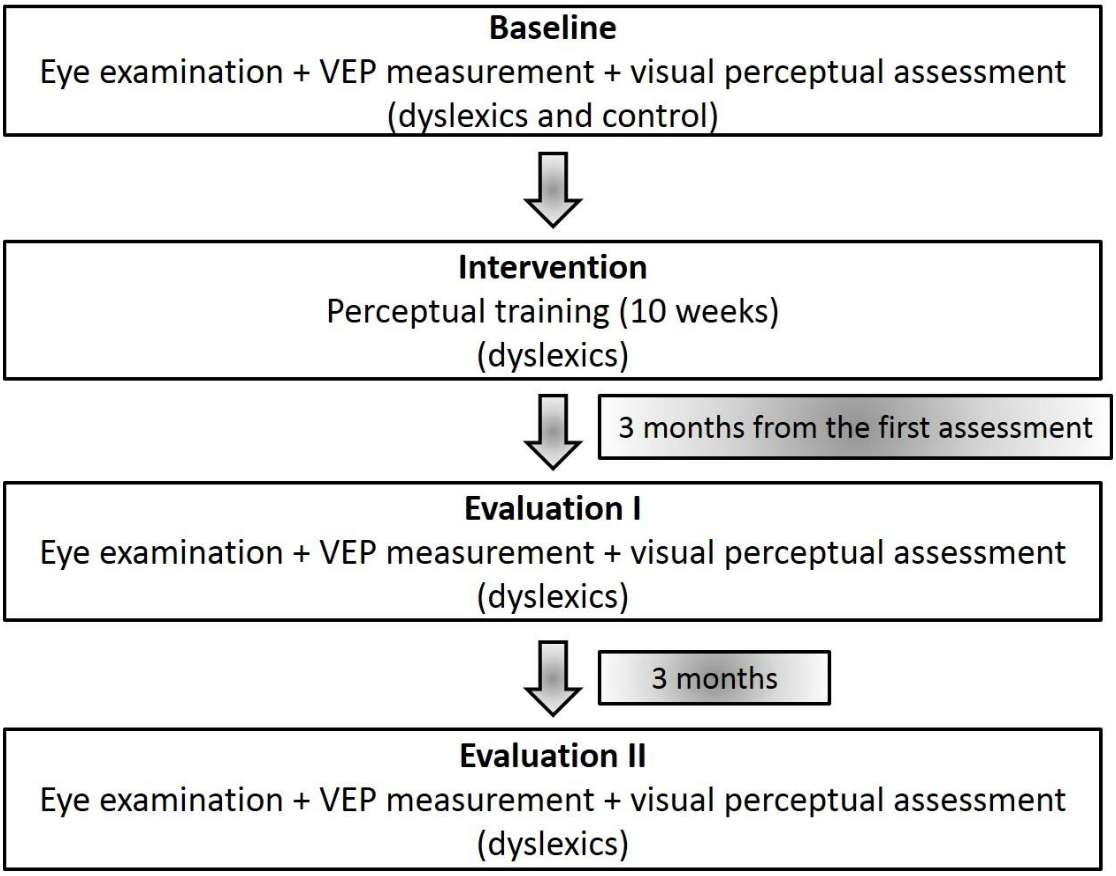

Fig. 2. Flowchart of the study

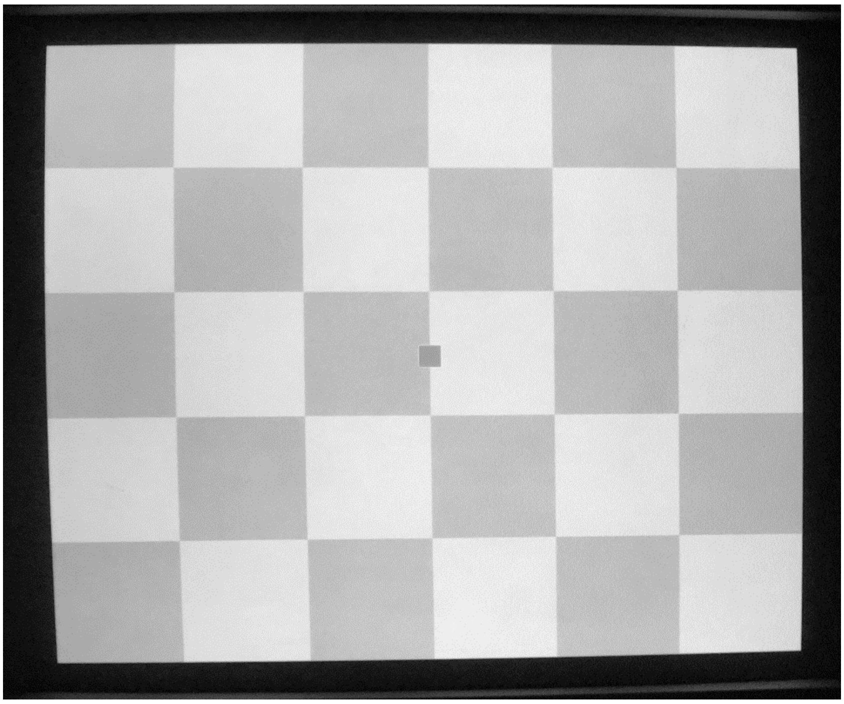

Fig 3. The VEP stimuli: checkerboard at 15% contrast with testing field size 15˚.

