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The effect of cognitive training on recall range and speed of information processing in the working memory of dyslexic and skilled readers

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ABSTRACT

Research indicates that impairment of working memory may be one of the factors that impede the ability to read fluently and accurately. Although the capacity of working memory is traditionally considered to be constant, recent data point to a certain plasticity in the neural system that underlies working memory, which can be improved by training. We examined whether dyslexic readers' recall span and speed of processing in working memory can be increased, enhancing the quality of their reading. Thirty five skilled readers and twenty six dyslexic readers were trained in working memory tasks and compared to control groups of fifteen skilled and fifteen dyslexic readers who complete a self-paced reading training regime. All subjects were trained over a six-week period. Reading and working memory indicators were collected before and after the two trainings. Brain activity using measures of event-related potential (ERP) were collected for the working memory training groups by using a working memory task (Sternberg task). Result indicated after working memory training the ability to store verbal and visual-spatial information in working memory increased, and decoding, reading rate and comprehension scores improved in both groups, although the gap between the dyslexic and the control groups in reading and working memory scores remained constant. The latency of the P300 component decreased and the amplitude increased in all participants following training. No training effect in any parameter was obtained in the self-paced reading training groups. These findings support the notion of

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plasticity in the neural system underlying working memory and point to the relationships between larger working memory capacity and enhancement of reading skills.

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1. Introduction

Deficits in working memory skills associated with developmental dyslexia are considered one of the underlying causes of the failure to acquire accurate and fluent reading (Baddeley, 1986; Cohen-Mimran & Sapir, 2007; De Jong, 1998). Working memory is a sub-system of the information processing system that enables short-term storage of information needed for processing and integration (Baddeley & Hitch, 1974). Numerous studies have examined the connection between working memory sub-systems and reading ability. Children and adults with reading disabilities exhibited significant difficulties in tasks involving working memory, especially those that entail processing in the phonological loop (Ackerman & Dykman, 1993; Cohen, Netley, & Clarke, 1984; Helland & Asbjørnsen, 2004; Palmer, 2000). The recall span of the dyslexic readers on these tasks was significantly lower than that of the skilled readers, and dyslexic subjects made inefficient use of the phonological loop, especially in the way visual information was translated into its phonological form, which impaired their ability to learn new words during reading (Hulme & Snowling, 1992; Palmer, 2000).

Working memory is limited by the number of items that can be remembered simultaneously (Baddeley & Hitch, 1974) and the length of time they can be stored (decay time) (Swanson & Ashbaker, 2000; Swanson & Siegel, 2001). Thus, efficient processing of information in working memory requires adequate capacity and rapid speed of processing within and between systems. Studies have pointed to significant differences in working memory span (Breznitz, 1997) and speed of information processing between dyslexics and skilled readers. Shorter working memory span (Bowers & Wolf, 1993; Catts, Gillispie, Leonard, Kail, & Miller, 2002) and slow speed of processing (Breznitz, 2003, 2006) were found to be sources of poor and dysfluent reading (Breznitz, 2003, 2006).

These findings raise the possibility that training aimed at increasing the recall span and speed of processing within working memory can improve the working memory performance of dyslexics during reading, and consequently may improve the quality of their reading.

The central nervous system develops and adapts to new life experiences. The changes are manifested on several levels: synaptic-molecular, cellular-neuronal, in cortical mapping, and within and between the various systems in the brain. The brain's plasticity is necessary for appropriate development of the nervous system (Breznitz, 2006), and enables the brain to change following training, which is an adaptive learning process of the brain to the changing environmental demands.

CogniFit Personal Coach (Cognifit, 2003) is a computerized program aimed at adults interested in preserving their cognitive skills and preventing age-dependent decreases. The uniqueness of this program is the Individualized Training System (ITS) – an interactive mechanism that "studies" the user's performance, suggests adaptive training programs, and responds during and following training. The present study used this program to train training three different modules of working memory: auditory memory – short-term memory and processing of verbal and non-verbal information presented in the auditory channel; visual verbal memory – short-term memory and processing of verbal information presented in the visual channel; and visuo-spatial memory – short-term memory of visual patterns and their spatial location.

The use of behavioral measures to study working memory and speed of information processing is limited by the fact that the information on the cognitive processing sequence is received only at the conclusion of the process. One methodology aimed at overcoming this limitation in reading research is electrophysiological measurement based on Event-Related Potentials (ERP), which measures electrical activity in the brain in response to internal and external stimuli. The amplitude and/or latency of several ERP components, or brain waves, related to various stages of information processing can be measured. ERP components reflect the time course of cognitive and sensory sub-processes, with millisecond resolution, that cannot be examined behaviorally. The P300, which is a positive component appearing approximately 300 ms after stimulus presentation, has been found to be related to updating in working memory (Grune, Metz, Hagendorf, & Fischer, 1996; Humphrey & Kramer, 1994; Smith-Spark & Fisk, 2007). One of the most

Table 1
Means, (standard deviations) and *t*-test results of comparisons between the total sample of dyslexic and regular readers on the reading, word recognition and memory tests.

