Effects of computerized cognitive training for children with dyslexia: An ERP study

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ABSTRACT

This feasibility study investigated the effects of adaptive computerized cognitive training on visual-spatial working memory (VSWM), and reading performance in children with dyslexia. Children were assigned into a VSWM training group that received a 5-week (~30 h) computerized adaptive training program focusing on VSWM, or a waitlist control group. Behavioral and ERP measures of VSWM-related indices and reading ability were taken at baseline, post-training/waiting, and 6-month follow-up to evaluate the effects of training. Results revealed the training group demonstrated significant behavioral improvements at post-training and at a 6-month follow-up in visual attention (IVA-CPT), response control (visual Oddball tasks), and VSWM (WMTB-C & visual 1-back tasks), compared to the control group. Although the training group did not show significant improvements in reading abilities at post-training, the improvement was significant at the follow-up assessment. In addition, relative to the control group, we observed greater P3b amplitudes on the visual 1-back task for the training group at post-training with a large effect. These preliminary findings suggest that an intensive cognitive training can serve as a potentially effective standalone or adjunctive training to improve cognitive control and reading abilities of children with dyslexia.

1. Introduction

Reading disorders are considered as one of the most pervasive learning problems (lifetime prevalence ranging from 4% to 10% in the general population; Sexton, Gelhorn, Bell, & Classi, 2012), and involve specific deficits in fundamental language skills, such as reading, comprehension, and spelling (Gathercole & Adams, 1994). A great deal of research has been devoted to studying the etiology of these disorders, and has identified deficits in auditory and phonological processing (Richardson, Thomson, Scott, & Goswami, 2004). Researchers have also identified a relationship between working memory (WM), executive attention, and reading disabilities, showing that children with reading disabilities display dysfunctional selective and sustained attentional processes (Marzocchi, Ornaghi, & Barboglio, 2009; Menghini et al., 2010), deficits in response control abilities (Savage, Cornish, Manly, & Hollis, 2006; Schoot & de Sergeant, 2000), and impaired phonological and visual-spatial working memory (VSWM; Gathercole, Alloway, Willis, & Adams, 2006; Pennington, 2008; Swanson, 1994).

WM is a cognitive system governing the temporary storage and manipulation of information and is assumed to include three
primary components: central executive, phonological loop, and visual-spatial sketchpad (Baddeley, 2003; Baddeley, Hitch, & Allen, 2019). Although these components work together, it is assumed that the visuo-spatial sketchpad and phonological loop maintain their own modality of WM storage, and that each of these limited storage faculties process ongoing relevant information respectively (Baddeley, 2003; Baddeley et al., 2019). As WM abilities are crucial for successful learning and academic outcomes (Swanson & Alloway, 2012), deficits in WM may influence the development of learning disabilities, such as reading disorders (Avtzon, 2012; Holmes, Gathercole, & Dunning, 2009; Loosli, Buschkuehl, Perrig, & Jaeggi, 2012). Prior work demonstrated that VSWM has a pivotal role in reading processes, which encompass multi-faceted visual sensory processes (e.g., letter/word representation and recognition). Dysfunctional VSWM can interfere with the normal development of visual representations, recognition, and recall of individual letters, consequently impairing the acquisition of automatic reading fluency resulting in semantic impairments (Giovagnoli, Vicari, Tomasetti, & Menghini, 2016). More recent findings from Shiran and Breznitz (2011) have emphasized the relationship between a larger VSWM capacity and reading skill improvement among dyslexic individuals, indicating a close linkage between these two constructs. They suggested that the reading skills deficits in dyslexia may reflect dysfunctional visuo-spatial WM subsystems.

The observed relationship between VSWM and reading abilities has led some to consider WM training as an alternative intervention (Dahlin, 2011; Holmes, Gathercole, & Dunning, 2009) to alleviate symptoms associated with reading disorders, compared to more traditional interventions that primarily focus on phonological awareness (Pirzadi et al., 2012). The WM training approach utilizes computerized cognitive training that aims to improve the number of items that can be actively recalled (i.e., recall span) and the speed of visuo-spatial WM processing. WM training has been shown to be beneficial in enhancing decoding of words, reading speed, and comprehension of written text in dyslexic readers (Shiran & Breznitz, 2011). A recent meta-analysis also reported that WM training can ameliorate reading deficits in children diagnosed with learning disabilities (Peijnenborgh, Hurks, Aldenkamp, Vles, & Hendriksen, 2016), improving various domains of WM and reading abilities (e.g., verbal WM, VSTM, and word decoding). Importantly, therapeutic gains were found to be maintained for up to eight months after training. Taken together, the current literature provides evidence that computerized training targeting the visuo-spatial component of WM yields significant improvement in WM among children with dyslexic problems.

