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**Auditory temporal processing and working memory: Two independent deficits for dyslexia**

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Abstract

Purpose. Dyslexia is a neurocognitive disorder with a strong genetic basis, characterized by a difficulty to acquire reading skills. Several hypotheses have been suggested in an attempt to explain the origin of dyslexia, of which some have suggested that dyslexic readers might have a deficit in auditory temporal processing, while others hypothesized that dyslexia origins from a deficit in working memory. The current study was designed to test whether working memory and/or auditory temporal processing can predict reading ability in normal and dyslexic readers.

Method. Fifty-three adults diagnosed with phonological dyslexia and 46 normal reading adults were tested on reading regular words, auditory temporal order judgment, and backward digit span.

Results. For dyslexic readers, both auditory temporal processing and working memory were correlated with reading, even after controlling for their covariance. However, no correlation between reading measures, temporal processing and working memory was found for normal readers.
Introduction

Developmental dyslexia, also known as specific reading disability, is a neurocognitive disorder with a strong genetic basis, characterized by a difficulty to acquire reading skills, in spite of normal intelligence and sufficient reading opportunities. Developmental dyslexia affects about 5 - 10% of the population (e.g., Shaywitz, 1996). Over the past decades several different hypotheses have been presented to explain the origin of dyslexia. The classic, phonological hypothesis posits that dyslexia represents a difficulty to learn and store the relations between letters and their matching sounds. A number of studies have reported that dyslexic readers have difficulties in reading regular and non-words, spelling, and manipulating speech sounds (e.g., Ahissar, Protopapas, Reid, & Merzenich, 2000; Ben-Artzi, Fostick, & Babkoff, 2005; Ramus, et al., 2003; M. Snowling, Bishop, & Stothard, 2000), although they have normal intelligence and reading comprehension (e.g., Ben-Artzi, et al., 2005; Ramus, et al., 2003; M. J. Snowling, 2001). However, the phonological hypothesis limits the origin of the deficit in dyslexia to the ability to process speech sounds, while other theories have shown dyslexic readers to have other perceptual and cognitive difficulties which are also reflected in their lower ability to read.

In addition to phonological difficulties, additional difficulties in the auditory domain have been reported among dyslexic readers, e.g., difficulties in frequency and amplitude discrimination (e.g., Amitay, Ahissar, & Nelken, 2002; Banai & Ahissar, 2004; France, et al., 2002; Goswami, et al., 2002), and auditory temporal resolution (e.g., Ben-Artzi, et al., 2005; Tallal, 1980). The latter findings have led to a second hypothesis, the auditory temporal resolution hypothesis, originally was suggested almost 40 years ago, by Tallal and colleagues (e.g., Tallal, 1980; Tallal
& Piercy, 1973a, 1973b). This hypothesis posits that reading impairment is caused by a fundamental perceptual deficit in processing rapid, auditory or visual, stimuli (Ben-Artzi, et al., 2005; Ram-Tsur, Faust, & Zivotofsky, 2006, 2008; Tallal, 1980). According to this model, speech, which is composed of brief stimuli presented rapidly, is especially vulnerable to deficit in temporal processing since this impairment reduces the ability of the individual to perceive critical elements in the speech stream accurately. This inability, in turn, disrupts the establishment of a stable phonological code (Ben-Artzi, et al., 2005; Meyler & Breznitz, 2005; Tallal & Piercy, 1973b).

The auditory temporal resolution hypothesis predicts that reading impaired children would have difficulty in processing linguistic, as well as non-linguistic stimuli. Studies conducted by Tallal and others (e.g., Ben-Artzi, et al., 2005; Ramus, et al., 2003; Reed, 1989; Tallal, 1980; Tallal & Piercy, 1973a, 1973b) indeed show that reading impaired children have difficulties in identifying the temporal order of two stimuli when they were presented rapidly, but not when they were presented at a slower rates (Ben-Artzi, et al., 2005; Breier, et al., 2001). Since Tallal’s classical experiments, difficulties in temporal processing among dyslexic readers have been reported by a number of researchers using a variety of different paradigms of temporal resolution or acuity: 1) backward masking (Ramus, et al., 2003); 2) gap detection (Van Ingelghem, et al., 2001); 3) categorical perception of phonemes and non-speech analogues (Breier, et al., 2001; Reed, 1989; Serniclaes, Sprenger-Charolles, Carre, & Demonet, 2001).