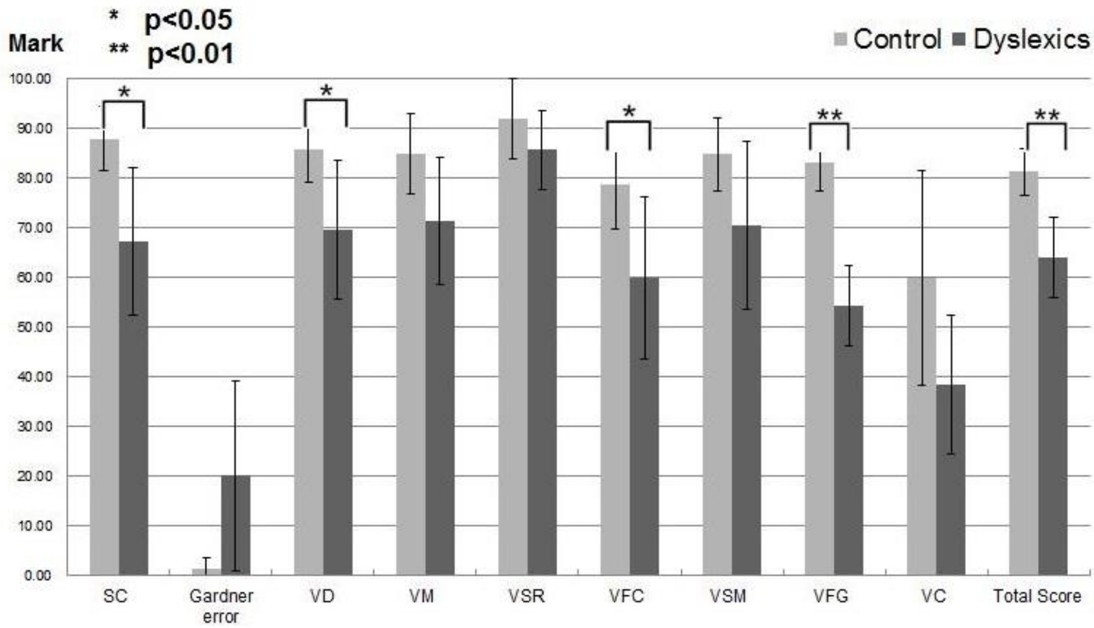

Fig. 4.Comparison of perceptual assessment baseline results (mean±SD) between dyslexic and control groups.

SC: Southern California test of Right Left discrimination; Gardner Error: Gardner Reversal Frequency Test (error score); Test of Visual-Perceptual Skill (non-motor) – Revised: VD: Visual Discrimination; VM: Visual Memory; VSR: Visual Spatial Relationships; VFC: Visual Form Constancy; VSM: Visual Sequential Memory; VFG: Visual Figure Ground; VC: Visual Closure.