In addition to behavioral WM indices, electroencephalography (EEG) work incorporating event-related potentials (ERPs) have also been utilized to evaluate the effects of cognitive training on WM and reading processes (Johnstone, Roodenrys, Phillips, Watt, & Mantz, 2010; Shiran & Breznitz, 2011). One prominent ERP component, the P300, has been shown to reflect updating content in WM (Shiran & Breznitz, 2011; Smith-Spark & Fisk, 2007) and as an indicator of WM load in the n-back paradigm (e.g., different n-back load; Brouwer et al., 2012; Christensen, Estepp, Wilson, & Russell, 2012). Particularly, the amplitude of P3b, a subcomponent of the P300, has been found to originate from the parietal lobe, a region implicated in attention and subsequent memory processing (Polich, 2007; Polich & Kok, 1995). A reduction in the P3b has been found in auditory and visual n-back tasks among children with developmental language impairments compared to healthy controls (Evans, Selinger, & Polliak, 2011). Evans et al. (2011) suggested that these children do not suffer deficits in processing speed, given that no differences were observed in terms of behavioral reaction time and latencies of P3b as compared to healthy controls. In contrast, they found lower accuracies in behavioral performance and an attenuated P3b amplitude in both auditory and visual n-back tasks, which indicates that this population is characterized by limited WM capacity. Taken together, a reduced P3b amplitude in the 1-back task (coupled with poor behavioral performance) provides strong support for the WM capacity deficits as an important neurocognitive factor associated with dyslexic problems. Thus, the P3b may serve as a reliable index for therapeutic changes in the underlying neural activity involved in the storage and processes of WM in the context of WM-focused cognitive training for children with dyslexia.

With the marked growth in computer-assisted training technologies, WM has also been an intervention target of computerized cognitive training in numerous studies (e.g., Gathercole, Dunning, Holmes, & Norris, 2019; Larsen et al., 2019; Peijnenborgh et al., 2016). Although existing data suggests that cognitive training may be beneficial in improving WM and reading abilities in dyslexic individuals (Loosli et al., 2012; Shiran & Breznitz, 2011), little work has been conducted to examine the effect of WM-focused training comprehensively, including the WM processes, their related neural processes, as well as relevant functional outcomes (i.e., reading abilities; Melby-Lervåg & Hulme, 2013; Melby-Lervåg, Redick, & Hulme, 2016; Shipstead, Redick, & Engle, 2012). This pilot study sought to investigate the effects of computerized adaptive WM training on VSWM performance and reading abilities of school-age children. Additionally, we recorded the P3b ERP as an underlying electroencephalographic indicator of WM improvement following training. We hypothesized that dyslexic children in a computerized cognitive training group would show significant improvement in our primary (i.e. VSTM and its related cognitive processes) and secondary (i.e. reading abilities and inhibitory control) outcome measures, compared to an age-matched waitlisted group. Furthermore, we hypothesized that these changes would be traceable through electroencephalographic recordings reflected by an increase in P3b amplitude in a corresponding WM task. Finally, we expected that these improvements would be maintained at six months after the training.

2. Method

2.1. Participants

Thirty-five (26 males) children aged 7 to 12 (\(M_{\text{Age}} = 8.2, SD_{\text{Age}} = 1.41 \)) years were recruited from three learning disability centers and one clinical neuroscience center (all located in Tehran, Iran). In order to qualify for this study, children had to score two standard deviations below the mean in the Reading and Dyslexia Scale (R&D Scale; Shokoohi-Yekta et al., 2014; Kormi-Nouri, Moradi, Moradi, Akbari-Zardkhaneh, & Zahedian, 2012) and received a dyslexia diagnosis by on-site psychologists at the clinical neuroscience center. All eligible children were assigned to one of two groups: computerized adaptive training (tDYS, \(n = 15\)), and a control group with no
training (cDYS \( n = 20 \)). Children were matched between the groups according to age (tDYS \( M = 8.2, SD = 1.43; \) cDYS \( M = 8.1, SD = 1.42 \)). The current sample showed non-verbal IQ within an average range, as measured by the Raven Colored Progressive Matrices (tDYS \( M = 95.2, SD = 8.96, cDYS = 96.9, SD = 11.07; \) Raven, Court, & SC Raven, 1977). Three children were receiving medications when entering the study, therefore, their parents were instructed to maintain the dosage consistently throughout the study. None of the children received reading-related treatments between the baseline and post-training assessment sessions. Of the original 35 children, two did not complete the R&D scale at post-training and only 11 children from tDYS group returned to complete a 6-month follow-up assessment. All children were right-handed, native Persian speakers, and had normal vision and hearing. There was no history of neurological or emotional disorders in any of the children. Prior to the study, parents provided a written consent for their children to participate in the study.

### 2.2. Procedure and materials

The tDYS group was assessed at baseline (BL), post-training (PT; 1.5 months on average after BL), and 6-month follow-up (6-m FU). The tDYS group received 30 sessions of 55–65 min of VSWM training after BL assessment (\( M_{\text{Hour}} = 31.76, SD_{\text{Hour}} = 10.47 \)). The cDYS was assessed at baseline and post-waiting (PW); and discontinued with the study and was offered to receive the same training after the PW session (See Table 1).