	Dyslexic readers ($N=41$)	Skilled readers ($N=50$)	T
Words per minute	72.12 (15.32)	115.26 (14.20)	−13.66***
Pseudowords per minute	34.55 (10.12)	65.02 (10.86)	−12.14***
Silent reading comprehension (correct from 17)	10.70 (1.82)	11.55 (2.3)	−1.8
Silent reading time (sec)	0.45 (0.19)	0.32 (0.11)	5.59***
Orthography : time (Min)	276.53 (79.62)	154.71 (36.33)	4.49**
Orthography : accuracy (correct from 46)	43.62 (2.61)	45.10 (2.13)	−2.64*
Phonological measure: Phoneme deletion time (min)	137.70 (76.41)	162.97 (25.31)	9.12***
Auditory memory	−0.21 (0.62)	.29 (0.75)	4.81**
Visual verbal memory	−0.24 (0.72)	0.38 (0.84)	6.98**
Visuo-spatial memory	−0.19 (0.65)	0.35 (0.82)	8.36**

*$p < 0.05$; **$p < 0.01$; *** $p < 0.001$.

common hypotheses on the connection between the P300 component and working memory is the context updating hypothesis (Donchin & Coles, 1988). According to this hypothesis, the P300 component constitutes the brain's response to updating information in working memory, and the latency changes according to the time required to process the stimulus and scan the information stored in working memory. A few studies have made use of electrophysiological measures to examine working memory in dyslexics. One study (Barnea, Lamm, Epstein, & Pratt, 1994) found that the P300 amplitude was lower for lexical than non-lexical stimuli in dyslexic readers, and the opposite for skilled readers. Reaction time and accuracy were significantly longer and poorer among the dyslexics than the controls for both the lexical and non-lexical tasks. Studies that examined the ERP records of dyslexics during word reading and decoding reported that the P300 component appeared approximately 50–90 ms later among the dyslexics (Breznitz, 2006; Breznitz & Misra, 2003; Miller-Shaul & Breznitz, 2004). These studies indicate that the ERP may be a useful index of the P300 component in the evaluation of brain activity stemming from the storage and processing of information in working memory among dyslexic readers.

The aim of the current study was to examine the effect of the CogniFit Personal Coach computerized training program on the recall range and speed of processing in working memory of dyslexic readers, and whether it affects reading ability. The study employs behavioral measures, and electrophysiological measures (multi-channel EEG) based on the ERP methodology.

2. Methods

2.1. Participants

91 University students participated in the study, 41 dyslexics that scored −1.5 STD in Hebrew normative diagnostic test for adult reading disabilities (Matal, 2007) and 50 skilled readers that

Table 2a
Experimental groups: changes in cognifit personal coach memory measures before and after memory training.

CogniFit personal coach measures[a]	Dyslexic readers $N=26$			Skilled Readers $N=35$			F		
	Before training	After training	T	Before training	After training	T	Main effect: training	Main effect: group	Interaction: training with group
Auditory memory	−0.20 (0.66)	0.26 (1.01)	8.63**	.26 (0.71)	0.44 (0.71)	6.67**	9.13** (1,59)	3.38* (1,59)	1.81 (1,59)
Visual verbal memory	−0.21 (0.71)	0.08 (1.17)	5.94*	0.34 (0.87)	0.77 (1.05)	4.65*	7.38** (1,59)	7.65** (1,59)	0.23 (1,59)
Visuo-spatial memory	−0.20 (0.72)	0.06 (1.17)	5.72*	0.37 (0.90)	0.80 (1.03)	4.81*	6.49* (1,59)	8.84** (1,59)	0.34 (1,59)

*$p < 0.05$; **$p < 0.01$; *** $p < 0.001$.
[a] CogniFit Personal Coach measures were normalized (*z*-scores) and compared to the standard values in the population.

Table 2b
Control groups : Changes in CogniFit Personal Coach memory measures before and after Self-paced reading regime.

CogniFit personal coach measures[a]	Dyslexic readers $N=15$			Skilled readers $N=15$			F		
	Before training	After training	T	Before training	After training	T	Main effect: training	Main effect: group	Interaction: training with group
Auditory memory	−0.21 (0.77)	−0.24 (0.73)	0.82	0.25 (0.71)	0.24 (0.66)	0.09	0.12 (1,28)	5.32** (1,28)	0.59 (1,28)
Visual verbal memory	−0.22 (0.74)	−0.22 (0. 73)	0.76	0.33 (0.77)	0.34 (0.63)	0.12	0.25 (1,28)	5.95** (1,28)	0.42 (1,28)
Visuo-spatial memory	−0.21 (0.73)	−0.22 (0.79)	0.32	0.36 (0.83)	0.35 (0.72)	0.16	1.15 (1,28)	7.72** (1,28)	0. 84 (1,28)

*$p<0.05$; **$p<0.01$; *** $p<0.001$.
[a] CogniFit Personal Coach measures were normalized (z-scores) and compared to the standard values in the population.

achieved 0 + STD in decoding and fluency subtests (Matal, 2007). Both groups were matched for chronological age (dyslexics $X=24.84\pm2.89$ years, and skilled readers $X=25.11\pm1.97$ years) and were within normal non-verbal IQ range as measured by the Raven Standard Progressive Matrices (Raven, 1960) [$T(2,89)=1.06$, $P=-1.22$ for the Raven matrix test: $X=109\pm2.13$ for the dyslexics and $X=110\pm1.11$ for the controls] and verbal Equal side (WAIS 1994) IQ subtest $X=9.37\pm1.23$ for the dyslexics and $X=8.72\pm1.31$ for the controls [$T(2,89)=1.06$, $P=-1.34$.