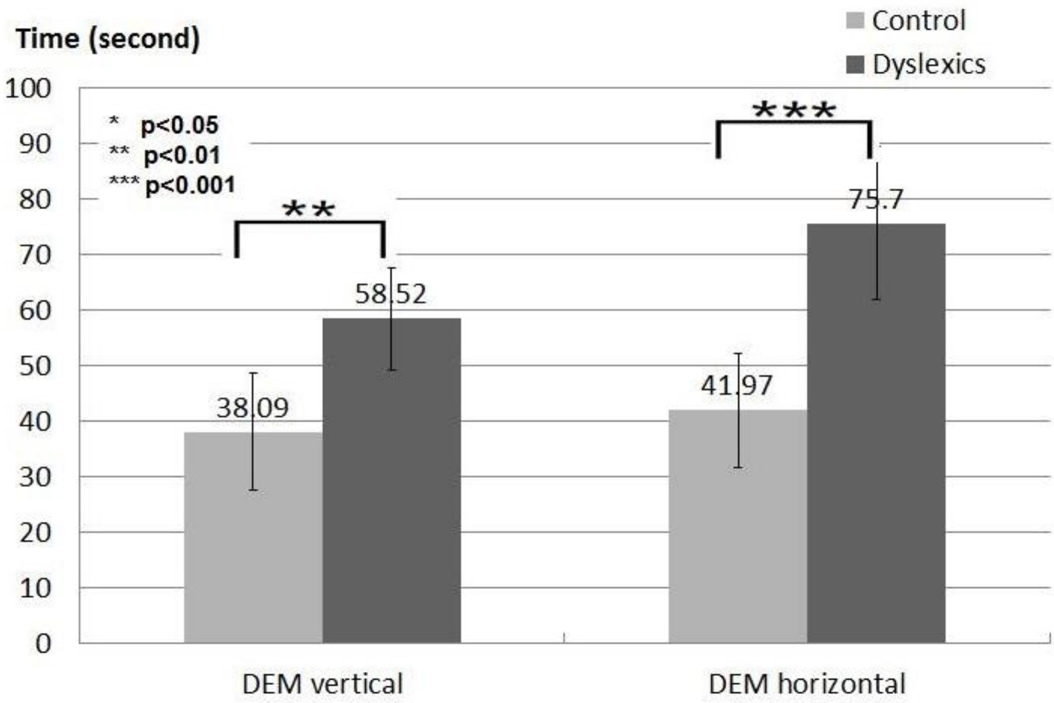

Fig. 5. Time (mean±SD) taken to complete the DEM tests

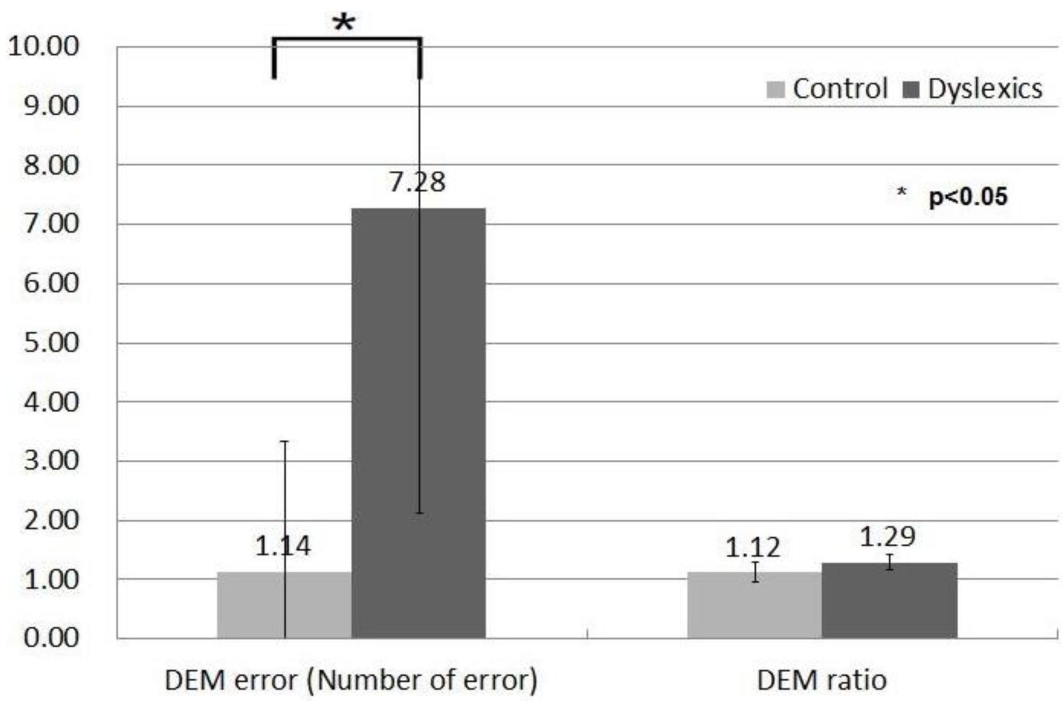

Fig.6. Number of error in DEM score (mean±SD) and DEM ratio (mean±SD) for dyslexics and controls.

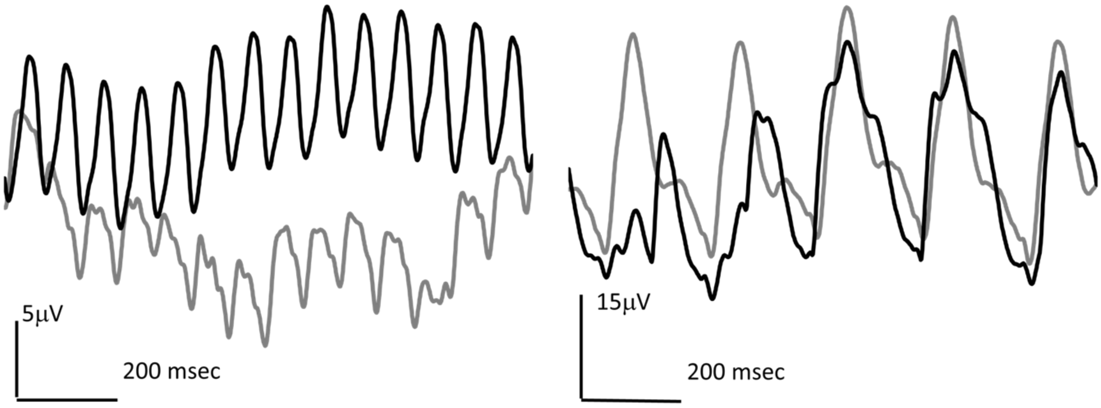

Fig. 7. Typical VEP waveforms obtained from a control subject (black line) and a dyslexic subject (grey line) for 15 Hz and 5 Hz stimulation using 15% contrast stimuli.

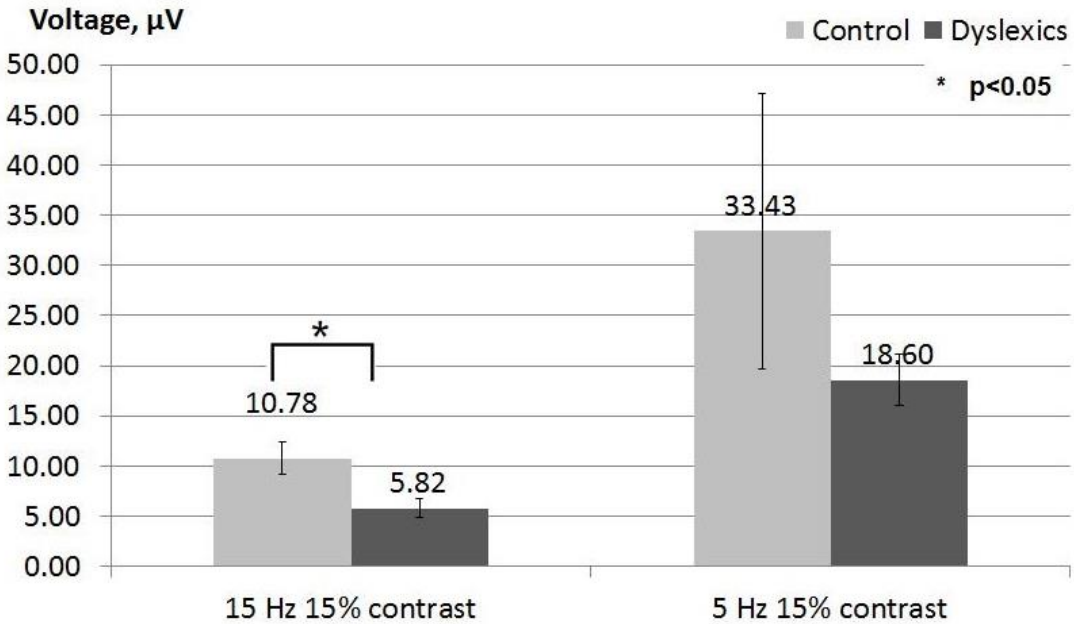

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Fig. 8. Comparison of baseline VEP amplitude (mean±SD) between controls and dyslexics.