<table>
<thead>
<tr>
<th>Measures</th>
<th>Subscales</th>
<th>Group</th>
<th>Baseline</th>
<th>Posttest</th>
<th>( F (df) )</th>
<th>Cohen’s D</th>
<th>Follow-Up</th>
<th>( t (df) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>WMTB-Ca</td>
<td>Forward Recall</td>
<td>tDYS</td>
<td>23.5 (3.8)</td>
<td>29.2 (2.9)</td>
<td>( 1 , 33 ) 18.48***</td>
<td>1.49</td>
<td>30.1 (3.3)</td>
<td>(8) – 5.54***</td>
</tr>
<tr>
<td></td>
<td>cDYS</td>
<td>21.7 (5.5)</td>
<td>21.3 (4.8)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Backward Recall</td>
<td>tDYS</td>
<td>19.9 (3.8)</td>
<td>23.9 (3.8)</td>
<td>( 1 , 33 ) 9.6**</td>
<td>1.08</td>
<td>24.8 (4.8)</td>
<td>(8) – 3.54**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cDYS</td>
<td>19.9 (5.2)</td>
<td>19.5 (3.5)</td>
<td></td>
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<tr>
<td>Maze Memory</td>
<td>tDYS</td>
<td>11.6 (6.3)</td>
<td>15.3 (5.1)</td>
<td>( 1 , 33 ) 4.73*</td>
<td>0.75</td>
<td>13.6 (3.9)</td>
<td>(8) – 1.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cDYS</td>
<td>8.9 (4.6)</td>
<td>9.7 (3.6)</td>
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<tr>
<td>R&amp;D Scaleb</td>
<td>Rhyming</td>
<td>tDYS</td>
<td>77 (26.2)</td>
<td>81 (14.2)</td>
<td>( 1 , 33 ) 0.13</td>
<td>0.12</td>
<td>87 (18.2)</td>
<td>(11) – 1.08</td>
</tr>
<tr>
<td></td>
<td>cDYS</td>
<td>80 (11.8)</td>
<td>82 (12.6)</td>
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<tr>
<td>Word Comprehension</td>
<td>tDYS</td>
<td>78 (17.2)</td>
<td>81 (16)</td>
<td>( 1 , 31 ) 0.005</td>
<td>0.01</td>
<td>92 (13.4)</td>
<td>(11) – 5.07***</td>
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<tr>
<td></td>
<td>cDYS</td>
<td>87 (11)</td>
<td>90 (11.3)</td>
<td></td>
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<tr>
<td>Phoneme Deletion</td>
<td>tDYS</td>
<td>64 (21.2)</td>
<td>70 (17.2)</td>
<td>( 1 , 31 ) 1.13</td>
<td>0.38</td>
<td>62 (22.9)</td>
<td>(11) 0.84</td>
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<tr>
<td></td>
<td>cDYS</td>
<td>70 (9.1)</td>
<td>69 (8.5)</td>
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</tr>
<tr>
<td>Letter Fluency</td>
<td>tDYS</td>
<td>76 (22.1)</td>
<td>83 (11.1)</td>
<td>( 1 , 31 ) 1.86</td>
<td>0.49</td>
<td>90 (11.7)</td>
<td>(11) – 2.08**</td>
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<tr>
<td></td>
<td>cDYS</td>
<td>87 (10)</td>
<td>88 (8.4)</td>
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<tr>
<td>Composite Score</td>
<td>tDYS</td>
<td>297 (75)</td>
<td>317 (37.5)</td>
<td>( 1 , 31 ) 2.47</td>
<td>0.54</td>
<td>332 (41.7)</td>
<td>(11) – 3.42*</td>
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<tr>
<td></td>
<td>cDYS</td>
<td>325 (26.3)</td>
<td>330 (31.5)</td>
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<tr>
<td>IVA-CPTc</td>
<td>Visual Response Control</td>
<td>tDYS</td>
<td>68 (32.1)</td>
<td>90 (20.3)</td>
<td>( 1 , 33 ) 10.75**</td>
<td>1.14</td>
<td>104 (25.5)</td>
<td>(9) – 3.38**</td>
</tr>
<tr>
<td></td>
<td>cDYS</td>
<td>84 (27)</td>
<td>77 (29)</td>
<td></td>
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</tr>
<tr>
<td>Visual Sustained Attention</td>
<td>tDYS</td>
<td>53 (18.1)</td>
<td>78 (19.3)</td>
<td>( 1 , 33 ) 12.34**</td>
<td>1.22</td>
<td>87 (19.7)</td>
<td>(9) – 4.87**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cDYS</td>
<td>63 (19.1)</td>
<td>61 (20.1)</td>
<td></td>
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<tr>
<td>Visual Oddball</td>
<td>Accuracyd</td>
<td>tDYS</td>
<td>14.6 (9.9)</td>
<td>26.6 (8.2)</td>
<td>( 1 , 22 ) 6.94**</td>
<td>1.12</td>
<td></td>
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<tr>
<td></td>
<td>cDYS</td>
<td>18.2 (9.9)</td>
<td>17.8 (12.6)</td>
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</tr>
<tr>
<td>Reaction Time</td>
<td>tDYS</td>
<td>519 (158)</td>
<td>511 (76)</td>
<td>( 1 , 22 ) 0.01</td>
<td>0.06</td>
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<tr>
<td></td>
<td>cDYS</td>
<td>567 (52)</td>
<td>554 (69)</td>
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<tr>
<td>Visual-1back</td>
<td>Accuracyd</td>
<td>tDYS</td>
<td>28.2 (21.4)</td>
<td>46.6 (14.5)</td>
<td>( 1 , 21 ) 4.89*</td>
<td>0.96</td>
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<tr>
<td></td>
<td>cDYS</td>
<td>39 (10)</td>
<td>38 (21.2)</td>
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</tr>
<tr>
<td>Reaction Time</td>
<td>tDYS</td>
<td>600 (73)</td>
<td>634 (86)</td>
<td>( 1 , 21 ) 3.42**</td>
<td>0.8</td>
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<tr>
<td></td>
<td>cDYS</td>
<td>656 (83)</td>
<td>617 (105)</td>
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</table>