Another hypothesis attempting to explain the origin of developmental dyslexia suggests that a deficit in working memory underlies reading difficulties in dyslexia, at least for a subset of
dyslexic reader who are found to have poor working memory, along with poor frequency and duration discrimination (Banai & Ahissar, 2004; Shankweiler & Crain, 1986). Working memory refers to the ability to process and manipulate information while being received, in order to use it for continuous behavior (Baddeley, 2003). Baddely hypothesized that working memory includes two systems of encoding sound-based (the phonological loop) and visual- and spatial-based information (the visuo-spatial sketchpad), as well as a generating system (the central executive). This latter system integrates the information received through the phonological loop and the visuo-spatial sketchpad, with already stored information, while also controlling and monitoring attention. According to the hypothesis, the primary function of phonological short-term memory is to support the long-term learning of the phonological structure of the language (Baddeley, Gathercole, & Papagno, 1998; Gathercole, Tiffany, Briscoe, & Thorn, 2005). Therefore, inadequate short-term memory will cause difficulties in learning the sound structure of new words (Gathercole, et al., 2005). In an attempt to understand the nature of working memory deficit among dyslexic readers, Jeffries and Everatt (2004) tested dyslexic children on a battery of tasks and found that the dyslexic readers were worse than the normal readers in the phonological loop and the central executive, but not in the visuo-spatial sketchpad. Based on similar findings, Archibald and Gathercole (2006) established the 'double-jeopardy' hypothesis for two independent deficits in working memory among children with language impairment: one in the phonological loop and one in the central executive.

Taken together, both the auditory temporal resolution deficit hypothesis and the working memory deficit hypothesis for dyslexia have competing suggestions for the origin of dyslexia that can explain the phonological deficits shown by dyslexic readers. Moreover, some
researchers suggest that working memory underlies the difficulties that dyslexic readers exhibit in auditory temporal resolution tasks, since it reduces the access to stored information (Banai & Ahissar, 2004). Several questions remain to be addressed regarding the reported deficits of dyslexic readers in working memory and auditory temporal resolution. First, to date, no study has actually tested the same dyslexic readers on both working memory and auditory temporal resolution to verify or reject the hypothesis that the deficit in auditory resolution is secondary to the deficit in working memory. Secondly, to date most studies have compared groups of normal readers with dyslexic readers on a number of measures. There are few if any studies that have been designed to test whether deficit in working memory and/or auditory temporal resolution can significantly predict deficit in reading performance. Therefore, the current study was designed to: 1) to evaluate both working memory and auditory temporal resolution in the same normal adult and dyslexic readers; and 2) to test whether working memory and/or auditory temporal resolution can predict reading ability in normal and dyslexic readers.
Methods

Participants

Fifty-three adults diagnosed with dyslexia (32 men, 21 women, mean age = 26.45, SD = 4.14), and 46 normal readers adults (30 men, 16 women, mean age = 24, SD = 2.84), participated in the study. The groups were similar in their educational status, but dyslexic readers were significantly older than the normal readers (p < 0.01). Diagnosis of dyslexia was based on having official diagnosis from a known diagnostic authority. Additional diagnostic tests that were conducted prior to participating in the study demonstrated poor phonological awareness among the dyslexic group (see Table 1). All participants were screened for normal hearing, and were native Hebrew speaking university or college students.

