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Poor Performance on Serial Visual Tasks in Persons With Reading Disabilities

Impaired Working Memory?

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The present study investigates the performance of persons with reading disabilities (PRD) on a variety of sequential visual-comparison tasks that have different working-memory requirements. In addition, mediating relationships between the sequential comparison process and attention and memory skills were looked for. Our findings suggest that PRD perform worse than normally achieving readers (NAR) when the task requires more than a minimal amount of working memory, unrelated to presentation rate. We also demonstrate high correlations between performance on the task with the most working-memory demands and reading-related skills, suggesting that poor working-memory abilities may be one of the underlying mechanisms of dyslexia. The mediating model analysis indicates that order judgment tasks are mediating to verbal working memory, suggesting that visual sequence memory precedes auditory sequence memory. We further suggest that visual tasks involving sequential comparisons could probe for poor working memory in PRD.

Keywords: *memory; dyslexia; perception*

The etiology of developmental dyslexia has been under investigation for more than 100 years. Because reading is a spatio-temporal process that begins with the decoding of serial visual information, many studies have focused on the different levels and skills of visual information processing and responses to nonorthographic tasks. Early findings revealed longer durations of visual information store and slower rate of transferring visual information in children with reading disabilities as compared to normally achieving readers (NAR; Lovegrove & Brown, 1978). These findings have been supported by other studies indicating that persons with reading disabilities (PRD) are slower in processing sequential visual information during the performance of nonorthographic tasks (Boden & Brodeur, 1999; Galaburda & Livingstone, 1993; Hairston, Burdette, Flowers, Wood, & Wallace, 2005; Keen & Lovegrove, 2000; Laasonen, Service, & Virsu, 2001) and that this deficit persists into adulthood (Breznitz & Meyler, 2003; Hayduk, Bruck, & Cavanagh, 1993).

In the auditory domain, based on comparisons in temporal order judgment (TOJ) between aphasic and nonaphasic persons, it was suggested that specific temporal aspects of central auditory processing may underlie language disorders in this population (Efron, 1963). This idea was adopted and applied first to children with specific language impairment (Tallal & Piercy, 1973) and then to children with dyslexia. Tallal (1980) showed that children with dyslexia have difficulty in determining the order of two computer-generated nonspeech tones presented at short interstimulus intervals (ISIs; 8 to 305 ms) but not at longer intervals (428 ms). Based on those findings, it was suggested that the phonological deficits of children with reading disabilities (Faust, Dimitrovsky, & Shacht, 2003; Snowling, 1996) are the result of auditory deficits in order judgment (Tallal, 1980), and that

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children with reading disabilities suffer from difficulties in perceiving and producing basic sensory-motor information in rapid succession—within tens of milliseconds (see Tallal, Miller, & Fitch, 1993, for a review). Further support for these deficits has been derived from studies that investigated higher-level dysfunctions in PRD and found that these individuals suffer from attention deficits as the result of sluggishness in shifting attention. This could result from difficulty in disengaging of attention, which in turn reflects on their sensory ability to process rapid information (Hari & Renvall, 2001; Hari, Renvall, & Tanskanen, 2001; Hari, Valta, & Uutela, 1999).

Despite the above evidence, the fast temporal deficit hypothesis is still a controversial theory. Several studies failed to identify systematic differences in TOJ between children with reading disabilities and control children and therefore suggested that large individual differences in performance on the TOJ task may be linked to verbal-labeling skill rather than to temporal processing (Heath, Hogben, & Clark, 1999; Marshall, Snowling, & Bailey, 2001; Nittrouer, 1999). Also, in a study that divided children with reading disabilities into two subgroups on the basis of their tonal TOJ performance and assessed several measures of phonological awareness, order processing of consonant–vowel speech sounds, and severe reading difficulties, there was no consistent relationship between tone-order deficits and the other skills (Bretherton & Holmes, 2003). This failure to find differences between children with and without reading disabilities in temporal resolution can be also be the result of the hypothesis that temporal processing may be developmentally limited. It has been suggested that temporal-resolution deficits that were found in younger children may improve as children mature and may not be directly involved in language and reading deficits after age 10 (Hautus, Setchell, Waldie, & Kirk, 2003).

This fast temporal deficit hypothesis was later broadened to a general timing hypothesis in vision, auditory, vestibular, and motor processing as the result of a magnocellular deficit (Stein & Walsh, 1997). Some of the studies found evidence that supports the temporal-processing deficit in dyslexia but only for the auditory modality and not as a global, pansensory deficit (Heim, Freeman, Eulitz, & Elbert, 2001). However, it was demonstrated in anatomical postmortem studies that adults with dyslexia have abnormalities in the visual magnocells in the lateral geniculate nucleus (Livingstone, Rosen, Drislane, & Galaburda, 1993) and the auditory magnocells in the medial geniculate nucleus (Galaburda, Menard, & Rosen, 1994). The magnocellular hypothesis suggested that impaired visual information processing for sequential stimuli with short ISIs is because of a deficit in sensory temporal processing that is at a lower level than the perceptual and cognitive systems (Stein & Walsh, 1997).

Despite the above, the magnocellular hypothesis remains controversial. Criticisms of this theory focus on failures to replicate findings indicating visual deficits (Johannes, Kussmaul, Munte, & Mangun, 1996; Victor, Conte, Burton, & Nass, 1993), and on the findings that visual impairments have been observed across a wide range of stimuli, not just in those depending on the magnocellular system (Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Farrag, Khedr, & Abel-Naser, 2002; Skottun, 2000).

A relatively new approach that challenges the magnocellular theory suggests that the basic perceptual impairment in PRD may be owing to their limited ability to retain and compare perceptual traces (Ben-Yehudah, Sackett, Malchi Ginzberg, & Ahissar, 2001). An interesting finding of this study was that during the performance of a temporal forced-choice task with a 500 ms ISI, only a marginally significant difference was found in contrast sensitivity between good readers and PRD, whereas in the longer ISI condition (1000 ms) the difference in contrast sensitivity became highly significant (Ben-Yehudah et al., 2001). The findings of a subsequent study by the same group (Ben-Yehudah & Ahissar, 2004) suggested that visual tasks requiring sequential comparisons are difficult for the majority of dyslexic individuals, whereas no difference was found between NAR and PRD for tasks involving simultaneous spatial-frequency discrimination. Based on these results, the authors concluded that the impairment in sequential comparisons in PRD cannot be attributed to shorter or longer ISIs and suggested that this difficulty in PRD may stem from deficits either in visual perception or in visual memory.