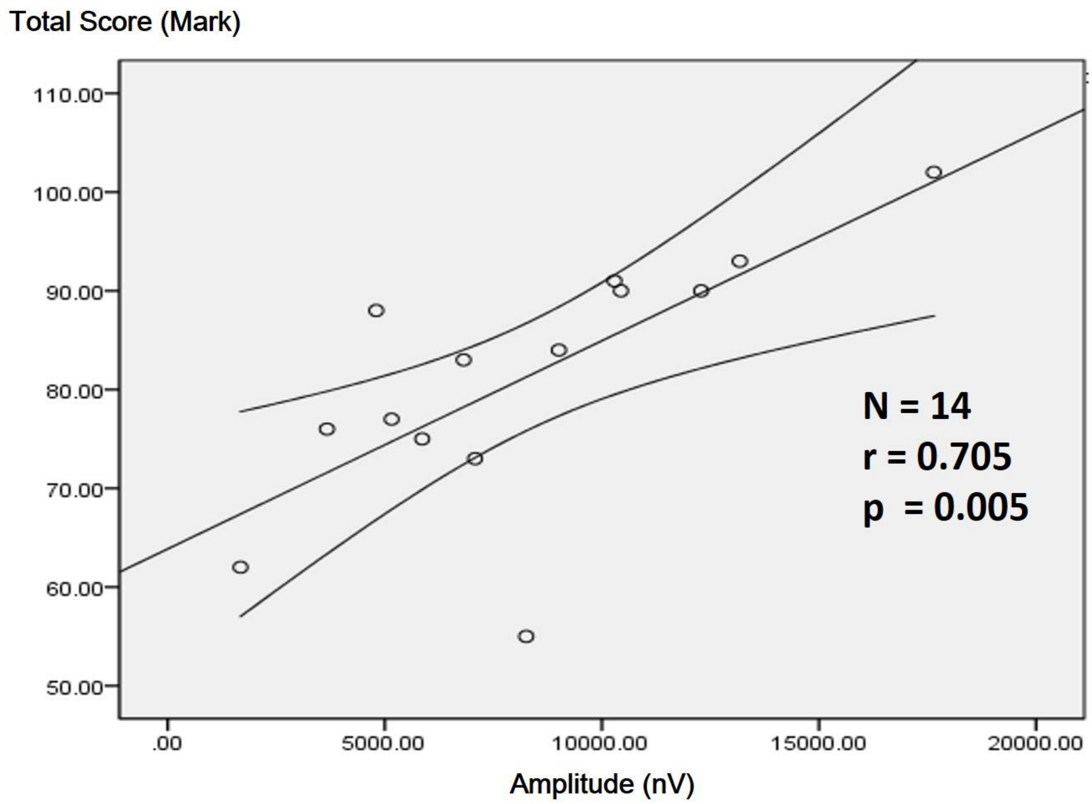

Fig. 9. TVPS Total Score as a function of VEP amplitude for 15Hz reversal frequency at 15% contrast stimulation. (Pearson correlation: r=0.705, p=0.005)

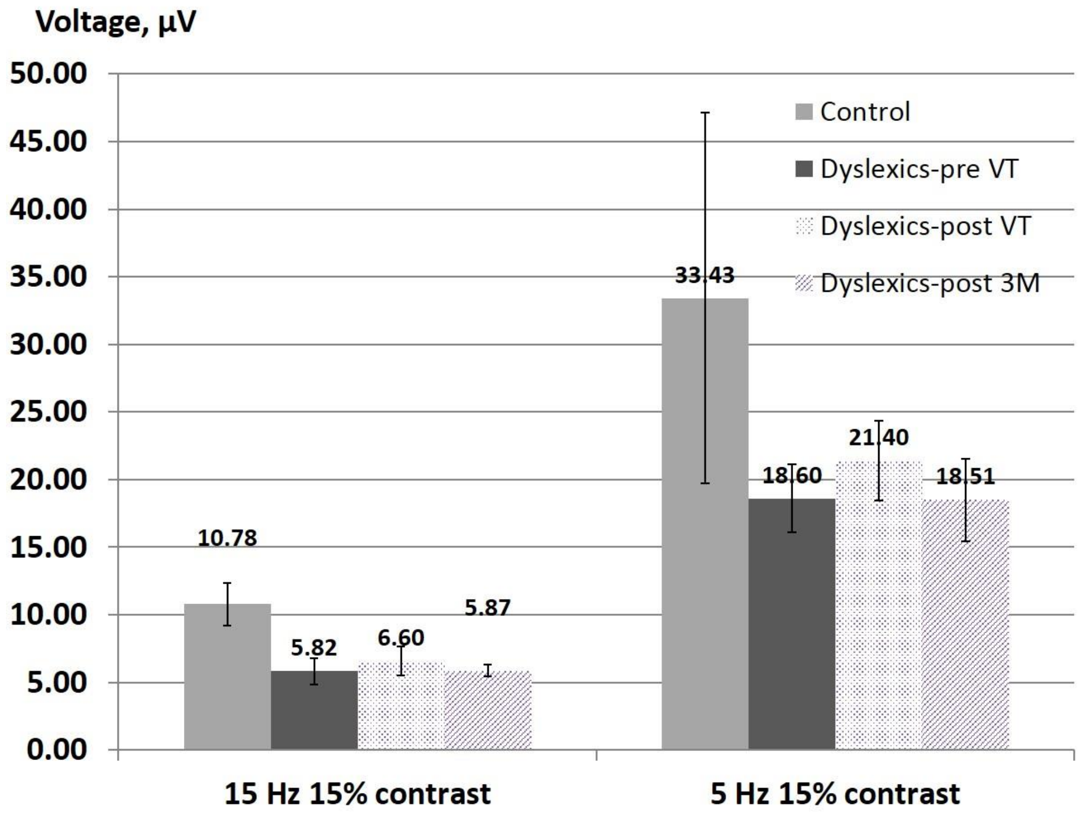

Fig. 10. Comparison of VEP amplitude (mean±SD) with 15% contrast stimuli in dyslexics among the study. (Dyslexics-pre VT: Baseline; Dyslexics-post VT: Evaluation I; Dyslexics-post 3M: Evaluation II, 3-months after intervention I)

Appendix I

Table I. Schedule of 10-weeks home based visual perceptual training.

	Training Exercises		Training Exercises
1st week	Continuous Motion Hart chart pursuit Ball Bounce	**6th week**	Parquetry block (Level 3) Three-in-a-row (Level 1) Dot-to-dot figures
2nd week	Hart chart saccades (1 sheet) b-d-p-q sorting Directional Triangle	**7th week**	Parquetry block (Level 4) Hart chart coordinates Jumbled pictures + computer game
3rd week	Hart chart saccades (2 sheet) Letter find Directional Maze (Level 1)	**8th week**	Three-in-a-row (Level 2) Visual tracing Hidden pictures + computer game
4th week	Parquetry block (Level 1 & 2) Letter reversal Flip forms	**9th week**	Rosner visual-motor technique Card concentration Jumbled pictures + computer game
5th week	Directional Maze (Level 2) Match rotated objects Find the word	**10th week**	Incomplete word Rosner visual-motor technique Visual memory (computer game)

The training schedules are listed in Table I. For the goals and the procedures of the exercises 1-17, please refer to Scheiman & Rouse (1994).