All were native Hebrew speakers from a middle-class background. All subjects were right-handed, displayed normal or corrected-to-normal vision in both eyes, and were screened for normal hearing. None of the participants had a history of neurological or emotional disorders, or attention deficit as measured by the D2 cancellation test (Brickenkamp, 1981) [$T(2,89)=1.39$, $P=1.17$, for the attention D2 test: $X=8.76\pm1.45$, for the dyslexic readers and $X=8.88\pm1.23$ for the controls].

All subjects gave their informed consent prior to inclusion in the study, and all were paid volunteers. The dyslexic readers were recruited through the Student Support Service of the University of Haifa, which assists students with learning disabilities. They were diagnosed as dyslexic during childhood and classified as

Table 3a
Experimental groups: reaction time and percent of accuracy changes on the Sternberg task as a function of Memory training.

Measures	Dyslexic readers $N=26$			Skilled readers $N=35$			F		
	Before training	After training	T	Before training	After training	T	Main effect: training	Main effect: group	Interaction: training with group
Accuracy percent positive probe	78.92 (17.01)	86.60 (10.35)	6.11**	88.85 (15.01)	94.40 (9.80)	5.94*	6.92* (1,59)	11.87*** (1,59)	0.13 (1,59)
Reaction time (ms) positive probe	1248.96 (497.44)	1082.18 (187.35)	5.85*	937.46 (257.38)	841.66 (183.79)	6.48**	6.66* (1,59)	20.71*** (1,59)	0.48 (1,59)
Accuracy percent negative probe	80.66 (20.95)	91.62 (8.85)	7.36**	89.72 (18.78)	96.24 (5. 95)	4.93*	5.68* (1,59)	9.85** (1,59)	0.42 (1,59)
Reaction time (ms) negative probe	1165.83 (253.24)	1131.11 (184.74)	2.40	934.74 (336.18)	888.95 (194.77)	4.52*	5.53* (1,59)	21.71*** (1,59)	1.41 (1,59)

*$p<0.05$; **$p<0.01$; *** $p<0.001$.

Table 3b
Control groups behavioral reaction time and percent of accuracy changes on the Sternberg task as a function of: self-paced reading regime.

Measures	Dyslexic readers $N=15$			Skilled readers $N=15$			F		
	Before training	After training	T	Before training	After training	T	Main effect: training	Main effect: group	Interaction: training with group
Accuracy percent positive probe	76.95 (15.01)	77.10 (11.99)	0.73	89.77 (13.02)	88.463 (14.75)	0.55	2.66 (1,28)	13.80*** (1,28)	0.12 (1,28)
Reaction time (ms) positive probe	1272.55 (186.21)	1279.34 (185.44)	0.78	946.58 (157.33)	958.06 (156.83)	1.04	1.12 (1,28)	14.19*** (1,28)	1.11 (1,28)
Accuracy percent negative probe	84.31 (23.90)	85.02 (19.97)	0.64	88.45 (15.60)	88.94 (15. 81)	0.23	0.10 (1,28)	3.83* (1,28)	0.052 (1,28)
Reaction time (ms) negative probe	1176.52 (153.30)	1184.42 (163.76)	1.03	936.32 (143.25)	930.07 (150.74)	0.98	1.03 (1,28)	15.70*** (1,28)	0.78 (1,28)

*$p<0.05$; **$p<0.01$; *** $p<0.001$.

impaired readers by the Student Support Service. The controls were recruited by notices posted on bulletin boards on the University campus. The experiment was approved by the University of Haifa ethics committee.

The subjects were divided into four groups based the Matal (2007) decoding and fluency subtests. There were two experimental and two controls each contained one group of dyslexic's and one of skilled readers. The experimental groups included 26 dyslexic and 35 skilled readers and the control 15 dyslexics and 15 skilled readers. The mean decoding-fluency score for the dyslexic readers in the experimental and the control groups were $X=67.11\pm1.45$ $X=$ and $X=68.66\pm2.05$ ($T=1.01$) and for the skilled readers $X=114.09\pm2.12$ for the experimental and $X=115.10\pm1.09$ ($T=.97$) for the control.

2.2. Background measures

2.2.1. General ability

1. Non-verbal: Raven Standard Progressive Matrices (Raven, 1960). This test examines analogous deduction and the ability to create perceptual connections independent of language and formal learning.
2. Verbal: Equal side sub-test (WAIS-3, 1994). This test measures verbal abstraction ability.
3. Normative Hebrew Decoding-Fluency sub-test measure for adults (Matal, 2007)

2.3. Experimental measures

2.3.1. Tests

2.3.1.1. Reading measures (decoding, fluency, comprehension)

- One minute tests of reading words and pseudowords (Shatil, 1997): The test includes lists of words and pseudowords that the subject is required to read aloud in one minute. Accuracy and decoding-fluency are scored.