In a previous study (Ram-Tsur, Faust, & Zivotofsky, 2006) we demonstrated that PRD have difficulties in sequential tasks involving same–different judgments when a comparison between two stimuli is requested. This deficit was found to be independent of the ISI in a range from tens of milliseconds to more than a second. No difference between PRD and good readers was found for the same comparison task in simultaneous presentations. These findings of impairment in sequential comparisons for PRD when they perform temporal tasks with longer ISIs raise questions regarding the "fast temporal deficit hypothesis." Based on those findings of impairment in sequential comparisons in PRD at short and long ISIs, we have suggested that a dual-mechanism impairment may explain the findings: Attention deficit may underlie their poor performance on temporal tasks with short ISI, whereas a working-memory impairment may underlie their poor performance on temporal tasks with long ISI.

In the current study we were interested in investigating the performance of PRD as compared to NAR in a sequential task consisting of a sequence of three stimuli over a range of ISIs. It was hypothesized that because PRD have an impaired ability to carry out sequential processing, they will show poor performance in processing three sequential stimuli. We were interested in determining if and how the type of judgment task, same–different judgment versus order judgment, influences the performance of PRD as compared to the performance of NAR. Because we have suggested that working memory is one of the two mechanisms that is impaired in PRD and that this impairment may lead to poor performance on sequential tasks but not on tasks that require less working memory (i.e., same–different judgment with minimum working-memory requirements), PRD may show better performance on these tasks as compared to tasks that require more precise working memory (i.e., order judgment). Ultimately, we were interested in exploring the relationship between the performance on sequential tasks and both working-memory and attention tests.

We hypothesize that poor performance on sequential tasks owing to limited retain-and-compare abilities will correlate with poor phonological and reading abilities. This is because limited memory can interfere with remembering the correct orthographic sequence pattern of the word and the correct sequence/order of the sounds (phonemes) of the word, and this in turn can lead to common mistakes of persons with dyslexia, such as sequence order mistakes and/or confusions with similar words. It has been previously demonstrated that limited retain-and-compare abilities correlated with reading abilities and memory tests. It was found that poor performance in visual discrimination during sequential presentation is correlated with poor performance in rapid naming, nonwords reading, and verbal and nonverbal memory tasks (Ben-Yehudah & Ahissar, 2004).

Method

Participants

Twenty-seven PRD adults (all men; mean age = 25 ± 2.7 years) and thirty-one NAR adults (all men; mean age = 26 ± 3.3 years) participated in the research. All participants were native Hebrew speakers and naive to the purpose of the study. All participants were tested on the *Snellen Visual Acuity* test and were only included if they had normal visual acuity. Participants were recruited by placing advertisements on the university campus and with direct mailing utilizing a database from the university center for assisting students diagnosed with learning disabilities. All participants had a minimum of several years of university education. The criterion for inclusion in the PRD group was a psycho-educational diagnosis of a developmental reading disability as determined by officially recognized testing agencies that led to approval by the university for testing leniencies granted to reading-disabled students. In addition, it was confirmed that all PRD participants had a current speed of pseudowords reading score (see below) of at least 1 *SD* slower than the control group average. Participants of both groups performed within the normal range on the Matrices subtest of the third edition of the *Wechsler Adult Intelligence Scale* (WAIS-III; Wechsler, 1997). Performance on other subtests was not a basis for participants' exclusion. The Bar Ilan University ethics committee approved the study, and all subjects gave their written, informed consent prior to participation in the study.

Psychometric Battery and Reading-Related Skills Tests

For evaluating achievement profiles, we used psychometric and reading-related tests. For assessing cognitive performance we used the following WAIS-III subtests: Matrices, Digit Span, and Digit Symbol**.** An estimation of intelligence abilities was derived from the Matrices subtest of the WAIS-III that resembles the *Raven's Advanced Progressive Matrices* (Raven, Raven, & Court, 1998), which is very highly *g*-loaded (general intelligence factor). The Matrices subtest is an abstract reasoning test that measures analogy skills.

The Digit Symbol Coding and Digit Span subtests of the WAIS-III were used to screen participants for distractibility (Anastopoulos, Spisto, & Maher, 1994). The Digit Symbol Coding subtest is a processing speed test that demands attention and concentration. The Digit Span is used as a measure of attention, concentration, sequencing, number facility, and auditory short-term memory (Coalson & Weiss, 2002; Hale, 2002).

In the Digit Symbol Coding, the participant was presented with a code of matched digits and symbols and was required to fill in the correct symbol for each presented digit as fast as possible. The Digit Span is a task that involves the immediate recall of a verbally presented series of digits.

As for the reading tests, the Hebrew written language includes both deep and shallow orthographies. In shallow orthography, the written Hebrew is pointed (which means that there is a high spelling-to-sound correspondence) and in deep orthography the script is unpointed (which means there is a low spelling-to-sound correspondence; Frost, 1994). To evaluate the participants' reading skills, we used speed-of-reading lists of single, unpointed words (measured in words per minute, WPM; Shatil, 1995b); pseudowords (pointed) per minute (PWPM; Shatil, 1995a); and a reading rate of an academic-level unpointed text (text speed; Shatil, 1997a).

The speed-of-reading list of single, unpointed words test included 217 words. The list was a mixture of different word types and included low-frequency and high-frequency words; words of various lengths (between 3 and 7 letters); verbs and nouns in various conjugations and declension; regular and irregular words (e.g., the word *achshaiv* in Hebrew that means now, is read differently as written *achshaio*); and homographic words (e.g., the word *miscenim*, which means poor, could be also read as *mesacnim*, which means risking). The pseudowords test consisted of a mixture of 86 types of pseudowords. Some of them were only roots (e.g., *drar*—the root is *drr*) and others were verbs and noun roots with additional morphemes (e.g., *hitgaze*—the root is *gzl*). Thus, the length of the pseudowords was between 3 and 6 letters. All the pseudowords were created following proper grammatical rules of Hebrew.

In scoring the single, unpointed words test and the pseudowords test, we included all words, those read correctly as well as those decoded inaccurately, that the participants read within 1 min. In the reading rate of an academic-level unpointed text test we timed the participant reading the entire passage and than calculated the reading rate as the total number of words (accurate and inaccurate) multiplied by 60 s divided by the whole text-reading duration in seconds.