*p values were adjusted based on Bonferroni-Holm method (Holm, 1979). * \( p < 0.05; **p < 0.01; ***p < 0.001. tDYS = Training Group, cDYS = Control Group; WMTB-C = Working Memory Test Battery for Children; IVA-CPT = Integrated Visual Auditory Continuous Performance Task; \( as \) = approached significance; Standard Deviations and Degrees of Freedom are in parentheses.

a Depicts a raw score; lower scores show greater difficulties.

b Depicts a standard score (mean = 100, SD = 15); lower scores show greater difficulties.

c The possible full-score is 40; higher scores show higher oddball detection.

d The possible full-score is 75. Higher scores show larger WM capacity.
trials. This was also the primary EEG task used to assess the P3b index during WM task performance (see section 2.4 for more detail about EEG).

2.2.2. Secondary outcome measures

These measures do not directly tap into VSWM processes, but were employed for the current study as secondary outcome measures to assess training effects on reading performance, and other WM-related processes (i.e., selective and sustained attention, and inhibitory control abilities).

Reading and Dyslexia Scale (R&D Scale). The R&D is designed to assess reading abilities of children in grades one to five in primary school. This test was designed and validated by Kormi-Noori and colleagues (2012) on 1614 Iranian children, demonstrating good sensitivity in diagnosing children with reading problems. We applied 4 subscales of this instrument which has shown high reliability coefficients (Moradi, Hosaini, Kormi Nouri, Hassani, & Parhoom, 2016), including: 1) Rhyming; 2) Word comprehension; 3) Phoneme deletion; and 4) Letter fluency (Kormi-Noori et al., 2012).

Visual Oddball Task (VOT). The visual oddball task is a commonly used paradigm to measure sustained attention in goal-directed behaviors in response to the novelty of stimuli. The current study’s VOT task included 200 trials, each of which presented a blue square for 800 ms at either the top or bottom of the screen with a black background (the squares were 4 cm apart, and 2 cm above/below the center of the screen). The inter-trial interval was 1200 ms. In target trials (= occurrence rate of 20%), a blue square was presented at the top spot, which should be responded. In non-target trials (= occurrence rate 80%), a blue square was presented at the bottom spot, which should be ignored.

Integrated Visual and Auditory Continuous Performance Task (IVA-CPT). The integrated visual and auditory continuous performance task measures sustained, selective, alternating, and divided attentional processes (Sandford & Turner, 2000). In addition, the integrated visual and auditory components of this task incorporate attentional and inhibitory processes, and quantify inattention and response control characteristics (Sandford & Turner, 2000), which are involved in the early attentional-filtering stages of WM processes (Stout, Shackman, & Larson, 2013). There were a total of 500 target (50%) and non-target (50%) trials randomly presented within 5 blocks, taking an average of 20 min to complete. Each trial began with a fixation point on the screen followed by either a visual or auditory presentation of target (“1”) or non-target (“2”) stimuli on the screen or over a headset. Participants were asked to respond promptly to target stimuli with a right mouse click but refrain from responding to non-target stimuli. It has been shown that the test-retest reliability coefficients of IVA ranges from 0.37 to 0.75 on the various scales and it has a high concurrent validity compared with other CPT tasks which shows reliable psychometric properties (Corbett & Constantine, 2006). This computerized test generates 22 output measures, including visual and auditory attentional and inhibitory properties. However, given the study hypotheses, we only used visual attention and visual response control item measures for the analysis (Corbett & Constantine, 2006).