Table 4
Experimental groups: Effect of memory training on P300 latency and amplitude (Pz electrode): mean (standard deviation).

Measures	Dyslexic readers $N=26$			Skilled readers $N=35$			F		
	Before training	After training	T	Before training	After training	T	Main effect: training	Main effect: group	Interaction: training with group
Latency positive probe	447.52 (84.0)	394.49 (60.53)	9.11***	399.47 (82.80)	365.41 (65.14)	6.64**	14.30*** (1,59)	3.91* (1,59)	1.89 (1,59)
Amplitude positive probe	4.07 (2.65)	4.39 (1.71)	3.67*	4.73 (2.70)	5.11 (1.81)	4.12*	4.46* (1,59)	4.32* (1,59)	0.89 (1,59)
Latency negative probe	468.75 (108.40)	418.47 (79.22)	6.87**	437.39 (139.10)	395.34 (88.66)	4.21*	9.56** (1,59)	3.4* (1,59)	0.23 (1,59)
Amplitude negative probe	4.18 (2.50)	4.42 (2.12)	2.21	4.30 (2.76)	4.58 (1.93)	1.94	3.18 (1,59)	1.06 (1,59)	0.45 (1,59)

*$p<0.05$; **$p<0.01$; *** $p<0.001$.

- Silent reading time and comprehension in context (Breznitz, 2006): Measured total reading time and multiple choice correct comprehension questions.

2.3.1.2. Word recognition measures

- Phonology: Phoneme analysis test (Shatil, 1997). The test measures time and accuracy during decomposition of pseudowords and composition of phonemes into pseudowords.

- Orthography: Parsing test (Breznitz, 1997). The subject to separates letter sequences into meaningful words and performance time and accuracy are measured.

2.3.1.3. Behavioral working memory measures
2.3.1.3.1. Short-term verbal working memory capacity

- Digit Span Forward (WAIS-III, 1994). The subtest examines accuracy when recalling digits forward (repeating them in the order presented).
- Digit Span Backward (WAIS-III, 1994). The subtest examines accuracy when recalling digits backward (repeating them in reverse order).
- CogniFit Personal Coach memory measures (Cognifit, 2004).
- Sternberg Memory task (Sternberg, 1966) (the ERP test version)

2.3.1.4. Electrophysiological measures Brain activity was examined during performance of a cognitive processing task – a Sternberg task (Sternberg, 1966) – requiring processing and storage in working memory. The Sternberg task is commonly used in behavioral and electrophysiological research on processing in working memory (adapted for use with ERP methodology, see Patterson, Pratt, & Starr, 1991). In the present study it consisted of a series of 5 digits presented visually on a computer screen located 1.5 m in front of the subject. Each digit appeared for 500 ms with an ISI of 700 ms, followed by a line of stars for 500 ms, followed after 1000 ms by a probe for 500 ms. The next series appeared after 2500 ms. The subject was asked to indicate whether the probe appeared (positive probe) in the series of digits presented by pressing the right joystick button when the probe appeared and the left when it did not (50 percent of the probes were positive). The task included 66 experimental series divided into two blocks of 33 series each. It is commonly believed that in order to retain the digit representations, the subject must activate the phonological loop after seeing the stimulus sequence on the screen (modeled on Barnea et al., 1994).

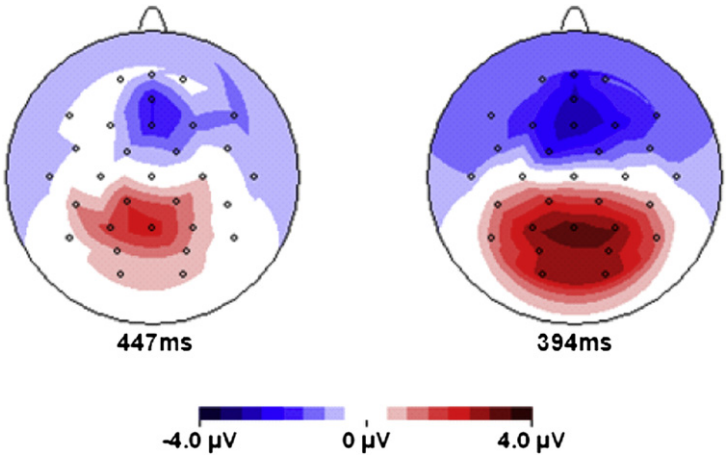

Fig. 1. Topographical map of the P300 component during performance of a Sternberg task in dyslexics before and after CogniFit Personal Coach training.

The research measures were behavioral reaction time and accuracy, and the P300 component latency and amplitude (related in the literature to working memory during performance of a Sternberg task) derived from EEG records.

2.4. Training materials

2.4.1. Experimental: Memory training: CogniFit Personal Coach Tasks (Cognifit, 2004)

2.4.1.1. Visual verbal working memory

- A series of objects was presented on a computer screen and the subject was asked to recall and identify the objects in the order they were presented as well as in reverse order.
- A series of digits was presented to the subject in both the visual and auditory channels (each channel separately and both together) and the subject was asked to repeat the series of digits in the order presented and in reverse order.