We also evaluated the participants' performance on a rapid automatized naming task. For this we used a Hebrew version of the conventional rapid automatized naming test (Denckla & Rudel, 1976) that included three subtests: Letters (RANletter); Symbols (RANsymbol); and a combination of Letters, Numbers, and Symbols (RAS; Breznitz, 1998). In these tests, the participants were instructed to read 50 items, arranged in pseudorandom order, as accurately and as quickly as possible.

The orthographic skills were evaluated by a written spelling test (Shatil, 1997c). The score was based on the number of spelling errors. The aim of this test was to examine automatic writing based on rapid recall of the orthographic form of the word. The participants were required to produce 30 unpointed spellings. Some of the words (about 30%) were homophones and therefore a short context was given [e.g., the word *eres* can be written either with the Hebrew letters *Ain* and *sin* ("lullaby") or with the Hebrew letters *Aleph* and *Samech* ("poison"). The context given for the first meaning was "lullaby song" and for the second meaning it was "snake poison"]. The word list included both verbs and nouns. The list was assembled from words with varying frequencies and lengths (between 3 and 6 letters).

In the Hebrew unpointed script there are letters (*yud* and *vav*) that indicate the identity of the vowel, and the word can be considered correctly spelled with or without those letters (e.g., the word "blind" in Hebrew can be written as either *ever* or *eiver*; another example is the word *mold*, which can be written as either *avesh* or *aovesh*). Thus, both the deep and shallow orthographies were considered correct spellings. Every word that was spelled incorrectly, regardless of the number of mistakes in the word, was scored as one error. The total score of mistakes was then multiplied by 3.33%.

Phonological awareness was examined through a Hebrew translation (Shatil, 1997b) of the Spoonerism task (Perin, 1983). In this task the participants are given several examples and are then orally presented with two words (such as King John) and asked to exchange the initial sound of each word (i.e., Jing Kon). The score was based on the number of correct answers.

Visual attention was assessed by the d2 test, which is a timed test of selective attention (Brickenkamp & Zillmer, 1998; Gordon, Montenegro, Culbertson & Zillmer, 1997). The targets are composed of the letters "d" and "p" with one, two, three, or four dashes arranged either individually or in pairs above or below the letter. The participant is given 20 s to scan each line of text and mark all the "d"s that have two dashes. The measured variables were (a) the concentration performance (CP), which reflects both the speed and the accuracy of performance; and (b) the fluctuation rate (FR), which measures the consistency of performance across trials. The CP derived from the number of correctly crossed out relevant items ("d"s with two dashes) minus the errors of omissions and commissions. The FR derived from the trial with the maximum total items processed minus the trial with the minimum total items processed.

Stimuli and Procedure

The following conditions and procedures were the same in all of the tasks. We used a Gabor patch in two directions: 45º and 135º. A two-alternative forced-choice (2AFC) paradigm was used. The beginning of each trial was demarcated by a tone and a "+" sign that was displayed in the center of the screen to direct the subject to fixate on the center of the screen. In all trials the participant was informed of a correct answer via a high tone and an incorrect answer with a low tone. Before each experiment the participant had several practice sessions to learn and understand the upcoming procedure. In all of the experiments there was no time limit for answering, although the participants were instructed to respond as rapidly and as accurately as possible. Between trials, the "+" sign was again displayed at the center of the screen.

Contrast-detection thresholds were assessed in all tasks, except for the perception task (see below). Contrast detection was varied in a two-down/one-up adaptive staircase procedure, converging on the value of 71% correct (Levitt, 1971). Contrast was increased by 1 dB following an incorrect response, and decreased by 1 dB following two consecutive correct responses. The stimulus contrast was defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$, where L_{max} and L_{min} are the maximum and minimum luminances, respectively (Michelson contrast). Detection thresholds (percentage contrast) were calculated as the average of the last 10 of 13 reversals. All tasks included six "catch trials" (except for the perception task) in which the Gabor had a permanent high contrast of 50% that was displayed to test for errors that did not stem from the difficulty of the perceptual detection. All participants performed close to 100% on the catch trials. The viewing distance was 90 cm. The three tasks (described below) were administered to each participant in a random order. The interval between a response and the next trial varied randomly between 1.0 and 1.5 s.

Perception of spatial orientation in NAR and PRD. All of the tasks described below require the participant to make a judgment based on spatial orientation detection (same or different judgment for two possible orientations). The objective of this task was to eliminate the possibility of differences between the two groups in this capability and to confirm that all participants understood and could accurately perform the tasks. Previous evidence supports the notion of an equally functioning parvocellular system in NAR and PRD subjects (Stein & Walsh, 1997) and thus this task was designed to stimulate mainly parvocells, i.e., stimuli with high spatial frequency, high contrast, and high luminance (Livingstone & Hubel, 1988; Merigan & Maunsell, 1993). The stimulus was presented on the center of the screen with a mean luminance of 40.5 cd m^{-2}. The participants were asked to push one button if the orientation of the lower part of the Gabor patch pointed to the right and to push a different button if the orientation of the lower part of the Gabor patch pointed to the left. The Gabor patch ($\sigma = 2°$) was displayed for 500 ms with 50% contrast. Contrast detection was varied in a two-down/one-up adaptive staircase procedure, converging on the value of 71% correct (Levitt, 1971). Spatial frequency was increased by 2 dB following an incorrect response, and decreased by 2 dB following two consecutive correct responses. The outcome of this task was a measure of spatial-frequency thresholds for the Gabor patch.

The results of a *t* test for independent samples comparing the performance of NAR and PRD groups revealed that NAR and PRD did not differ on this task, ts < 1. This means that, in the following tasks, if a difference is found between the two groups, it is not because of a difference in orientation perception or a lack of understanding of the task requirements.

Short temporal task. Contrast-detection thresholds of same–different judgments were measured for a series of two flickering Gabor patches that appeared sequentially in the center of the screen. This procedure was repeated in four separate blocks that differed in their ISIs. The four different ISIs used were 30, 500, 1000, and 1500 ms. There are several reasons for using these ISIs in the sequential tasks (short temporal task; see below for long temporal task). The medium and long ISIs (500, 1000, 1500 ms) were chosen to explore and provide more information for the new "retain-and-compare" paradigm that was recently suggested as a primary cause for dyslexia (Ben-Yehudah et al., 2001). To compare and contrast our results with theirs, we used similar ISIs to those used by Ahissar and her research group (that in turn was based on previous work by Borsting et al., 1996, and by Spinelli et al., 1997). The shortest ISI (30 ms) was added for two reasons: The first is that in the fast temporal deficit hypothesis, based on experiments in the auditory modality, it was suggested that children with reading disabilities suffer from difficulties in perceiving and producing basic sensory-motor information in rapid succession—within tens of ms (see Tallal et al., 1993, for a review). The second reason was to explore the performance of the two groups when perceptual memory is required. The participants were asked to indicate by means of a button push whether the two displays had the same or different orientations. The Gabor patches were each displayed for 500 ms, with a low mean luminance of 5.7 cd m^{-2}, and had a spatial frequency of 0.5 cpd ($\sigma = \lambda = 2°$) with a flicker frequency of 10 Hz.