1. Ball Bounce
2. b-d-p-q sorting
3. Card concentration
4. Continuous Motion
5. Directional Maze
6. Directional Triangle

7. Dot-to-dot figures
8. Find the word
9. Flip forms
10. Hart chart coordinates
11. Jumbled pictures

    Besides giving worksheet for training, computer game was also given as training, below are some examples of computer game:

    http://www.agame.com/game/daily-difference, Accessed 5 Feb 2018.

    http://www.agame.com/game/the-princess-on-the-pea.html, Accessed 5 Feb 2018.

12. Letter find
13. Letter reversal
14. Parquetry block
15. Rosner visual-motor technique
16. Three-in-a-row
17. Visual tracing
18. Hart chart pursuit

    The goal of the exercise is to develop more accurate pursuit eye movement. The participant stands about 1 meter away from the Hart chart taped at eye level on the wall. He reads the letters of the first row from right to left, then the second row, and so on all the way down the chart. He should move his eyes only, keep his head and body still, and also keep good rhythm and accuracy.

19. Hart chart saccades (1 sheet)

The goal of the exercise is to develop more accurate saccadic eye movement. The participant stands about 1 meter away from the Hart chart taped at eye level on the wall. He reads the first and last letters of the first row, then the first and last letters of the second row, and so on all the way down the chart. He should move his eyes only, keep his head and body still, and also keep good rhythm and accuracy. If he does well with the first and last letters, he may try the second and second to last letters. If he does well, next are the third and third from last letters and so on.

20. Hart chart saccades (2 sheet)

The goal of the exercise is to develop more accurate saccadic eye movement. This exercise is nearly same as the Hart chart saccades (1 sheet), the only difference from Hart chart saccades (1 sheet) is two Hart charts taped on the wall. The participant stands about 1 meter away from the hart charts taped at eye level on the wall. He reads the first letter of the first row of the Hart Chart on right and last letter of the first row of the Hart Chart on left, then the second letter of the first row of the Hart Chart on right and last letter of the second row of the Hart Chart on left, and so on all the way down the charts. He should move his eyes only, keep his head and body still, and keep good rhythm and accuracy. If he does well with the first and last letters, then he may try the second and second to last letters. If he does well, next are the third and third from last letters and so on.

21. Hidden pictures

The exercise is for developing one's visual closure, which is the ability to aware of visual clues to allow him to percept without all the details being presented. Worksheet (Figure Ia) is given to the participant, and there is a picture/shape which is covered partially. It is used to match the same picture/shape at below. Besides providing worksheet for training, computer game is also used, below are some examples of computer game:

http://www.agame.com/game/secret-story-hidden-objects, Accessed 5 Feb 2018.

http://www.fukgames.com/game/16391/alladin-s-quest, Accessed 5 Feb 2018.

22. Incomplete words

The exercise is for developing one's visual closure, which is the ability to aware of visual clues to allow him to percept without all the details being presented. Worksheet (Figure Ib, Ic) was given to the participant, there are letters or words with some parts of line are missing. He needs to imagine the missing parts and answer what the letters or words are.

23. Match rotated objects

The exercise is for developing one's visual form constancy and visualization, which help the participant to be able to recall visually presented material and manipulate the images mentally. Worksheet (Figure Id) is given to the participant who is asked to look at the first shape of the first row. There are four shapes following the first one, and one of the four shapes is not a rotated form of the first one. The participant needs to answer which one is not the rotated form of the first shape. If he cannot give the correct answer, examiner will guide him to rotate the first shape mentally and check whether the rotated shape matches with the other four shapes one by one. If he can do it, try the next row.

24. Visual memory (computer game)

The exercise is for developing one's visual memory, which is the ability to form an image of visual input and recall visual information. Below are an examples of computer game:

http://www.agame.com/game/memmals-memory-game-2, Accessed 5 Feb 2018.

http://www.fukgames.com/game/16391/alladin-s-quest, Accessed 5 Feb 2018.

Reference:

Scheiman, M.M., Rouse, M.W.R. (1994). Optometric management of learning-related vision problems. St. Louis: Mosby.