2.4.1.2. Non-verbal auditory working memory

- The subject was asked to identify the longer of two sounds presented sequentially.
- A series of sounds from different instruments was presented and the subject was asked to recall the order in which they were played and the instruments that produced them.

2.4.1.3. Visuo-spatial working memory

- Objects were presented in different locations on a computer screen and the subject was asked to recall the location and shape of the object.
- The subject was asked to recall the order in which windows opened on the computer screen.

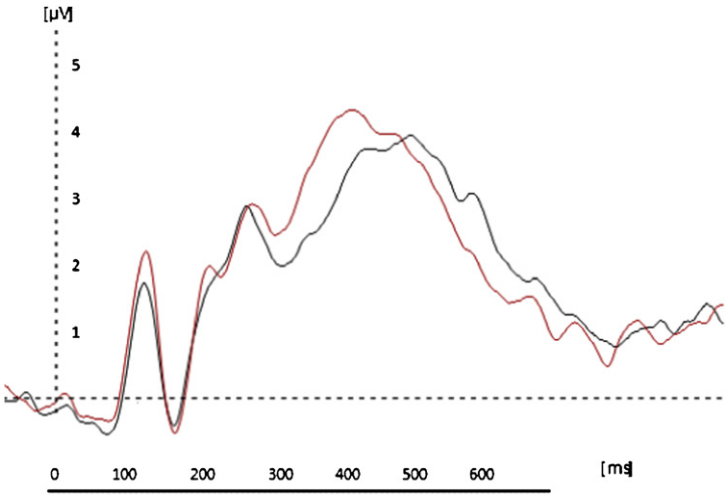

Fig. 2. Changes in P300 latencies in the dyslexics (Pz average) during performance of a Sternberg task following CogniFit Personal Personal Coach training (positive probe).

- The subject was asked to complete a series of pictures presented for short periods on the computer screen.

The training session was divided into 3 parts, like the evaluation session, with the tasks presented in order of increasing difficulty, enabling the subjects to train poor skills while maintaining strong skills, with a low level of frustration.

3. Control training program

3.1. Self-paced reading training (RT)

Subjects read 50 sentences (Breznitz & Nevat, 2004) per session at their own pace (self-paced reading) from a computer screen. Each sentence was comprised of between 7 and 14 words, with one content-related multiple choice reading comprehension question per sentence, in order to confirm reading. Words for the sentences were taken from a bank of frequent Hebrew words (Frost, 2002). The sentences were tested and verified for their level of difficulties in previous studies (see Breznitz, 2006). By pressing a computer key the sentence appeared on the computer screen and the subject started reading it, when finished the subject pressed another key and the sentence disappeared from the computer screen followed by comprehension question. Choosing the correct answer eliminates the question and the answer from the screen and is followed by presentation of additional sentences on the computer screen. Reading time from the appearance to disappearance of each sentence from the screen was registered.

3.1.1. Instrumentation

Thirty-two channels of electroencephalographic (EEG) activity were obtained using a Bio-Logic Brain Atlas IV computer system with brain mapping capabilities. The potentials were sampled at a rate of 250 Hz (dwell time = 3.9 ms) beginning 1000 ms before stimuli onset. A full array of electrodes was placed according to the International 10/20 system (Jasper, 1958) utilizing an Electro-cap (a nylon cap fitted over the head with 9 mm tin electrodes sewn in). During data collection, electrode impedance was kept below 5 Kilo ohm using an electrolyte gel (Electro-gel) that reduces electrical impedance, and a gel (Nuprep) that increases reception. Sampling was taken from thirty-one scalp electrodes dispersed

Table 5a
Experimental groups: changes in reading measures following memory training: mean (standard deviation).

Measures	Dyslexic readers $N = 26$			Skilled readers $N = 35$			F		
	Before training	After training	T	Before training	After training	T	Main effect: training	Main effect: group	Interaction: training with group
Words per minute	71.19 (16.31)	79.23 (18.85)	9.78***	115.03 (18.24)	120.65 (17.34)	4.20*	13.45*** (1,59)	98.11*** (1,59)	2.04 (1,59)
Pseudowords per minute	34.57 (10.19)	38.54 (11.17)	5.34*	64.03 11.81	68.87 (10.66)	4.86*	10.65** (1,59)	121.35*** (1,59)	1.98 (1,59)
Silent reading comprehension (correct from 17)	10.80 (1.85)	12.16 (2.22)	4.68*	11.45 2.5	13.17 (1.91)	3.90*	19.3*** (1,59)	3.66 (1,59)	0.27 (1,59)
Silent letter reading time (sec)	0.47 (0.18)	0.43 (0.14)	3.1*	0.30 0.13	0.25 (0.05)	3.6*	9.39** (1,59)	28.74*** (1,59)	0.29 (1,59)
Parsing time	272.48 (80.65)	231.88 (76.79)	11.45***	155.74 (37.24)	142.0 (32.85)	3.34*	37.05*** (1,59)	46.65*** (1,59)	9.05** (1,59)
Parsing (correct from 46)	43.64 (2.65)	43.76 (2.72)	0.31	44.90 (2.16)	45.15 (1.19)	0.95	0.44 (1,59)	6.54* (1,59)	0.05 (1,59)
Phoneme deletion time	181.0 (75.43)	148.37 (62.06)	8.45***	93.71 (23.08)	90.25 (19.64)	1.9	13.02*** (1,59)	37.10*** (1,59)	8.50** (1,59)
Segmenting time	94.88 (22.87)	88.88 (26.01)	3.72*	70.22 (27.20)	60.54 (14.44)	6.43**	10.45** (1,59)	21.64*** (1,59)	0.57 (1,59)