Spatial task. Two flickering Gabor patches were displayed simultaneously on the screen separated by 5.74 deg. This procedure was repeated in three separate blocks that differed in the duration of stimulus presentation. The three durations were 500, 1000, and 2500 ms. Participants were asked to indicate by means of a button push whether the two Gabor patches had the same or different orientations. The spatial frequency of the Gabor patch was 0.5 cpd ($\sigma = \lambda = 2°$) and the flicker frequency was 10 Hz. The Gabors were displayed with a mean luminance of 5.7 cd m^{-2}.

Long temporal task. Contrast-detection thresholds for same–different judgments and accuracy for order judgment were measured for a sequence of three (as opposed to two in the short temporal task) central flicker Gabor

Table 1
Results of Performance on Psychometric Tests

Parameters	NAR[a] (*SD*)	PRD[b] (*SD*)	*t* Value	*p* Value
Age	25.3 (2.7)	26.7 (3.3)	−1.67	*ns*
Cognitive measures				
Matrices +	13.9 (2.3)	13.4 (2.9)	0.77	*ns*
Digit span +	10.7 (2.0)	8.9 (2.8)	2.8	0.007
Digit symbol coding +	11.2 (2.8)	8.6 (2.6)	3.5	0.001
Reading measures				
WPM (speed)	125.7 (20.6)	86.8 (23.2)	7.60	0.000
WPM (errors)	0.35 (0.839)	3.33 (3.721)	–4.33	0.000
PWPM (speed)	70.5 (16.8)	52.3 (26.0)	3.67	0.003
PWPM (errors)	2.06	10.59	–5.53	0.000
PASS (speed)	72.9 (9.2)	108.0 (29.0)	–6.90	0.000
RAN letter	20.5 (6.0)	24.6 (4.1)	–3.25	0.004
RAN symbols	34.3 (4.5)	46.0 (11.3)	–4.92	0.000
RAS	20.2 (4.4)	27.5 (5.1)	–5.88	0.000
Orthographic				
Spelling (errors)	5.5 (15.6)	33.4 (3.3)	–6.99	0.000
Phonological awareness				
Spoonerism	5.5 (5.5)	3.9 (2.3)	3.14	0.002
Attention-d2				
CP	207.9 (38.6)	168.7 (37)	4.22	0.000
FR	12.9 (6.4)	11.8 (6.0)	0.63	*ns*

Note: + = scaled score; NAR = normally achieving reader; PRD = person with reading disabilities; WPM = words per minute; PWPM = pseudowords per minute; PASS = oral passage reading rate; RAN = rapid automatized naming; RAS = rapid alternating stimuli; CP = concentration performance; FR = fluctuation rate.
a. $n = 31$.
b. $n = 27$.

patches. Each stimulus appeared for 500 ms. This procedure was repeated in four separate blocks that differed in their ISI. The four different ISIs were 30, 500, 1000, and 1500 ms. Participants were asked to push button “A” if the one of the three Gabor stimuli had a different orientation and to push button “C” if all three Gabor stimuli had the same orientation. If the participant pressed the “A” button, the following question appeared on the screen: “Which target was different, A, B, or C?” (i.e., first, second, or third Gabor patch, respectively).

In trials in which the first two stimuli differ, it is possible to make the same–different decision even before the third stimulus appears. Because this task was aimed at investigating sequential processing of three stimuli, we wanted to eliminate such trials. The distribution of the trial types was therefore as follows: In 10% of the trials the first Gabor was different from the other two, in 10% of the trials the second Gabor was different from the others, and in the remaining 80% of the trials the first two stimuli were the same. Out of these, in 50% the third was also the same and in 50% it was different. It is these 80% for which the data are presented. The trials were presented in a randomized order and mixed with the “catch trials.” The spatial frequency of the Gabor patches was 0.5 cpd ($\sigma = \lambda = 2°$), and the temporal frequency was 10 Hz, which was displayed with mean luminance of 5.7 cd m^{-2}.

Apparatus

All the psychophysical experiments were administered in a dark room and the subjects were given several minutes in which to dark-adapt. We used the VSG2\5 system (Cambridge Research Systems Ltd, Rochester, UK) for designing the experiments. The stimuli were displayed on a 21 inch SONY GDM-F520 Monitor with a frame rate of 170 Hz. The experiments were controlled by and the data analyzed using Matlab (version 7.0). ColorCAL colorimeter was used to calibrate the screen (Cambridge Research Systems Ltd, Rochester, UK). The responses of the participants were recorded by a CB6 response box (Cambridge Research Systems Ltd, Rochester, UK).

Results

Psychometric Measures

Table 1 summarizes the performance of the NAR and the PRD groups on the cognitive and reading-related tests, along with the statistical significance.

As indicated in Table 1, PRD and NAR participants did not differ in mean scaled score of the Matrices subtest, typically used to match groups for cognitive abilities.

Table 2
Results of Performance on Psychophysics Tasks

Results of Performance on Psychophysics Tasks at Different ISIs	NAR (*SD*)	PRD (*SD*)	*p* Value
Short temporal task			
30	2.8 (0.6)	3.5 (1.4)	
500	2.7 (0.4)	3.0 (0.8)	
1000	2.7 (0.7)	3.5 (1.3)	
1500	2.6 (0.4)	3.2 (1.4)	0.04
Spatial task			
500	2.2 (0.4)	2.2 (0.5)	
1000	2.2 (0.4)	2.3 (0.5)	
2500	1.9 (0.5)	2.2 (0.5)	0.120
Long temporal task			
30	2.9 (0.5)	3.2 (1.3)	
500	2.8 (0.6)	3.2 (1.3)	
1000	2.7 (0.7)	2.9 (0.7)	
1500	2.6 (0.4)	3.0 (1.1)	0.171
Long temporal task accuracy			
30	0.3 (0.1)	0.2 (0.1)	
500	0.5 (0.1)	0.4 (0.1)	
1000	0.5 (0.08)	0.5 (0.1)	
1500	0.5 (0.1)	0.4 (0.08)	0.002

Note: NAR = normally achieving reader; PRD = person with reading disabilities.