2.3. Cognitive training program

The tDYS group received BrainWare Safari© (a computer-based cognitive skills development program in a video-game format for 6 year-old and older) training designed by Learning Enhancement Corporation (Illinois, USA, in 2005). With increasingly difficult levels, there is a new/unexpected challenge at each level that aims to promote the development of skills required to successfully continue with the training. Once a user completes a level it cannot be repeated, forcing the user to continue at a higher level of challenge. BrainWare Safari offers 20 exercises as a comprehensive training package. For the current pilot project, we used a WM training program consisting of 6 gamified training tasks that primarily focused on VSWM. These tasks are designed based on well-known WM task paradigms. Each of these tasks became increasingly more difficult as participants made progress. VSWM Span Task asked participants to recollect the spatial location of “X” marks that were briefly presented in a 3 X 3 grid (with the number of “X” increasing from 1 to 6). VSWM Sequential Task asked participants to trace and indicate the serial locations of the target stimulus (i.e., a small colored square) that appeared sequentially across different spots (up to 6) in a 3 X 3 grid. VSWM Pattern Recognition Task asked participants to identify the grid pattern of a briefly presented target (e.g., 2X3 with a unique colored pattern) among 4 options (which include 3 distracter patterns). VSWM Pattern Drawing Task asked participants to replicate the previously viewed spiderweb-like pattern by connecting several dots with lines. VSWM Memory Maze Task asked participants to replicate the visuospatial pathway after watching a target cue (i.e., arrow) navigates through a circular maze toward the center. VS Simultaneous Memory Task asked participants to recollect several moving objects presented simultaneously on the screen from the previous trial. To see the trend of improvement from the first to the last session, the training gain index was generated based on the achieved difficulty points (= number of levels passed) across all the training exercises divided by the total number of minutes ($M_{\text{Min}} = 1906$, $SD_{\text{Min}} = 628.37$) spent throughout the entire training sessions. Therefore, higher scores of this index indicated larger improvements of underlying WM processes given the amount of time spent on the training.

2.4. Training procedure

The training consisted of 30 sessions lasting a duration of 55–65 min. The tDYS group engaged in five sessions a week for six weeks while the cDYS group was placed on a waiting list to receive the same training after PW assessment. All training sessions were administered in one of the psychology clinics with a room designed specifically for computerized practices and training. Four trainers (including the 1st and 5th authors) administered each session to provide instructions and verbal encouragement for each subject to fully attend to training. At a given training session, there could be up to three participants practicing the tasks.
2.5. Computer hardware & EEG data acquisition and processing

All computerized tasks were administered using a Dell computer with 2 GB of RAM and 3.4 GHz processing speed, and presented on a 17” monitor. Four children did not participate in the EEG part of the study. Additionally, eight participants’ EEG data were removed from analyses due to excessive movements (three) or technical difficulties (five). Participants were seated in a chair at a distance of approximately 50 cm away from the monitor and EEG recordings were obtained during the Visual 1-back. EEG was recorded using a Mitsar-EEG device (Mitsar Co. LTD, Russia) with a 21 Ag/AgCl electrode fitted nylon cap with the following sites according to the 10/20 International System of Electrodes (Fp1/Fp2, F3/F4, C3/C4, P3/P4, O1/O2, F7/F8, T3/T4, T5, T6, Pz, Cz, Fz). Impedances were kept below 5kΩ, and data were notch filtered (50 Hz). All signals were digitized at 250 Hz. Raw EEG data were referenced to the average value (A1 + A2)/2 of the left (A1) and right (A2) ear lobe. All data were filtered with a Butterworth bandwidth of 0.3–50 Hz. Horizontal and vertical electrooculogram (EOG) activity were recorded from electrodes placed 1 cm to the left and right of the external canthi for the horizontal, and an electrode under the right eye, referenced to the left mastoid for the vertical.

Wineeg software (Mitsar Co. LTD, Russia), EEGLAB (Delorme & Makeig, 2004), and ERPLAB (Lopez-Calderon & Luck, 2014) were used for ERP analyses and quantification. EOG electrodes were used to remove blink artifacts from the EEG data. ERP data was segmented −200 to 800 ms from the onset of the stimuli with a 200 ms baseline correction. Only ERPs of correct responses were used for the statistical analyses. P3b has been shown to reflect changes within the underlying neural activity involved with the storage and processes of WM (Brouwer et al., 2012; Evans et al., 2011). Therefore, the analysis and quantification of the ERP waveforms was limited to the P3b component for the visual 1-back task, which became prominent 250–500 ms after stimulus onset at the brain parietal region (the Pz electrode) based on visual inspection.