Reading

Regular words. Hebrew written language has both deep and shallow orthographies. In shallow orthography, the words are pointed creating high spelling-to-sound correspondence, and in deep orthography the words are unpointed, creating a low spelling-to-sound correspondence (Frost, 1994). To evaluate reading skills, we used reading regular, unpointed words (Shatil, 1995b) (For a detailed explanation about punctuation in Hebrew, see Ram-Tsur, Faust, & Zivotofsky, 2008). This task was designed to measure the amount of correct words per minute the participant is able to read. The participant was presented with a list of 217 solitary unpointed words. The words included low and high frequency words, words with different lengths (3 to 7 letters), verbs and nouns in different declensions, and homographs (i.e., words that can be read differently without punctuation). Each participant was asked to read the words as fast and correct as he can during
one minute. The score reflects the number of words per minute the participant read correctly (Shatil, 1995b).

Temporal processing

Dichotic TOJ. Subjects were presented with a pair of 15 msec duration 1.8 kHz tones, presented dichotically, (the first tone to one ear the second tone to the other ear) and were required to reproduce the order in which they heard the tones (left first then right; or right first then left). Tone combinations were presented in a random order with inter-stimulus interval (ISI) = 5, 10, 15, 30, 60, 90, 120 or 240 msec. This task minimizes the use and need for working memory, since the subject responds to a single pair of stimuli that are separated by no greater than 240 msec. The order of the presentation of ISIs was also random. Each ISI value was repeated 16 times, resulting in a total of 256 trials. After every 32 trials subjects received a short recess. Percent correct was recorded for each participant for each ISI, and threshold was obtained as the ISI for 75% correct.

Prior to experimentation, participants were required to fulfill a training phase. To familiarize the participants with the tones, participants were first presented with six examples of the tone in one ear, then six examples of the tone in the other ear. Training then proceeded with 24 trials, 12 tones in each ear, randomly intermixed. On each trial, the participant was required to identify the sound location by pressing the correct key. Visual feedback ("right"/"wrong") was provided for each response. In the last stage of the familiarization phase, the stimuli were presented in random order, with no feedback, until the participant met the criterion of 20 correct responses in 24 consecutive trials. Participants who were successful in the familiarization phase were then
presented with 16 pairs of stimuli in two possible patterns: left-right, right–left, with ISIs of 240 and 60 msec, resulting in 64 pairs of stimuli. Participants were to identify which pattern they heard by pressing the key for the first sound followed by the key for the second sound. Visual feedback was provided on all training trials. No feedback was provided during the experimental session (Ben-Artzi, et al., 2005).

**Working memory**

Working memory was measured using the WAIS-III subtest for backward digit span. In this subtest, the experimenter reads aloud lists of digits at a rate of one digit per second. Immediately after the set of digits had been read, participants were instructed to report back the digits verbally in the reverse order they heard it. Participants received two trials at each set size starting at set size 2 and working up to set size 8. Testing was terminated when participants were incorrect on both trials of a given set size. The digit backward score was the number of digit backward trials where all digits were reported accurately in the correct reverse order (maximum score of 14) (Wechsler, 1997). Backward digit span is a subtask of the digit span subtest, and was used as an indicator for working memory (Gathercole & Pickering, 2000)

**Apparatus**

Psychophysical tasks were presented using a Pentium1 personal computer that controlled the stimulus presentation and recorded responses and response time. Auditory stimuli used in the psychophysical tasks were generated by a sound-generator device (TDT-system II: Tucker-Davis Technologies, Gainesville, FL), and then presented binaurally through TDH-49 headphones. Tasks were programmed using Matlab™ software version 6.5.
Screening for hearing sensitivity was performed using Danplex DA64 or Maico Hearing Instruments Ltd MA32 audiometers.

Procedure.
The results reported in the current study are part of a larger study including a large battery of psychophysical, lingual and cognitive tasks. The experiment was carried out in three sessions, approximately two hours each. Two sessions included the psychophysical and cognitive tasks, in random order, and one session included all the lingual tasks. Order of sessions across participants was fully counterbalanced. Prior to experimentation, subjects received full explanation about the study, signed an informed consent, and were screened for normal hearing. Participants were paid an amount in NIS equivalent to $75 for completing the entire study. The study was approved by the Bar-Ilan University Institutional Human Studies Review Board.
Results

1. Reading, Working Memory and Temporal Processing for Dyslexic and Normal Readers

Table 2 presents descriptive and inferential statistics of reading, dichotic TOJ thresholds and digit span for dyslexic and normal readers. As can be seen, dyslexic readers showed poorer reading and working memory scores and higher dichotic TOJ thresholds.