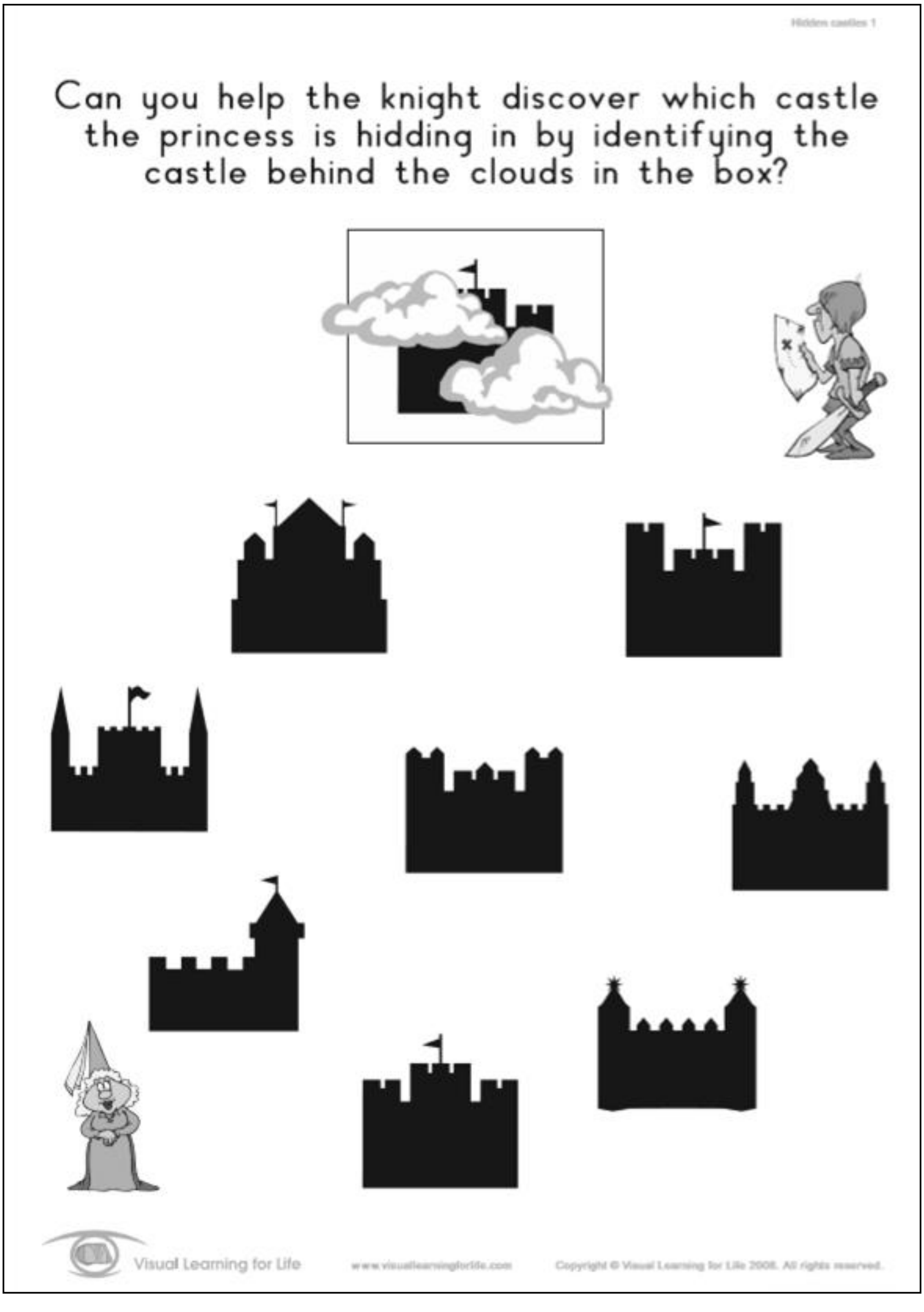

Fig. A1a. Example of worksheet to train visual closure

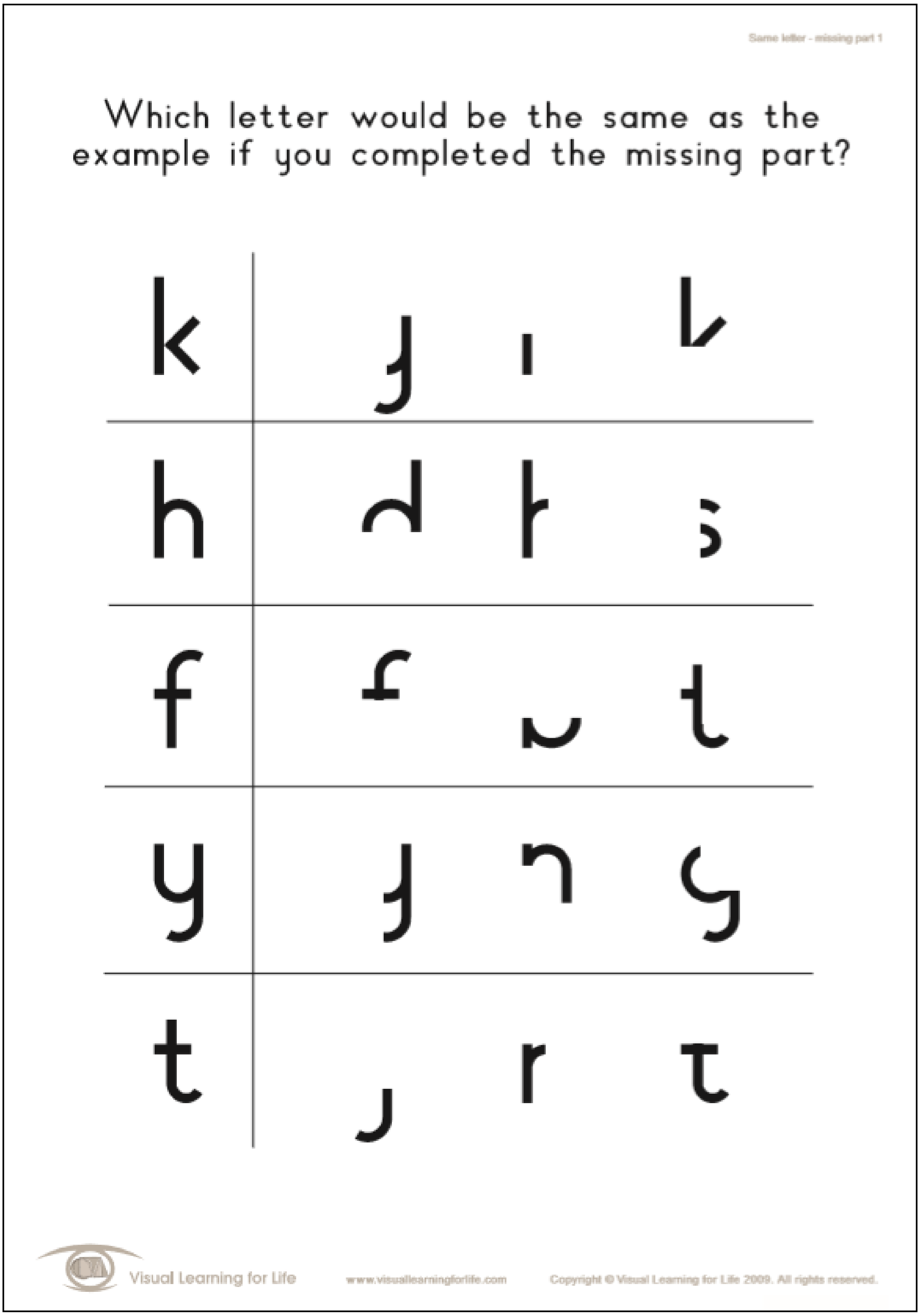

Fig. Ib. Example of worksheet to train visual closure

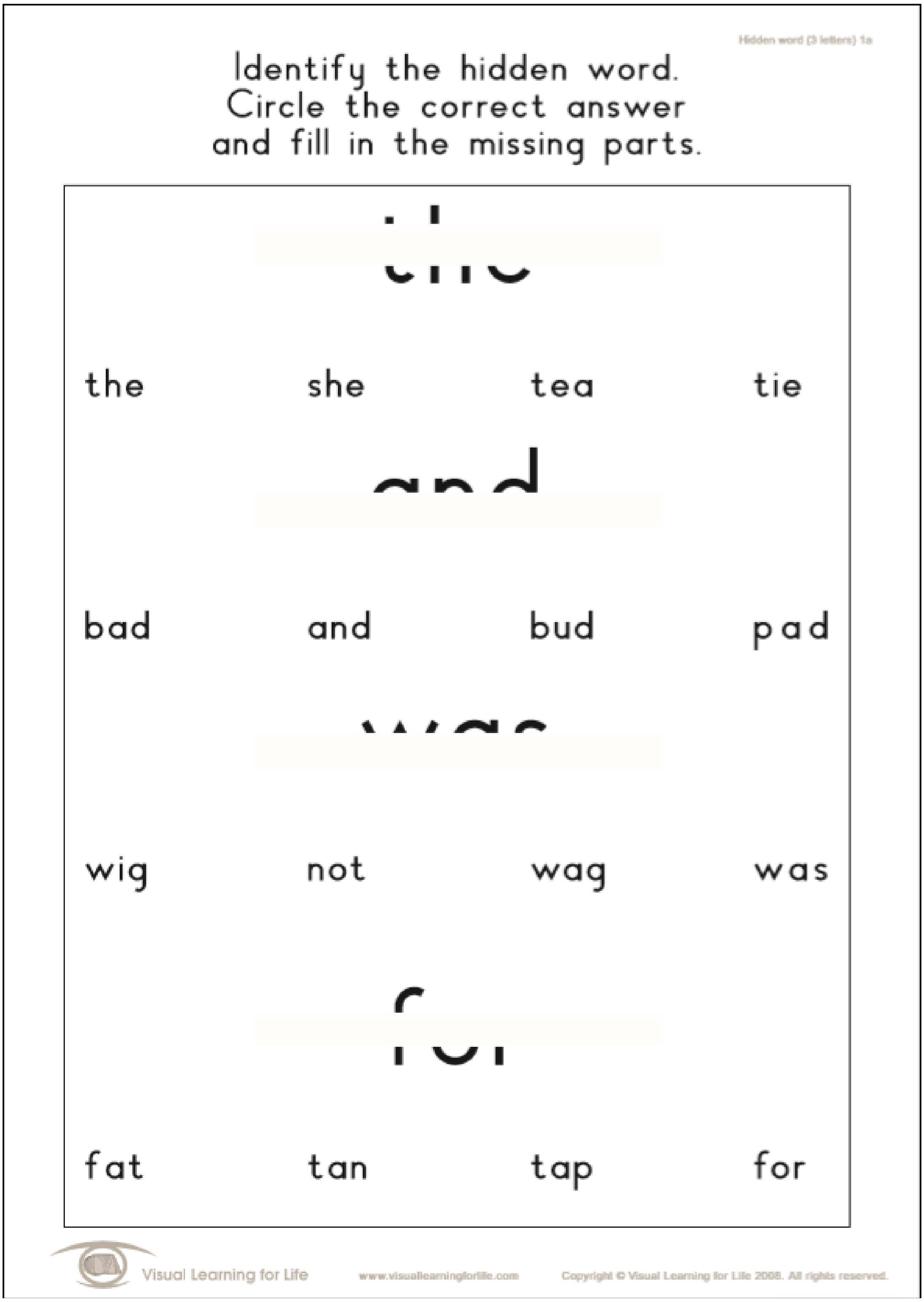

Fig. Ic. Example of worksheet to train visual closure

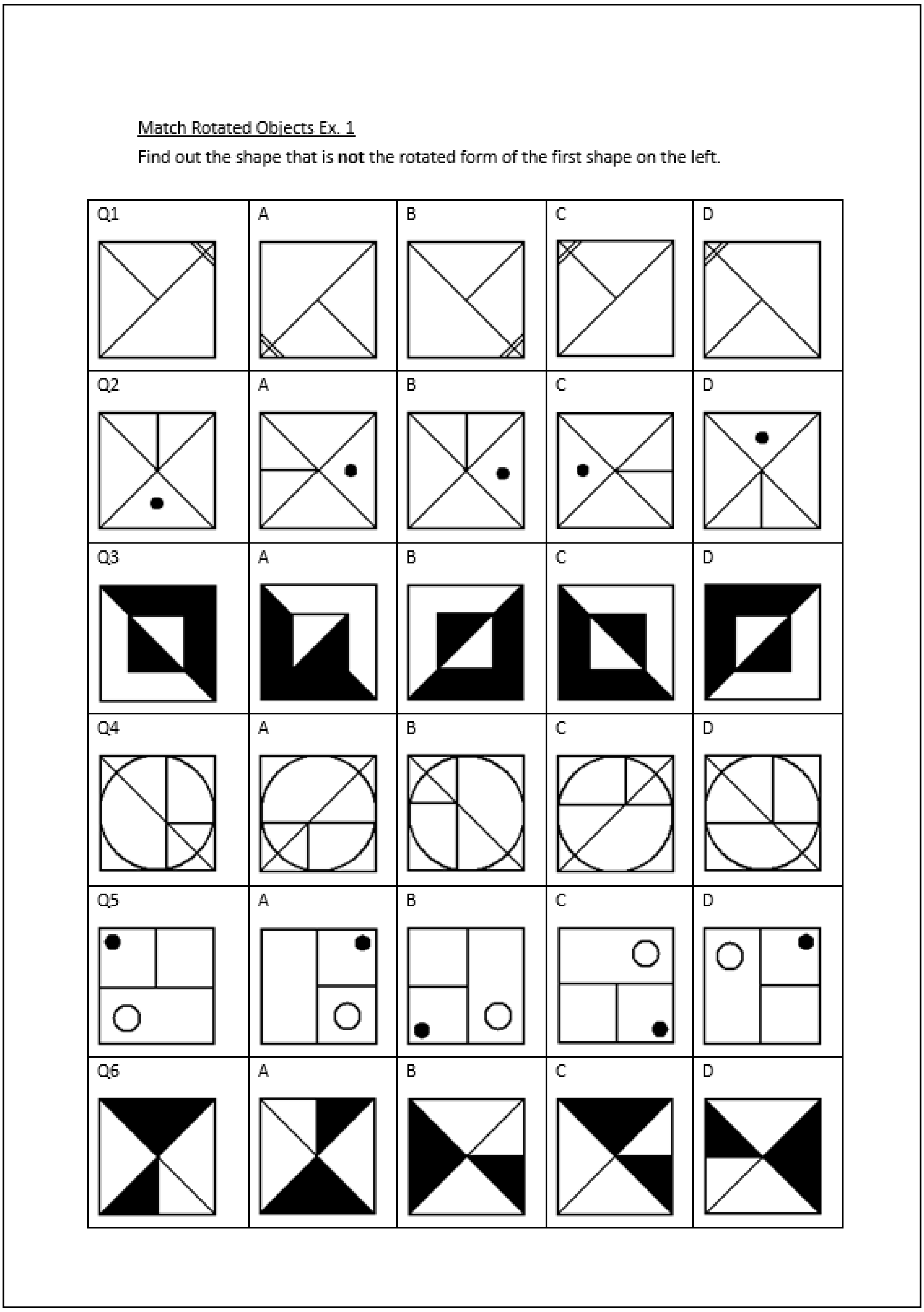

Fig. Id. Example of worksheet for Match Rotated Objects

Appendix II

Learning effect of visual perceptual assessments

Eight control subjects aged 7.8 ± 0.4 years who did not differ in age from the dyslexic group ($p = 0.623$) permitted evaluation of learning effects on the visual perceptual assessments (Table II). The same visual perceptual assessments were done at the initial visit and then repeated 3 months after the first assessment. No training or intervention was provided during this period. The aim was to evaluate the learning effect in the visual perceptual