*$p < 0.05$; **$p < 0.01$; *** $p < 0.001$.

over the scalp; PF1, PF2, F7, F3, FZ, F4, F8, T3, C3, CZ, C4, T4, T5, P3, PZ, P4, T6, O1, O2, PO3, PO4, FC1, FC2, FC5, FC6, CP1, CP2, CP5, CP6, AFZ, FPZ. One electrode was applied diagonally below the left eye to monitor eye movements. All were referenced to average reference (the outputs of all the electrodes are summed and averaged) and grounded to the right mastoid. The EEG records were registered using a commercial program developed for this purpose (Bio-Logic Brain Atlas), and cerebral sampling was carried out every 3.9 ms (CogniFit Personal Coach Training).

The subjects' cognitive abilities were first evaluated by 17 short computerized tasks in a one-hour session divided into 3 parts: tasks the subject performed well, tasks the subject performed moderately well, and tasks the subject performed poorly. Results were compared to standardized norms to determine each subject's level. According to the results of this evaluation, the training program was adapted to the subject's personal requirements and abilities.

3.2. Procedure and training regime

The study was carried out in 4 stages.

Stage 1: Subjects selection and experimental and control group division.

Stage 2: Pre-training measures: Prior to trainings, behavioral reading, CogniFit Personal Coach and Sternberg measures were collected from all subjects. The ERP data during performance of a Sternberg task were collected only for the dyslexics and the regular readers that underwent the working memory training.

Stage 3: Training sessions: Each training program consisted of 24 sessions, over the course of 6 weeks, with 4 sessions a week of approximately 15 minutes each.

The experimental group underwent training of cognitive abilities related to working memory (CogniFit Personal Coach). The control was trained with self-paced reading program (Breznitz & Nevat, 2004).

Stage 4: Post-training diagnosis: Additional parallel forms of the behavioral reading, CogniFit Personal Coach and Sternberg measures were collected from all subjects. The ERP data during performance of a Sternberg task were collected only for the dyslexics and the regular readers that underwent the working memory training.

3.3. ERP data analysis

EEG records were divided according to probe appearance and averaged separately: records in which the probe appeared (positive probe) and a correct answer was given (right joystick button), and records in which the probe did not appear (negative probe) and a correct answer was given (left joystick button). The records were analyzed by the Brain Products Vision Analyzer software. Data were divided into short records of 2000 ms based on stimulus signal for each stimulus in the experiment. Each record contained 100 ms prior to stimulus onset, and 1900 ms from stimulus onset including stimulus appearance, duration and subject response. Frequencies higher and lower than the desired range (0.3–30 Hz) were filtered to eliminate frequencies stemming from noise and not from cognitive activity. Gratton and Coles algorithm was applied to remove electrical activity from the data associated with eye activity.

Baseline correction was carried out by comparing the time segment in which the cognitive activity was recorded (post stimulus appearance) to the time segment in which no cognitive activity occurred (100 ms prior to stimulus appearance).

All stimuli from the same type were combined for averaging. This procedure was carried out for each subject separately.

Identification of ERP wave peaks was performed automatically by the program, with the most positive peak marked within the 300–700 ms range post-probe presentation. The marking was validated by the experiments and took into consideration data collected in the research literature on the topography of the P300 component.

Subjects whose accuracy was below 60% were not included in the analysis of the results in order to remove segments resulting from guessing (1 dyslexic reader and 1 skilled reader).

The differences in the behavioral working memory Sternberg task (accuracy and reaction time) before and after training were determined by repeated measures ANOVA Group (dyslexic/skilled readers) × Training (working memory training/No training).

The differences in the ERP amplitudes and latencies working memory Sternberg task before and after training were determined by repeated measures ANOVA Group (dyslexic/skilled readers) × Task × Electrode.

4. Results

No significant differences in any of the IQ measures were found between dyslexic and skilled readers (Table 1); however, the IQ scores were held fixed on all statistic analyses. Significant differences between the dyslexic and the controls were obtained in most of the reading and memory measures (Table 1).

The significant effect of memory training was found among both of the dyslexics and the skilled readers in the experimental group (Table 2a). However no training effect was found in the control reading groups (Table 2b).