2. Reading Ability and Temporal Processing / Working Memory

Figures 1 and 2 present associations between digit span and dichotic TOJ and the two reading variables. As can be seen, although the correlation with reading was significant both with dichotic TOJ ($r = -.49, p < .001$) and with backward digit span ($r = .38, p < .001$), the correlation patterns are different for dyslexic and normal readers. Therefore, separate correlation analyses for each group were performed. The results showed that whereas for normal readers, neither dichotic TOJ nor digit span were significantly correlated with reading ability ($r = -.13, p > .05$ and $r = -.04, p > .05$, respectively), both of them were associated with reading ability for the dyslexic readers ($r = -.38, p < .05$ and $r = .31, p < .05$, respectively).

In order to examine the unique contribution of temporal processing on reading capacity, beyond working memory ability, for dyslexic and normal readers, a multiple regression was conducted for dyslexic readers' data, with the number of words read correctly as the predicted variable. Table 3 shows that both digit span and TOJ threshold were significant predictors for regular words reading.
Discussion

Adult dyslexic readers were significantly poorer than normal readers in both the digit span test and in dichotic temporal order judgments. Furthermore, among the dyslexic readers, reading ability could be significantly predicted by their performance on the working memory and on the dichotic TOJ tasks, supporting these abilities as two independent factors that influence on reading skills. However, for the normal reader, performance on working memory and on dichotic TOJ was not related to reading ability.

Findings of auditory temporal resolution deficit in children with dyslexia and in adult dyslexic readers have been reported for the past four decades. The first reports were published by Tallal in what is considered now classic studies, in which subjects with reading and language impairments were required to reproduce the order of two high and low frequency brief tones, and made significantly more TOJ errors than normal readers when tones’ duration was relatively short (75 ms), rather than long (250 ms), and/or when the ISI was relatively short (150 ms), rather than long (300 ms) (Tallal, 1980; Tallal & Piercy, 1973a). Tallal’s results were replicated by a number of other researchers, who used similar and other methods and showed that dyslexic readers need longer ISIs to reproduce the order of two tones, and that this ability is related to their reading and phonological ability (e.g., Ahissar, et al., 2000; Ben-Artzi, et al., 2005; Breier, et al., 2001; Ramus, et al., 2003; Reed, 1989). However, these findings were not replicated by others (e.g., Adlard & Hazan, 1998; Hill, Bailey, Griffiths, & Snowling, 1999; Mody, Studdert-Kennedy, & Brady, 1997; M. J. Snowling, 2001). According to Tallal et al. (e.g., Tallal, 1980; Tallal & Piercy, 1973a, 1973b) dyslexic readers should have greater difficulty than normal readers in
discriminating the temporal order when the stimuli are separated by short ISIs. However, a number of studies have reported data that do not support this prediction. For example, Mody, Studdert-Kennedy and Brady (1997) found no difference between dyslexic and normal readers in reproducing the order of speech stimuli (/ba/-/sa/ or /da/-/ʃa/), when the stimuli were separated by short ISIs (10 to 100 msec). Although Marshall et al. (2001) did find dyslexic readers to be poorer than normal readers in reproducing the order of two 100 and 305 Hz tones, they did not find a group × ISI interaction, thus contradicting Tallal's prediction that dyslexic readers would have a TOJ deficit when the stimuli are separated only by short ISIs. Supporting the TOJ deficit hypothesis, in the current study we found that dyslexic readers' auditory temporal resolution threshold, as measured by dichotic TOJ, was significantly longer than the threshold of normal readers. These findings support previous studies showing an auditory temporal resolution deficit in dyslexia.

Based on the need for an adequate verbal working memory in order to read properly, several studies have examined working memory among dyslexic readers and have reported deficient verbal working memory in dyslexia (e.g., Banai & Ahissar, 2006; Brambati, et al., 2006; Gathercole & Pickering, 2000; Jeffries & Everatt, 2004; Ram-Tsur, et al., 2006, 2008). In the current study we also found that the working memory of dyslexic readers, as measured by the backwards digit span task, was significantly poorer than normal readers. These findings support the hypothesis of poorer working memory in a population of adult dyslexic readers.