2.6. Statistical analyses

To examine whether the VSWM training led to a significant change in the dependent variables (see Table 1 for the list of variables) at PT, 2 (Group: tDYS and cDSY) × 2 (Time: BL and PT) repeated measures ANOVA tests with Greenhouse-Geisser adjustment were employed. Paired sample t-tests were also administered to test significant differences between BL and FU for the tDYS group. We incorporated a highly stringent correction procedure based on the Bonferroni-Holm method (Holm, 1979) to control for the potential inflation of type 1 error due to multiple comparisons. We have applied the correction procedures for each domain consisting of interrelated measures. All statistical pre-requisites were checked for the equality of covariance, and the variance of dependent scores’ error (i.e. Box Test of Equality of Covariance Matrices and Leven’s Test of Equality of Error Variance, respectively).

3. Results

3.1. Baseline characteristics

No significant group differences were observed in gender, age, and IQ (all with \( p > .14 \)). There were no significant differences between the tDYS and cDYS at the BL phase on all outcome measures (all with \( p > .01 \)).

3.2. Behavioral outcomes

Separate repeated measures ANOVAs demonstrated significant Group (tDYS or cDSY) by Time (BL or PT) interaction effects, across the subscales of WMTC (FBR, BBR, and MM) as well as accuracy level of V1-Back task (Table 1; Fig. 2). This interaction effect indicated that the tDYS group showed a significant improvement across the VSWM-related outcome measures, whereas the performance of the cDSY group remained unchanged at the PT assessment. In contrast, there was no significant Group by Time interaction effect on reaction time of the V1-Back task. Thus, it appeared that processing speed did not benefit from the training, whereas other VSWM components demonstrated training effects. Significant paired samples t-test results were also obtained when comparing VSWM performance of the tDYS group in BL vs. FU, highlighting that the durability of the training gains such that the tDYS group’s improvement was still significantly higher than baseline assessment after 6 months (Table 1). All pairwise comparisons were adjusted using Bonferroni-Holm method (Holm, 1979).

Moreover, there was a significant Group (tDYS and cDSY) by Time (BL and PT) interaction, in the secondary outcome measures including Visual Response Control (VSC) and Visual Sustained Attention (VSA) subscales of IVA-CPT and the Visual Oddball task. These significant interactions indicated greater improvements in visual response control and sustained attention as well as oddball detection abilities in the tDYS group than the cDSY group over time. A paired samples t-test comparing BL with FU revealed that the tDYS group performance in visual response control and visual sustained attention abilities were significantly higher at 6-month follow-up than at BL, suggesting the durability of the training gains. Therefore, these results suggest that our cognitive training improved untrained but VSWM-related attentional processing and maintained its therapeutic effects over the 6-month follow-up period. The tDYS showed 7% increase in the subscales and the composite scores of Reading and Dyslexia Scale after the training compared to only 1.5% increase for the cDSY, but this was a non-significant trend for tDYS to outperform cDSY with a medium sized effect. Nevertheless, paired sample t-tests results indicated that the tDYS showed a significant improvement at the FU compared to the BL on the composite score of the Reading and Dyslexia Scale.

Overall, these findings showed that multiple aspects of VSWM-related attentional and inhibitory processes (i.e. visual sustained and selective attention; visual response control) were enhanced at post training with its effects maintained at 6-month FU for the
tDYS group. Additionally, we examined the correlation between the training gain index obtained over the duration of training and the gain in primary outcome measure on the V-1back (quantified as the contrast between the BL and PT scores). Results showed a significant correlation between them, \( r(15) = .58, p < .05 \) (See Fig. 1), which indicates that the amount of training progress achieved by participants (as assessed by the training gain index) was positively associated with the level of improvement on the V-1back task.

3.3. EEG outcomes

Using P3b amplitudes at Pz electrode for correct trials at PT as the dependent variable, an analysis of covariance (controlling for P3b amplitudes at Pz electrode for correct trials at BL) revealed a non-significant trend for tDYS to show greater P3b than cDYS, but with a large effect size (Table 2; \( F(1, 21) = 4.25, p = 0.051, \eta^2_p = 0.175 \), a large effect; Fig. 3). This result indicated a 35% P3b signal increase after the training for the tDYS, compared to only 5% that of the cDYS group. In contrast, the P3b latency did not differ between the two groups (Table 2; \( p = 0.52 \)). Importantly, changes occurred from BL to PT (= improvement gains) in the primary outcomes of VSWM (i.e. combined score of WMTB-C) and P3b amplitude signal change from BL to PT showed a non-significant but medium-to-large correlation for the tDYS group (\( r(14) = 0.46, p = 0.07 \); Fig. 4), indicating that the improvement in WM performance from BL to PT for the tDYS group was accompanied by the increase in P3b amplitude.