Behavioral measures for the Sternberg task (reaction time and accuracy) in the memory training group (Table 3a) indicated that when the positive probe was presented, a main effect of group was found. The dyslexics' accuracy was significantly lower and their reaction time significantly longer than that of the skilled readers. A main effect of training was obtained for both groups. Following memory training, accuracy increased significantly and reaction time decreased significantly for the dyslexics and the skilled readers. Significant Group effect was found also in the self-paced reading training group, the dyslexics achieved lower accuracy scores and longer reaction time as compared to the skilled readers. However, no training effect was found (Table 3b).

When the negative probe was presented a main effect of group was found in the reaction time measure. The dyslexics reader's reaction time was significantly longer as compared to the controls (see Table 3a).

No training effect on the Sternberg task was found either among the dyslexics or among the skilled readers that were trained in the self-paced reading program (Table 3b).

The P300 component latency and amplitude among the experimental groups (as detected on the Pz electrode) for the two Sternberg conditions (positive and negative probe) before and after training are summarized in Table 4. When the positive probe was presented, the P300 latency following training

Table 5b
Control groups: changes in reading measures following: self-paced reading regime.

Measures	Dyslexic readers $N=15$			Skilled readers $N=15$			F		
	Before training	After training	T	Before training	After training	T	Main effect: training	Main effect: group	Interaction: training with group
Words per minute	68.98 (13.20)	70.13 (15.17)	1.54	115.54 (14.11)	116.32 (15.27)	0.96	1.31 (1,28)	72.55*** (1,28)	1.18 (1,28)
Pseudowords per minute	35.52 (12.16)	35.96 (12.04)	0.26	66.40 (9.67)	65.53 (10.14)	0.45	1.53 (1,28)	98.47*** (1,28)	1.56 (1,28)
Silent reading comprehension (correct from 17)	11.31 (1.74)	11.07 (2.55)	0.31	12.45 (2.68)	12.64 (1.75)	0.23	1.52 (1,28)	2.59 (1,28)	0.34 (1,28)
Silent letter reading time (sec)	0.44 (0.12)	0.446 (0.15)	0.08	0.32 (0.16)	0.30 (0.14)	0.11	1.14 (1,28)	23.26*** (1,28)	1.43 (1,28)
Parsing time	275.56 (70.51)	270.60 (78.21)	1.31	160.40 (42.13)	153.56 (38.68)	1.24	1.14 (1,28)	38.46*** (1,28)	1.02 (1,28)
Parsing (correct from 46)	43.98 (3.67)	44.36 (2.90)	0.53	44.83 (2.22)	45.14 (1.66)	0.38	1.24 (1,28)	25.43*** (1,28)	1.27 (1,28)
Phoneme deletion time	183.25 (74.80)	178.97 (75.12)	1.01	93.44 (23.10)	92.86 (24.04)	0.76	1.33 (1,28)	78.90*** (1,28)	1.34 (1,28)
Segmenting time	93.48 (22.65)	92.56 (20.17)	0.96	67.99 (24.49	65.81 (19.42)	1.42	1.53 (1,28)	95.21*** (1,28)	1.56 (1,28)

*$p < 0.05$; **$p < 0.01$; *** $p < 0.001$.

was significantly shorter in both memory training groups (Table 4, Figs. 1 and 2); the dyslexics' latencies were significantly longer and the amplitude was significantly lower than those of the skilled readers. The P300 amplitude was significantly higher after training on both groups. When the negative probe was presented, the P300 latency following training was significantly shorter in both research groups; the dyslexics' latencies were significantly longer than those of the skilled readers; and the amplitude was significantly lower for the dyslexics than for the skilled readers.

The dyslexics' reading scores before memory training were significantly lower than those of the skilled readers for all reading measures except oral reading comprehension (Table 5). Following memory training, there was a significant increase in all measures except orthographic accuracy test. There was no training effect in the self-paced reading groups in any of the research parameters.

5. Discussion

The results of this study demonstrate the limited capacities of both the verbal and the visuo-spatial working memory sub-systems in adult dyslexic readers, suggesting that both their phonological and orthographic processing is impaired. Although these findings are in line with those of previous studies (Ackerman & Dykman, 1993; Cohen, Netley, & Clarke, 1984; Helland & Asbjørnsen, 2004; Jorm, 1983; Palmer, 2000; Roodenrys & Stokes, 2001; Smith-Spark & Fisk, 2007; Smith-Spark et al., 2003) there is disagreement, regarding the existence of a visuo-spatial information storage and processing deficit among dyslexics. Some studies confirm it (Helland & Asbjørnsen, 2003) while others do not. Data of the current study support the notion that a working memory deficit among dyslexics is not specific to verbal processing but rather also relates to deficit in the sub-system of working memory responsible for processing visuo-spatial information (see also Cohen-Mimran & Sapir, 2007; De Jong, 1998; Smith-Spark & Fisk, 2007). Support for the notion that dyslexic readers exhibit a deficit in the visual system can be found in (Stein & Walsh, 1997). There it was claimed that this impairment can be seen at the early level of the visual perception stage. It can be argued that this deficit might also continue to affect a later stage of processing in visuo-spatial information storage in the working memory system.