performance over the three month interval. The results of the visual perceptual assessments in the 3-month duration are shown in Figure II. Paired t-tests showed no statistically significant change in most assessments except for visual form constancy ($p = 0.009$) and TVPS-R total score ($p = 0.007$). There was no significant change found in any DEM test items.

How does the learning effect influcence the comparison of the visual perceptual assessment results between dyslexic and control subjects?

The unpaired t-test was used to compare visual perceptual performance changes in the dyslexic subjects after training and in the second group of controls after a three months interval, to confirm the effect of training. There was no significant difference ($p = 0.986$) between the change in the score for visual form constancy in the two groups.

However, significant difference (p = 0.01) in the change in TVPS total score was found (Table II).

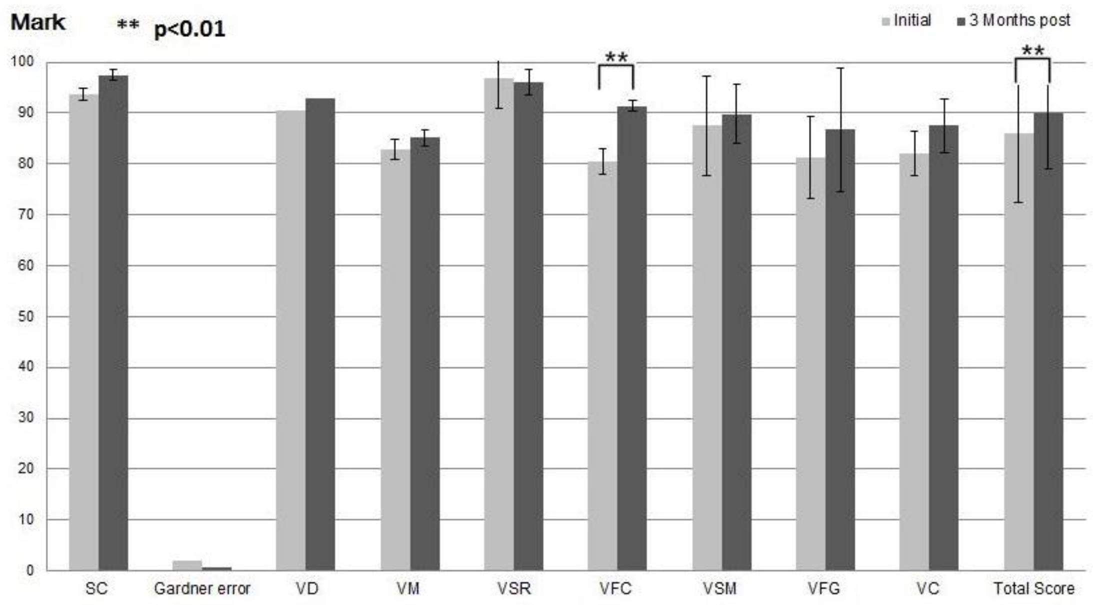

Fig. II. Visual perceptual assessments score in 3 months interval in control group to evaluate the learning effect.

SC: Southern California test of Right Left discrimination; Gardner Error: Gardner Reversal Frequency Test (error score), Test of Visual-Perceptual Skill (non-motor) – Revised; VD: Visual Discrimination, VM: Visual Memory; VSR: Visual Spatial Relationships; VFC: Visual Form Constancy; VSM: Visual Sequential Memory; VFG: Visual Figure Ground; VC: Visual Closure.

Table II. Comparison of the performance changes between the dyslexic subjects after training and the second group of controls

	Dyslexic (N=7)	Control (N=8)	Unpaired t-test
	Mean ± SD	Mean ± SD	
Age	7.67 ± 0.60	7.80 ± 0.44	t=0.50, p=0.623
TVPS--VFC	1.71 ± 5.09	1.75 ± 1.39	t=0.018, p=0.986
TVPS total score	16.43 ± 10.72	4.50 ± 3.38	t=3.00, p=0.01*