![Fig. 1. Association between Training Gain and the V-1back Task Performance Gain from BL to PT for the tDYS group. *BL = baseline; PT = Post-training.](image1)

![Fig. 2. WMTB-C Combined Subtest Scores across Time for cDSY (left) and tDSY (right). Red lines reflect mean change, dashed lines reflect individual score change from BL to PT, and boxplot reflects variability in each group during each test session. Working memory scores significantly improved in the Dyslexia group after training, but there was no change in the Healthy Control group.](image2)
4. Discussion

Previous studies have suggested that WM training may be beneficial for improving WM and reading abilities in dyslexic individuals (Dahlin, 2011; Loosli et al., 2012; Shiran & Breznitz, 2011). However, the literature still lacks sufficient evidence on whether computerized training focused on VSWM processes can benefit children with dyslexia (Melby-Lervåg & Hulme, 2013; Melby-Lervåg et al., 2016; Shipstead et al., 2012). The current pilot study investigated the effectiveness of computerized adaptive WM training on VSWM processes.

Table 2

Mean Parietal P3b amplitude (µV) of Match Trials in the Visual 1-back for the tDYS (n = 14) and cDYS groups (n = 9).

<table>
<thead>
<tr>
<th>Measure</th>
<th>ERP Component</th>
<th>Group</th>
<th>Baseline</th>
<th>Posttest</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-1back</td>
<td>P3b Amplitude Pz (µV)</td>
<td>tDYS</td>
<td>4.9 (5.66)</td>
<td>7.43 (4.9)</td>
</tr>
<tr>
<td></td>
<td>cDYS</td>
<td>4.97 (4.27)</td>
<td>3.76 (2.54)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P3b Latency Pz (ms)</td>
<td>tDYS</td>
<td>372 (25.20)</td>
<td>389 (24.14)</td>
</tr>
<tr>
<td></td>
<td>cDYS</td>
<td>388 (25.97)</td>
<td>392 (21.12)</td>
<td></td>
</tr>
</tbody>
</table>

µV = microvolt; ms = millisecond; Parentheses show standard deviations.

Fig. 3. Waveforms from the Target Trials V1-Back Task across Time for cDSY (A) and tDSY (B).

Figures A & B show the ERP plots obtained for the match trials of the V1-Back task on the P3b component emerging at approximately 400 ms post-stimulus at the parietal region (Pz), across both BL and PT phases. Red and Blue shaded areas are representing standard deviation for each time point.

Fig. 4. Association between P3b (Pz) Amplitude Increase and the WM Overall Score Increase from BL to PT for the tDYS group.  ^ WM overall Score = combined score of VSWM subscales of WMTB-C; BL = baseline; PT = Post-training.

training on VSTM related cognitive processes. Our results showed that the tDYS group had significantly better performance across multiple measures obtained at the PT phase compared to the cDYS group. The specific training analyses showed that there was a significant positive correlation between gains in attentional and VSTM exercises obtained through the training with improvement gains in measures of VSTM (V1-Back task) at the PT phase, although the training tasks did not overlap with the primary outcome measures of VSTM. Our data are consistent with prior works conducted on children with reading disabilities (Avtzon, 2012; Holmes et al., 2009), and typically developing children (Loosli et al., 2012). Our study also revealed that these children suffered from a lower P3b amplitude at the parietal regions associated with a limited WM capacity compared to their healthy counterpart (but with no deficit in processing speed). Similarly, we observed an increased P3b amplitude and similar latencies after the training. Thus, our findings indicate the possibility that the larger P3b amplitude induced by the VSTM training underlies the increased behavioral WM capacity observed in the relevant tasks (i.e. V1-Back, WMTB-C). Relatedly, previous studies reported “functional changes in large-scale fronto-parietal networks” (Thompson, Waskom, & Gabrieli, 2016; Westerberg & Klingberg, 2007) and a larger amplitude of P300 component following training (Shiran & Breznitz, 2011). Accordingly, Shiran and Breznitz (2011) argued that the improved P300 magnitude of a visual WM task after the training can be attributed to a higher level of automation within the VSTM system, therefore, leaving more WM storage available to represent and process the meaning of words and texts. 

Our preliminary ERP data suggest that the post-training behavioral enhancements for the training group were accompanied by traceable neural signatures through larger ERP amplitudes of P3b component across the VSTM task (i.e., V1-back task). Despite the low sample size of the current study, and the inherent difficulty in acquiring EEG data among children with dyslexia due to their larger brain signal variabilities (Malins et al., 2018; Norton, Beach, & Gabrieli, 2015), our data revealed the non-significant trend for the tDYS group to show a larger deflection of P3b amplitude after training (with large sized effects), relative to the cDYS group. Importantly, we observed that only the tDYS group demonstrated a strong association between the P3b signal increase from BL to PT (35% increase on average) with the improved performance occurred from BL to PT for our primary VSTM outcome measure (i.e. WMTB-C). Evans et al. (2011), examining visual and auditory 1-back task in children with developmental language impairments, reported that these children suffered from a lower P3b amplitude at the parietal regions associated with a limited WM capacity compared to their healthy counterpart (but with no deficit in processing speed). Similarly, we observed an increased P3b amplitude and similar latencies after the training. Thus, our findings indicate the possibility that the larger P3b amplitude induced by the VSTM training underlies the increased behavioral WM capacity observed in the relevant tasks (i.e V1-Back, WMTB-C). Relatedly, previous studies reported “functional changes in large-scale fronto-parietal networks” (Thompson, Waskom, & Gabrieli, 2016; Westerberg & Klingberg, 2007) and a larger amplitude of P300 component following training (Shiran & Breznitz, 2011). Accordingly, Shiran and Breznitz (2011) argued that the improved P300 magnitude of a visual WM task after the training can be attributed to a higher level of automation within the VSTM system, therefore, leaving more WM storage available to represent and process the meaning of words and texts. 