The main symptom of phonological dyslexia is poor phonological processing which is reflected in difficulty of the dyslexic reader to analyze, synthesize and manipulate speech sounds (M.
Snowling, et al., 2000). Along his line, studies have shown poor basic phonological abilities among dyslexic readers, which, in turn gave rise to the hypothesis that the dyslexic readers were deficient only in phonological processing, but not in processing non phonological, auditory material (e.g., Mody, et al., 1997; M. Snowling, et al., 2000; Vellutino, Fletcher, Snowling, & Scanlon, 2004). In the current study we found, as expected, poor reading and phonological processing among dyslexic readers. However, we also found that working memory and auditory temporal resolution were not only poorer among dyslexic readers, but were independently associated with their reading ability. Thus, it appears that both working memory and auditory temporal resolution are basic abilities that are involved in reading among dyslexic readers (Banai & Ahissar, 2004; Ben-Artzi, et al., 2005; Reed, 1989; Tallal, 1980; Wright, Bowen, & Zecker, 2000). The complementary finding, that among the normal readers performance on a digit span task and on a dichotic TOJ task did not predict reading ability, leads to the suggestion that working memory and auditory temporal resolution are utilized by the dyslexic in the processing associated with reading in a manner that is not used by the normal reader. The lack of significant prediction of working memory and auditory temporal resolution among the normal readers for their reading ability cannot be attributed to a ceiling effect, i.e., to a shortened range neither in the digit span test nor in the dichotic TOJ task, since both distributions are normally distributed after the measures were transformed for the analysis. The immediate use of working memory and of auditory temporal resolution in the processing of reading by the dyslexic readers and the absence of their use among the normal reader therefore, suggest that the neurological mechanisms utilized by the normal reader are unavailable for use by the dyslexic reader. Similar findings were reported by Marshall et al. (2001) when testing young normal readers aged 6 to 13.
on auditory repetition test and on reading measures. Performance on their auditory repetition test was not related to reading measures when controlled for age and IQ.

The present findings indicate that not only are dyslexic readers deficient as a group both in working memory and in auditory temporal resolution when compared to the normal reader, but within the dyslexic group, the ability of the individual dyslexic to read, is significantly predicted by their performance on digit span and on dichotic TOJ. Although each of the two cognitive functions, i.e., working memory and auditory temporal resolution, was deficient among dyslexic readers and was related to their reading ability, the analysis indicated that working memory and auditory temporal resolution are not significantly correlated. These findings imply that deficiency in working memory and in auditory temporal resolution are two independent sources of difficulty for the dyslexic reader in processing written material. Two independent deficits each of which predicts reading ability in a population of dyslexic readers may help explain the large inter-individual differences found in this population (Ramus, et al., 2003; Reid, Szczerbinski, Iskierka-Kasperek, & Hansen, 2007; Wright, et al., 2000). Similarly, while addressing the issue of the relatively large inter-individual differences found among dyslexic readers, Wright et al. (2000) suggested that reading problems are in fact multidimensional in nature. According to these and other investigators (Ramus, et al., 2003; Reid, et al., 2007) dyslexia may not be the result of a sole deficit, but, rather, the product of several degraded processes. They suggested that the deficits may be in both the auditory and visual processing of written material.