However, as can be seen in Table 1, NAR performed better than dyslexics on both screening factors for distractibility: Digit Symbol Coding and Digit Span. In agreement with previous results, as compared to NAR, PRD were significantly impaired on all reading tests (Pennington, Van Orden, Smith, Green, & Haith, 1990; Ransby & Swanson, 2003). In addition, the PRD group was significantly impaired on CP as compared to the NAR group. However, there was no significant difference between PRD and NAR on the FR across trials. Taken as a whole, these findings indicate that, as compared to NAR participants, the PRD participants had lower concentration ability that cannot be attributed to fluctuation in attention.

Psychophysical Measures

Table 2 summarizes the performance of the PRD and the NAR groups for all psychophysical tasks, along with the statistical significance.

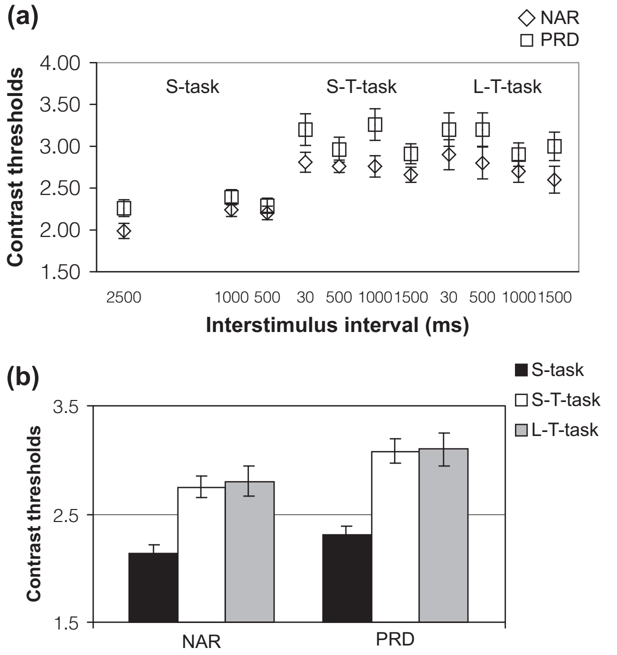
Short temporal and spatial tasks. An analysis of variance (ANOVA) for repeated measures conducted on contrast-detection thresholds on the short temporal task, with group (NAR, PRD) as a between-subject variable and ISI (30, 500, 1000, 1500 ms) as a within-subject variable, revealed a significant effect only for group, $F(1, 54) = 4.45$, $p < 0.05$, with higher thresholds for the PRD group ($M = 3.10$) than for the NAR group ($M = 2.75$). No significant effects were found for both ISI, $F(3, 52) = 2.70$, $p > 0.05$, and Group × ISI interaction, $F(3, 52) = 1.16$, $p > 0.05$.

As for the spatial task, we tested the performance of both groups on three simultaneous presentation durations: short (500 ms), medium (1000 ms), and long (2500 ms). A two-way ANOVA for repeated measures conducted on contrast-detection thresholds with group as between-subjects factor and presentation duration (500, 1000, 2500 ms) as within-subjects factor, revealed a significant effect of presentation duration, $F(2, 53) = 4.98$, $p = 0.01$. No significant effects emerged for both group, $F(1, 54) = 2.49$, $p > 0.1$ and Group × Presentation Duration interaction, $F < 1$. These results show poor performance of PRD only for the temporal task, independent of ISI, within a wide range of between tens of milliseconds to more than a second. However, no significant difference was found between the two groups on the spatial task. These findings have been extensively discussed in a previous paper (Ram-Tsur, Faust, & Zivotofsky, 2006).

Performance of contrast-detection threshold on the long temporal task. An ANOVA for repeated measures was conducted on contrast-detection thresholds for the “long temporal” task, with group (NAR, PRD) as a between-subject variable and ISI (30, 500, 1000, 1500 ms) as a within-subject variable. As threshold distribution was highly skewed for ISI of 1500 ms, the analysis was conducted on the square-root transformation of this variable. Results revealed a significant ISI effect, $F(3, 52) = 3.03$, $p < 0.05$. However, no significant effects emerged for both group, $F(1, 54) = 1.92$, $p > 0.1$, and Group × ISI interaction, $F < 1$.

The thresholds may not be the best measure to evaluate the PRD performance, because PRD adults have experienced decades of academic difficulties, and thus may have a stricter criterion for stating that a stimulus is present. We therefore conducted an additional ANOVA for repeated measures on *d* primes. Hit rate was defined as the proportion of “different” answers for stimuli for which the third stimulus was indeed different from the other two stimuli. False-alarm rate was defined as the proportion of “same” answers, for stimuli for which the third stimulus was different from the other two stimuli. Cases with false-alarm rates of 0 or hit rates of 1.0 were adjusted using the “standard” correction method (see MacMillan & Creelman, 1991): False-alarm rates of 0 were replaced with 1/(maximum number of false alarms), and hit rates of 1.0 were replaced by 1/(2 × maximum number of targets). The results revealed no significant effects of ISI, $F < 1$; group, $F(1, 53) = 2.43$, $p > 0.05$; or ISI × Group interaction, $F(3, 53) = 1.68$, $p > 0.05$. This additional analysis strengthens the findings of the thresholds analysis.

Figure 1
Contrast-Detection Thresholds for Each Group on the Spatial and Temporal Tasks. (a) The Contrast Thresholds of Each Group on Each Condition. Error Bars Represent SEM. (b) The Mean Contrast Thresholds of Each Group on Each Task. Error Bars Represent SEM



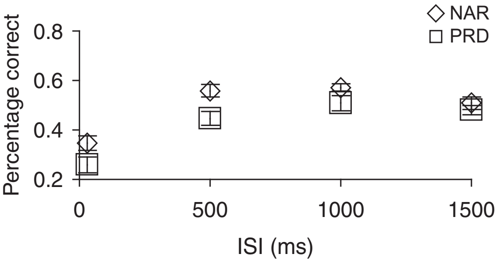
Note: NAR = normally achieving readers; PRD = persons with reading disabilities; S-task = spatial task; S-T-task = short temporal task; L-T-task = long temporal task.