The ERP data measured during performance of the Sternberg tasks revealed different P300 latency times in dyslexic and skilled readers, with the dyslexics' times significantly longer than the skilled

readers'. This finding supports previous studies that reported slower latency times among dyslexics on a Sternberg task (Barnea et al., 1994). It has been claimed that latency time changes in accordance with the time required to process and catalog the target stimulus (probe) and to scan the information stored in working memory (Donchin & Coles, 1988). Cross-referencing the latency data with the longest reaction time in the dyslexic groups raises the possibility of an additional deficit in dyslexics: a deficit in the rate at which information stored in working memory is scanned and compared to the target stimulus. Previously it was suggested that the speed at which information is entering to the information processing system might affect the quality its processing (e.g., Breznitz, 2006). There it was claimed that dyslexic readers process alphabetic information in a slower manners as compared to skilled readers (see also Kail, 1994). The slowness was already found at the early perception level (Breznitz & Misra, 2003; Breznitz, 2006). Our current study supports the notion that this slowness, which was exhibited in behavioral and ERP measures, continues to the working memory stage. The working memory system with its limited capacity and rapid decay (Baddeley & Hitch, 1974) is known as the bottleneck of the information processing (Perfetti & Hogaboam, 1975), and speed of processing of the information is crucial for its effectiveness.

The P300 amplitude was found to be significantly lower among the dyslexics than the skilled readers on both Sternberg conditions (positive and negative probe). This finding is consistent with previous studies that reported significantly lower P300 amplitude among dyslexics on a wide range of tasks: lexical decision (Taylor & Keenan, 1990), Sternberg (Barnea et al., 1994), visual oddball (Erez & Pratt, 1992), and auditory oddball tasks (Holcomb, Ackerman, & Dykman, 1986). Previous studies found that the P300 amplitude decreased as the number of items in the Sternberg task increased (Pratt, Michalewski, Barrett, & Starr, 1989). Kramer, Schneider, Fisk, and Donchin (1986) attributed the change in P300 amplitude with series size to the allocation of processing and attention resources to the comparing of the probe to the series stimuli. As the series increases in size, more processing resources are directed toward maintaining the items in working memory using the repeated recall system; the result is fewer processing resources available for the comparison process, which is reflected in increased P300 amplitude. Based on earlier reports of a deficit among dyslexics in the central executive, which allocates processing and attention resources to sub-systems of working memory (Cohen-Mimran & Sapir, 2007), the lower P300 amplitude in the dyslexics in the present study may reflect larger processing difficulty and greater demand for resources allocated to maintaining information in working memory in this group. It may be claimed that due to the storage failure, fewer processing resources are available for comparing the probe to information stored in working memory.

In general, studies found relationships between cognitive trainings that are not specifically related to reading (e.g., phonology, morphology) and enhancement of reading skills among learning disabled subjects (see Slate, Meyer, Burns, & Montgomery, 1998; Tallal, 1993; Törmänen, Takala, & Sajaniemi, 2008). Studies that examined the effect of working memory training on working memory performance from behavioral, functional and anatomical perspectives (Holmes, Gathercole, & Dunning, 2009; Klingberg, 2010; McNab et al., 2009) indicated plasticity in the neural system underlying working memory. Following continuous and adaptive training of working memory, increased cortical activity was observed in pre-frontal and parietal areas parallel to improved performance on working memory storage and processing tasks (Klingberg, 2010; Olesen, Westerberg, & Klingberg, 2004). Holmes et al. (2009) reported that adaptive working memory training among children with learning disabilities was associated with substantial and sustained gains in working memory. The gains in working memory were associated with improved mathematical ability following training.

In our study, the amplitude of the P300 component increased and latency shortened significantly following training in both experimental groups. Based on Kramer et al. (1986), higher amplitude may reflect fewer processing resources allocated to maintaining information in working memory and the consequent availability of more resources for comparing the probe to information stored in working memory. In other words, the higher amplitude following training in both experimental groups while performing the working memory tasks may reflect a lower level of difficulty in maintaining a series of digits in working memory. The lower level of difficulty may indicate higher level of automation in the phonological working memory system which leaves more resources in the working memory available for understanding the meaning of words and text. Several studies have found that reading comprehension depends heavily on working memory (Cain, Oakhill, & Bryant, 2004). Recently, working

memory has been linked to reading comprehension difficulties independent of word recognition difficulties (Oakhill, Cain, & Bryant, 2003). Working memory plays a major role as it holds recently processed information to make connections to the latest input, and it maintains the idea of information for the construction of an overall representation of a text. Swanson and O'Connor (2009) reported that working memory influences reading comprehension performance. There it was claimed that limited working memory "supply" and not word attack test and fluency affect reading comprehension the most. It is conceivable that in the current study, working memory training enlarges the working memory "supply," namely the capacity and speed of processing in the working memory system and enhanced the reading skills. The fact that the self-paced reading training did not affect not working memory nor reading skills among any of the reading level groups might support the notion that the enlargement of working memory supply might contribute more for reading effectiveness and not direct and focused reading. It is important to note that the effectiveness of these results were more pronounced among the dyslexic subjects as they had more to gain in reading as compared to the skilled reading group.

It can be concluded that our findings support the notion of plasticity in the neural system underlying working memory and point to a relationship between larger working memory capacity and enhancement of reading skills. It is clear that more research in this direction is required.

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