As noted above, the present findings support a conclusion that the dyslexic reader and the normal reader use different neuropsychological mechanisms to read. Similar conclusions were reached
in a number of imaging studies that concluded that dyslexic readers were utilizing different regions of the brain than normal readers, while reading. The imaging literature is not consistent in identifying the specific brain regions used by the normal reader and by the dyslexic reader. Nevertheless, the pattern of all these studies seems to indicate the use of different brain regions by the normal reader and the dyslexic reader while performing a reading task. For example, Conway et al. (2008) found dyslexic readers to have greater activation in auditory cortex than normal readers while performing auditory working memory tasks. Brambati et al. (2006) found less activation in the posterior temporal cortical regions of dyslexic than in normal readers while reading. According to Silani et al. (2005), the decrease in activation seems to be related to altered density of grey and white matter in this region. Temple (2002) reported that dyslexic readers had decreased activation in the left temporo-parietal cortex in response to phonological stimuli and decreased activation in left prefrontal cortex in response to rapid auditory stimuli. Brosnan et al. (2002) showed that dyslexic readers had less activation than normal readers in pre-frontal regions, while performing tasks that are considered to be dependent on pre-frontal processes. Vasic et al. (2008) suggest that hyper activation in other regions (for example, inferior frontal regions) may be caused by an attempt to compensate for the decrease in other regions (for example, left parieto-temporal and occipito-temporal regions). In summary, while there does not seem to be any consistency among the various studies, as to the specific brain regions involved in reading by normal readers and by dyslexic readers, all of the studies appear to conclude that the two populations use different brain regions to perform reading-based tasks.

Several questions may be raised regarding the present findings. The data indicating that reading ability by the dyslexic reader can be predicted by the performance on working memory and on
auditory temporal resolution, whereas the reading ability of the normal reader cannot be so predicted were generated by adult normal readers and adult dyslexic readers. The question may then be legitimately raised as to whether the same difference would be found whether the comparison made between the very young, beginning normal versus dyslexic readers or not. Perhaps all readers, both normal and dyslexic begin reading by using neuro-psychological mechanisms that are dependent upon working memory and auditory temporal resolution and only begin to differ when the reading skills become well established. A second question that may be raised is whether there are circumstances or conditions that would also cause the normal adult reader to use and be dependent upon working memory and temporal resolution similar to the adult dyslexic reader (e.g., learning to read a foreign language) so that the reading ability of the normal reader would also be predicted by working memory and auditory temporal resolution.
References


Table 1

*Means and SDs of Dyslexia Diagnostic Tests for Dyslexic and Normal Readers*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Dyslexic readers</th>
<th>Normal readers</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>Phoneme deletion</td>
<td>16.08</td>
<td>3.37</td>
<td>19.43</td>
</tr>
<tr>
<td>Spoonerism</td>
<td>3.60</td>
<td>1.76</td>
<td>5.52</td>
</tr>
<tr>
<td>Pig Latin</td>
<td>3.43</td>
<td>2.35</td>
<td>5.09</td>
</tr>
</tbody>
</table>

*Note:* ***p < .001*
Table 2

*Means and Standard Deviations of Reading Variables, Dichotic and Gap Detection Thresholds and Digit Span for Dyslexic and Normal Readers.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Dyslexic readers</th>
<th>Normal readers</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>Skew</td>
</tr>
<tr>
<td>Regular words*a</td>
<td>80.75</td>
<td>26.83</td>
<td>-.26</td>
</tr>
<tr>
<td>Dichotic TOJ*b</td>
<td>126.58</td>
<td>77.39</td>
<td>.78</td>
</tr>
<tr>
<td>Sqrt Dichotic TOJ*b</td>
<td>10.13</td>
<td>2.94</td>
<td>-.02</td>
</tr>
<tr>
<td>Backward digit span</td>
<td>6.34</td>
<td>1.92</td>
<td>.42</td>
</tr>
</tbody>
</table>

*Notes:* a – Number of words read correctly; b – in msec

***p < .001
Table 3

Multiple Regression Predicting Number of Regular Words Correctly Read by Backwards Digit Span and Dichotic TOJ

<table>
<thead>
<tr>
<th>Variable</th>
<th>Beta</th>
<th>t</th>
<th>$R^2$</th>
<th>F</th>
<th>$R^2_{change}$</th>
<th>F_{change}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backwards digit span</td>
<td>.34</td>
<td>3.24**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dichotic TOJ</td>
<td>-.24</td>
<td>2.90**</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

** $p < .01$
Figure 1. Reading regular words by dichotic TOJ for Dyslexic and normal readers
Figure 2. Reading by digit span for dyslexic and normal readers