Figure1(a) shows the performance of NAR and PRD groups on each of the above tasks (short and long temporal tasks and spatial task) for the conditions of each task. Figure 1(b) presents the means thresholds for each group (NAR vs. PRD) on the three tasks.

The results of the long temporal task, which show no group difference, seem to contradict our findings regarding the short temporal task, in which there was a group difference that we interpreted as indicating a sequential-processing deficient in PRD. Our explanation for this difference relates to the working memory capacity demands on each task as detailed in the Discussion.

Performance on order judgment accuracy in a long temporal task. An ANOVA for repeated measures was conducted on contrast-detection thresholds for the long temporal accuracy task, with group (NAR, PRD) as a between-subject variable and ISI (30, 500, 1000 and 1500 ms) as a within-subject variable. Results revealed significant differences for both ISI, $F(3, 54) = 35.61$, $p < 0.001$, and group, $F(1, 56) = 10.11$, $p < 0.01$, effects. Overall, the PRD group made more mistakes ($M = 0.42$) than the NAR group ($M = 0.50$). However, because accuracy rate for an ISI of 30 ms was around 30% for both groups, suggesting a floor effect, a second analysis was performed without the 30 ms ISI condition. Results were similar to those of the full analysis. Finally, the Group × ISI interaction was not found to be significant, $F(3, 54) = 1.05$, $p > 0.1$. Figure 2 demonstrates the performance of each group on order judgment accuracy for the different ISI conditions. These findings indicate that sequential processing deficits in PRD in order judgment accuracy are independent of the ISI in a range of between tens of millisecond to more than a second.

Figure 2
The Accuracy in Long Temporal Judgment Order Task for Each ISI (Interstimulus Interval) Condition. Error Bars Represent SEM



Note: NAR = normally achieving readers; PRD = persons with reading disabilities.

Mediating relationship between performance on temporal comparisons and cognitive abilities. It has been suggested, although not yet demonstrated, that the impairments of PRD in sequential visual tasks may stem from deficits in working memory and/or attention (Ben-Yehudah & Ahissar, 2004; Ram-Tsur, Faust, & Zivotofsky, 2006). Thus, we were interested in examining the mediating relationship between the tasks' performance and the performance of both groups (NAR and PRD) on verbal working-memory and attention tests.

To test whether the differences between NAR and PRD groups in cognitive tasks are mediated by differences between the groups in temporal comparison processing, we used the Baron and Kenny (1986) equation. Specifically, we tested the mediating effects of contrast-detection threshold of each task (short temporal, long temporal, and spatial tasks) and accuracy in the order judgment of the long temporal task on the relationship between group and each of the following three cognitive functions: digit span (verbal working memory), and CP and FR from the d2 test. Table 3 presents the results of all these mediating models.

As indicated in Table 3, there was a significant mediating effect of the accuracy of order judgment on the long

Table 3
Temporal Mediating Results Between Group and Cognitive Functioning (Verbal Working Memory and Attention Performance)

Dependent Variables	Mediating Variables	*Z* Value	*p* Value
Digit span	short temporal task	1.87	0.06
	spatial task	1.31	> 0.05
	long temporal task	0.70	> 0.05
	long temporal task accuracy	2.22	0.02
d2-CP	short temporal task	1.13	> 0.05
	spatial task	0.30	> 0.05
	long temporal task	0.40	> 0.05
	long temporal task accuracy	1.50	> 0.05
d2-FR	short temporal task	0.84	> 0.05
	spatial task	0.93	> 0.05
	long temporal task	0.64	> 0.05
	long temporal task accuracy	1.51	> 0.05

Note: CP = concentration performance; FR = fluctuation rate.

temporal task between group and verbal working memory. In addition, there was a marginally significant effect for the performance in the short temporal task as a mediator between group and verbal working memory. No other task was found to mediate the relationship between group and the tested cognitive functions. Note that the two groups did not differ in attention fluctuation rate (Table 1).

Figure 3 presents the temporal-comparison mediating effects of the long temporal accuracy and short temporal tasks in the relationships between group and digit span. As can be seen in Figure 3(a), the *negative* relationship between group and digit span, such that good readers have higher scores, is explained by the *negative* relationship between group and temporal-comparison abilities and the *positive* relationship between temporal abilities and cognitive skills. A similar pattern can be seen in Figure 3(b), with the correlation signs flipped as the result of it being a threshold and not an accuracy measurement.

Our findings suggest that processes involved in sequential visual-comparison tasks are mediating to verbal working memory. We wanted to test our model also in the inverse direction; that is, if low performance in sequential visual-comparison tasks is mediating to verbal working memory, a nonmediating relationship on this direction will support our hypothesis that sequential visual-comparison tasks are mediating to verbal working memory. If verbal working memory is mediating group and sequential visual-comparison tasks, our previous suggestion is not supported.

To this end, we tested the mediating effects of digit span performance on the relationship between group and contrast-detection thresholds in the short temporal task and the performance in the accuracy of order judgment in the long temporal task. Table 4 presents the results of all these mediating models.

Table 4
Cognitive Mediating Results Between Group and Tasks

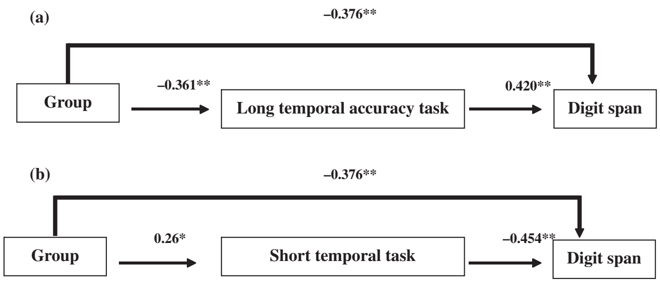
Dependent Variables	Mediating Variables	*Z* Value	*p* Value
Digit span	short temporal task	2.17	0.03
	long temporal task accuracy	1.7	> 0.05

Figure 4 presents the cognitive mediating models postulating relationships between group and digit span for long temporal accuracy and short temporal tasks. As can be seen in these figures, the pattern of mediation differs for the long and short temporal tasks. For the long temporal tasks, shown in Figure 4(a), the negative relationship between group and temporal processes, such that good readers have higher scores, is explained by the fact that good readers have higher scores on the digit-span task, and performance on digit span is positively related to long temporal processes. However, as shown by Figure 4(b), for the short temporal tasks, the positive relationship between group and temporal processes, such that good readers have lower scores, is explained by the fact that good readers have higher scores on the digit-span task, and performance on digit span is negatively related to short temporal processes. The results indicate that only the order judgment task (long temporal accuracy task) is mediating to verbal working memory, but there is a relationship between the short temporal task and verbal working memory.