Our findings are consistent with prior research indicating the association between enhanced WM processing and improved reading abilities (Dahlin, 2011; Horowitz-Kraus & Breznitz, 2009; Loosli et al., 2012; Peijnenborgh, 2016; Shiran & Breznitz, 2011). Although the R&D Scale does not measure all aspects of reading abilities, its subscales can tap into fundamental reading processes such as phonological awareness, basic word knowledge, verbal fluency and production, and reading fluency, which have been shown to be impaired among children with reading difficulties (Goldfield, Gencarella, & Fornari, 2016; Kormi-Nouri et al., 2008). Existing evidence suggests that performance on these R&D scales is associated with WM abilities. For example, using the subscales of the R&D, Kormi-Nouri and colleagues (2008, 2012) have shown that letter fluency is associated with semantic memory processes. These researchers have also argued that both word comprehension and letter fluency (which can be assessed by the R&D scale) reflect effortful WM processes (e.g., retrieving, storing, and monitoring words) that significantly influence reading fluency.
(Jalali-Moghadam & Kormi-Nouri, 2017). Thus, the R&D is a useful instrument to assess relevant reading skills in investigating the impact of WM training for children with reading problems. Overall, the converging behavioral and ERP data in the current study suggest that a potent dose of computerized VSWM cognitive training may serve as a useful intervention for children with reading difficulties. The self-administered, computerized cognitive training approach can result in the development of a cost-efficient, accessible, and portable intervention, which may be used as a standalone training program or could be combined with a traditional intervention focused on other aspects of reading (e.g., phonological awareness) as an adjunctive treatment program.

4.1. Limitations

Several limitations of the current feasibility study should be noted. First, using a quasi-experimental design, we assigned a small group of children with dyslexia non-randomly to the two groups. Although the tDYS and cDYS group did not differ in baseline measures, future research needs to employ a stringent random assignment procedure with a larger clinical sample with reading problems. Second, using the assessment-only waitlist group as a comparison group without a follow-up assessment is a methodological limitation of the current study. Importantly, we cannot exclude the possibility that the improved outcomes in the tDYS group at PT were due to non-specific WM training-irrelevant factors (e.g., attention from the experimenter, expectancy effects, or general cognitive practice which may not be relevant for the target visuospatial WM processes), as the waitlist group underwent only assessments. However, a waitlist control is an appropriate comparison group when one starts intervention development work, as it can help disentangle the training effects form other extraneous factors (such as spontaneous recovery over time, regression toward mean; Nock, Janis, & Wedig, 2008). Further, 6-month follow-up outcomes should also be interpreted tentatively for the IDYS group, given the lack of the comparison group at this phase, as the cDYS discontinued with the study after post-waiting assessment to receive treatments without an unduly long waiting time. Despite these methodological limitations inherent in the waitlist-controlled study, our preliminary findings suggest that continuing research is warranted to further develop visuo-spatial WM training as a potentially beneficial cognitive intervention for children with reading problems. The future research should be more sufficiently powered with a more stringent comparison groups (e.g., a credible placebo intervention, or an established intervention for dyslexia such as phonological awareness training; Galuschka, Ise, Krick, & Schulte-Körne, 2014) with more adequate follow-up assessment data, to rigorously examine the potential effects of computerized visual-spatial WM training for reading problems.

Third, while specifically focusing on the VSWM abilities in training, the training did not address other aspects of reading processes such as phonological awareness, vocabulary, comprehension, and fluency. Further research is needed to understand more specific mechanisms of change in this type of training program and what particular aspects of training are most effective for improvement in reading. Lastly, we did not systematically assess and address subtypes of Specific Learning Disorders with reading impairment (i.e. word reading deficits, fluency deficits, or reading comprehension deficits) as outlined in DSM-5 (American Psychiatric Association, 2013). Future research should particularly focus on specific types of reading difficulties to further shed light on effectiveness of computerized training on this developmental disorder.

4.2. Conclusion

This study aims to contribute to the current literature by demonstrating favorable neurocognitive outcome indices by intensive cognitive training focused on VSWM, which suggests that the VSWM training can serve as a potentially effective training program to improve cognitive processes that are central to reading abilities (i.e. WM, selective attention, inhibitory control) among children with dyslexia. Further research is warranted to examine more specific mechanisms of this training program and its clinical utility.

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