Correlations between perceptual tasks and reading-related skills tests. We hypothesized that poor working memory would interfere with reading-related skills and that this could account for common reading mistakes observed in dyslexia. To test this hypothesis, we calculated the correlation between performance on perceptual visual tasks and reading-related tests using Pearson correlations.

We ranked the perceptual visual tasks on the basis of demand in terms of working memory required. The task with the highest degree of working-memory demands is the order judgment accuracy in the long temporal task, because the participant is required to retain in memory and compare sequences of three stimuli and to decide which of the three is the different one. The task with little or no working memory is the spatial task, because the participant sees the two stimuli simultaneously and does not need to store anything to compare the two stimuli.

Figure 3
Temporal Mediating Model Between Group and Digit Span for (a) Long Temporal Accuracy and (b) Short Temporal Accuracy



Note: Numbers are Pearson correlations.
*$p < 0.05$. **$p < 0.01$.

Table 5
Pearson's Correlations Between Perceptual Tasks and Reading-Related Tests

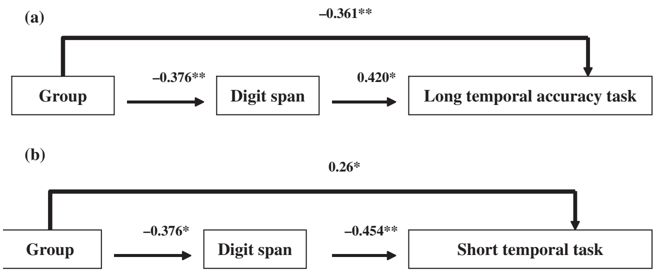
Reading-Related Skills Tests	Long Temporal Task Accuracy	Long Temporal Task	Short Temporal Task	Spatial Task
WPM (speed)	0.32*	–0.03	–0.10	–0.00
WPM (errors)	–0.28*	0.02	0.14	0.08
PWPM (speed)	–0.23	0.07	0.08	0.07
PWPM (errors)	–0.19	0.05	0.05	–0.08
PASS (speed)	–0.43**	0.03	0.13	0.08
RAN letter	–0.11	–0.02	0.00	0.07
RAN symbol	–0.30*	0.09	0.21	0.24
RAS	–0.39**	0.02	0.11	0.12
Orthographic				
Spelling (errors)	–0.28*	0.05	0.15	0.10
Phonological awareness				
Spoonerism	–0.39**	–0.21	–0.37**	–0.31

Notes: WPM = words per minute; PWPM = pseudowords per minute; PASS = oral passage reading rate; RAN = rapid automatized naming; RAS = rapid alternating stimuli. The correlation coefficient is indicated.
*$p < 0.05$. **$p < 0.01$.

Contrast-threshold detection of the short and long temporal tasks involves medium working-memory requirements. Table 5 presents the results of Pearson correlations between visual perceptual tasks and reading-related tests.

As indicated in Table 5, there were significant correlations between the order judgment accuracy in the long temporal task and almost all reading-related skills. However, no correlations were found between the other perceptual tasks and reading-related tasks, except for one correlation between the short temporal task and phonological awareness. Therefore, we conclude that participants with low performance on the sequential tasks with the highest degree of working-memory demands have low/poor abilities in reading-related tests.

Figure 4
Cognitive Mediating Model Between Group and (a) Long Temporal Accuracy and (b) Short Temporal Accuracy



Note: Numbers are Pearson correlations.
*$p < 0.05$. **$p < 0.01$.

Discussion

Summary of the Results

Taken as a whole, these results indicate that in an order judgment task (long temporal accuracy task) for a sequence of three stimuli, PRD show poorer performance as compared to good readers, independent of the ISI. These findings support our previous study, which tested sequential processing abilities of PRD for a sequence of two stimuli in a same–different judgment task (short temporal task; Ram-Tsur, Faust, & Zivotofsky, 2006).

The findings of the present study indicate that when PRD and good readers are compared on the performance of a same–different judgment task (long temporal task) for a sequence of three stimuli, no significant difference between the two groups is found. These findings can be explained by the specific design used in our task in which the first two of the three Gabors always had the same orientation. This design may reduce the load on working memory. To further clarify this point, we refer to one orientation of the Gabor as "a" and to the other orientation of the Gabor as "b." In a "same" trial, we assume that the process involved in the comparison of a sequence of three Gabors with the same orientation is very similar to the comparison of a sequence of two Gabors with the same orientation. However, on the "different" trial there is a difference between the comparison of two sequential Gabors and three sequential Gabors. On the long temporal task we included in our analysis only trials with a sequence of "a–a–a" on the "same" condition and "a–a–b" on the "different" condition (see the Method section). We suggest that a comparison of "a–a–b" is easier than a comparison of "a–b," because in the former comparison the second stimulus reinforces the representation of the first stimulus in short-term memory, thus facilitating the comparison with the third Gabor. Because good readers do not suffer from sequential comparison deficits, this facilitation does not necessarily influence their comparison abilities as it might do for the PRD group. To test this claim, we measured the performance on a sequential task in order judgment accuracy—a task that is a more demanding in terms of working memory requirement—for three sequential Gabors with a forced choice containing three alternatives. In addition, the use of same–different judgments instead of order judgments (i.e., two-alternative forced choice as opposed to three-alternative forced choice) may have created conditions that are less demanding in terms of working memory. Apparently, the comparison of three stimuli with same–different judgment requires even less working memory than the same–different comparison between sequences of two stimuli (short temporal task). We suggest that this further indicates that the low performance in sequential comparisons of PRD as compared to good readers is the result of high cognitive impairments and not of low-order deficits.

In addition, we found that temporal tasks (short temporal and long temporal accuracy tasks) do mediate groups and verbal working memory (digit span). However, in the opposite direction, we found that working memory mediates only same–different comparisons in a task involving sequences of two stimuli (short temporal task). This indicates that only the order judgment task is mediating to verbal working memory, suggesting that visual sequence memory precedes auditory sequence memory. However, we further suggest that for both tasks (same–different and order judgment) the poor performance of PRD may be attributed, among other things (e.g., attention abilities), to poor working memory that is responsible for comparing sensory stimuli (Mesulam, 1998).

We did not find mediating relationships between attention abilities and temporal task performance. It is worth noting, however, that we tested the participants only on two aspects of attention. Our PRD participants differed from the good readers only on CP (but not on FR performance). It has been suggested that PRD are sluggish in shifting attention as a result of their difficulty in disengaging attention (Hari & Renvall, 2001; Hari et al., 1999). Our measure of concentration performance included shifting attention abilities in addition to other variables such as impulsiveness (commissions errors). Perhaps a more "pure" assessment of attention shifting would highlight the hierarchical relationship between the attention component and the performance on sequential tasks. We further suggest that poorer performance of PRD on sequential tasks with less or no comparison requirement (such as a double-step saccade) and thus less dependence on working memory, may be explained by their dependence on attentional abilities. This, in turn, may explain some of the present study's findings that impairments of PRD in sequential tasks are limited to short ISI durations (e.g., Hairston et al., 2005; Hari et al., 1999; Ram-Tsur, Faust, Caspi, Gordon, & Zivotofsky, 2006; Tallal, 1980).

Relationship Between Perceptual and Cognitive Abilities

An early and still well-accepted theory suggests that perceptual impairments (low-level functions) in people with dyslexia are the cause of their impaired speech perception, which eventually leads to phonological processing and reading impairments (i.e., deficits in high-level functions, Stein & Walsh, 1997; Tallal, 1980; Tallal et al., 1993). This assumption is based on a 'bottom–up' explanation for the correlation between perceptual and cognitive abilities (Andersson & Lidestam, 2005; Warren, 1993a, 1993b).

More recently, it has been suggested that high-level deficits might account for phonological and perceptual deficits of PRD (Banai & Ahissar, 2004; Hari et al., 1999; Hari et al., 2001). In a review that minimized the direct effect of cognition on early vision it was nonetheless demonstrated that high-level deficits may account, albeit indirectly, for perceptual deficits (Pylyshyn, 1999). It has also been shown that sophisticated cognitive processing is much faster than has previously been demonstrated and, therefore, top–down mechanisms in visual processing may be enhanced (Michel, Seeck, & Murray, 2004). Moreover, there is evidence that the interaction of sensory cortical areas by gating sensory input is effected by top–down attentional modulation (Johnson & Zatorre, 2005).

Based on the above, and evidence for involvement of parietal areas in both working memory (Jonides et al., 1998; Reinvang, Magnussen, Greenlee, & Larsson, 1998) and attentional tasks (Hari & Renvall, 2001), we have suggested (Ram-Tsur, Faust, & Zivotofsky, 2006) a dual, high-level mechanism for deficits in sequential comparisons in PRD. This mechanism includes attention and memory dysfunctions, both located in the parietal lobe (Corbetta, Shulman, Miezin, & Petersen, 1995; Kibby et al., 2004; Posner, Walker, Friedrich, & Rafal, 1984), in PRD that accounts for their poor performance on sequential tasks (Amitay et al., 2002; Banai & Ahissar, 2004; Ben-Yehudah & Ahissar, 2004; Hari & Kiesila, 1996; Hari et al., 2001; Hood & Conlon, 2004). A recent fMRI study revealed that neuronal interactions between occipito-temporal, parietal, and frontal regions are task-dependent and stimulus-dependent (Mechelli, Price, Friston, & Ishai, 2004). This could explain why some studies found deficits only on rapid temporal sensory information processing in PRD. Thus, different tasks may lead to different neuronal interactions and, therefore, for tasks that require more attentional processing (and little or no working-memory processing), it has been found that PRD are impaired only when rapid sequential processing is involved. In contrast, on tasks that require both attention and working memory, PRD perform poorer on a wider range of shorter and longer ISIs owing to the cognitive impairment. However, it should be noted that there are several studies that did not find evidence of a deficit in rapid temporal processing in PRD (Heath et al.; 1999, Marshall et al., 2001; Nittrouer, 1999).

Can Visual Sequential Processing Be Used as a Probe to Working-Memory Deficits in Reading Disabilities?

Based on the new findings from the mediating analysis, we suggest that poor performance on visual sequential comparison tasks is a predictor for poor verbal working memory in PRD. However, we assume that temporal tasks with low or no comparison demands (e.g., same–different task with a sequence of three stimuli in which the second stimulus reinforces the memory of the first—long temporal accuracy task), cannot serve as a probe to verbal working memory.

A previous study has suggested that PRD, particularly those with poor auditory-frequency discrimination, were particularly poor in the sequential comparison paradigm. The authors showed that poor auditory-frequency discrimination probes PRD that have particularly impaired working memory (Banai & Ahissar, 2004). Taken together, these findings and those of the present study may allow for the generalization of our conclusion that poor performance of PRD on sensory sequential comparison tasks can probe for poor working memory. This linkage between sequential visual and auditory processing and verbal working memory may be important for understanding the reading process and the source of the difficulties experienced by PRD. According to this claim, PRD, as well as novice readers, decode written symbols and map them to their sounds sequentially. The working memory participates in this decoding process and in merging the sounds that have been retained to form a complete word (Baddeley, 1986).

We have demonstrated high correlations between performance on the task with the highest working memory demands (order judgment accuracy in the long temporal task) and reading-related skills. We therefore suggest that having a limited working memory for retaining visual and auditory information can interfere with remembering the right orthographic sequence pattern of the word and the right sequence/order of the sounds (phonemes) of the word. This limited working memory can thus lead to sequence order mistakes and/or confusions with similar words. These kinds of mistakes (reversal mistakes and exchanging with similar words) are very common in persons with dyslexia. Furthermore, those mistakes of the phonological output lexicon might interfere with the next level of the reading process, the semantic level, which affects reading comprehension.

Improving the working memory of PRD is essential for improving their language and reading abilities. Working memory is used to hold new information before it is discarded or transferred into long-term memory. Some memory strategies may increase the ability to retain more information thereby broadening the mental lexicon, which can in turn improve the speed and accuracy of word recognition.

Conclusions

We have suggested a dual-mechanism impairment in PRD in the performance of sequential tasks involving a comparison. In the present article we demonstrated that such deficits are not related to the ISI in a range of between tens of milliseconds and more than a second for sequences of two and three stimuli. This is true only when the task requires more than a minimal amount of working memory. In addition, we have tried to explain how the dual-mechanism impairment could explain some of the findings regarding temporal deficits limited to short ISIs. Furthermore, we showed that visual tasks involving sequential comparisons could probe for poor working memory in PRD.

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