Temporal Processing Deficits in Hebrew Speaking Children With Reading Disabilities

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The purpose of this study was to assess to what extent specific reading disabilities and poor phonologic processing in children who read Hebrew, a primarily consonant orthography, are related to central auditory temporal processing deficits (TPDs).

Twenty-four Hebrew-speaking children (ages 10–13) with and without reading disabilities were asked to discriminate auditorily pairs of syllables (/ba/ vs. /pa/) that differ by voice onset time (VOT) only. Two paradigms were used, 1 with a short interstimulus interval (ISI) (50 ms) and 1 with a long ISI (500 ms). Event-related potentials (ERPs) were measured in response to the two syllables in an auditory oddball task.

Results showed significantly lowered accuracy, longer reaction times, and prolonged P3 latency among the group with reading disabilities compared with the control group. No significant differences were found between the short ISI task and the long ISI task. However, significant correlations were found between the phonologic processing tasks and the short ISI task.

These findings in the Hebrew language are consistent with findings from other languages and add support to the central TPD hypothesis of reading disabilities. The discussion highlights how investigating different orthographic systems can deepen our understanding of the role TPD plays in reading.

KEY WORDS: reading disability, temporal processing, evoked response potentials, auditory

Specific reading disability (RD) is a developmental reading disorder whose primary cause remains elusive (McArthur & Bishop, 2001). One of the main issues as yet unresolved is whether RD and the phonologic processing deficits that underlie it (e.g., Share, 1994; Stanovich, 1986; Torgesen, Wagner, & Rashotte, 1994) are related to the inability of the brain to process rapidly changing acoustic signals, as originally proposed by Tallal and her colleagues (e.g., Tallal, 1980; Tallal, Sainburg, & Jernigan, 1991). The present study aimed to assess to what extent deficits in phonologic processing in Hebrew speaking children with RD are related to central auditory temporal processing disorders.

According to the temporal processing deficit (TPD) hypothesis, individuals with developmental dyslexia are unable to process rapidly changing and serially ordered brief speech signals such as formant transitions, spectral noise associated with plosives, differences in voice onset time (VOT) in voiced and unvoiced consonants, and the like. Children with such deficits may have difficulties developing the phonologic skills needed to map phonemes to graphemes and to effectively and automatically decode and encode words while reading and writing. As demonstrated by

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various studies, these deficits are neither speech-specific nor auditory-specific, but rather reflect a more general problem involving processing rapidly changing temporal stimuli across all sensory modalities (Eden, Stein, Wood, & Wood, 1995; Heiervang, Stevenson, & Hugdahl, 2002; Helenius, Uutela, & Hari, 1999; Lovegrove, 1996; Rey, De Martino, Espesser, & Habib, 2002; Stein, 2001; Talcott et al., 2000; Tallal, 1980; Witton, Stein, Stoodley, Rosner, & Talcott, 2002).

Some researchers (e.g., Studdert-Kennedy & Mody, 1995) have challenged the TPD hypothesis, arguing that the deficits that have come under the rubric of auditory temporal processing may reflect deficits in discriminating or identifying speech stimuli. Rather than reflecting deficits in temporal perception itself, these deficits are merely manifested when stimuli are presented rapidly. This view has been supported by studies that failed to find lower level auditory processing deficits in individuals with RD (Bishop, Carlyon, Deeks, & Bishop, 1999; Mody, Studdert-Kennedy, & Brady, 1997; Nittrouer, 1999; Schulte-Korne, Deimel, Bartling, & Remschmidt, 1999). Also, some studies have demonstrated deficits in temporal order discrimination of nonverbal stimuli in individuals with RD, but these deficits were not specific to rapidly presented stimuli (Amitay, Ben-Yehuda, Banai, & Ahissar, 2002; Cacace, McFarland, Ouimet, Schrieber, & Marro, 2000).

Recently, Breier et al. (2001) showed that English speaking children with RD have difficulty in processing speech and nonspeech stimuli containing similar brief auditory temporal cues. To assess the perception of phonemic contrast, they used two syllables (/ga/ vs. /ka/) that are differentiated on the basis of their VOT contrast (i.e., the time between the release of a plosive and the beginning of vocal fold vibration). Several previous studies have demonstrated that English speakers with specific language impairments (SLI) and/or dyslexia are significantly impaired in discriminating between CV syllables based on VOT differences (e.g., Elliott, Hammer, & Scholl, 1989; Manis et al., 1997).

In the present article, we were interested in exploring whether children with RD in Hebrew, a language that uses very different VOT values from those reported in English, will have difficulties in processing auditory cues of VOT. Different languages have different methods of phonetic realization of VOT that may be negative (vibration beginning earlier than the release-voicing lead), zero (vocal-cord vibration has begun simultaneously with the release of the plosive consonant) or positive (vibration beginning after the release-voicing lag). In English, for example, the original values of voiced stops were articulated as zero (0 ms) while voiceless stops were articulated as long-lag stops (73 ms) (see Manis et al., 1997). Hebrew-speaking individuals produce a long VOT lead of –100 ms for voiced plosives and a short to intermediate VOT lag of +20 ms for voiceless ones (Most, Tobin, & Mimran, 2000). As can be seen, the difference between voice and voiceless stops in English (i.e., 73 ms) is shorter than in Hebrew (i.e., 120 ms). Nevertheless, a difference of 120 ms can still be considered a brief cue. Moreover, in English voiceless plosives in a CV syllable are highly aspirated and as such they are provided with an additional cue to voicing. The noise associated with consonant release is much less pronounced in Hebrew and as such VOT may play a greater role in voicing distinction.

Another important question is whether impaired temporal processing has similar effects across different orthographical systems. Several researchers have argued that reduced sensitivity to dynamic auditory and visual stimuli among individuals with RD may contribute to the poor development of literacy skills irrespective of the language within which the reading difficulty is manifest (Laasonen, Service, & Virsu, 2001; Talcott et al., 2003). However, some studies have demonstrated relatively low correlations between processing of brief rapid stimuli and reading measures in some shallow orthographies with regular grapheme–phoneme correspondence (Helenius et al., 1999; Laasonen et al., 2001). In German (Schulte-Korne et al., 1999), for example, accuracy in speech discrimination between /ba/ and /da/ was not significantly correlated with phoneme counting. Similar results were obtained for Norwegian readers (Heiervang et al., 2002) when no significant correlations were found between rapid nonverbal auditory stimuli and reading ability. The results from those studies were different from those found in deeper orthographies (i.e., where the relation of orthography to phonology is more opaque) such as English (Breier et al., 2001) and French (Rey et al., 2002). The latter studies found that the ability to perceive brief cues of speech stimuli was highly correlated with phonological processing. Hence, it is plausible that readers of all alphabetic orthographies may be influenced by temporal processing abilities via the phonological processing skills. However, this mechanism is finely tuned to the particular structure of every language.

Hebrew might provide an opportunity to further examine the connection between temporal processing, reading, and the orthography of the language. Hebrew employs two versions of the same orthography. One version, *pointed* orthography, represents both consonants and vowels (Shimron, 1993). Consonants are represented by letters, vowels by diacritic marks (dots and strokes, usually below, sometimes above or in the middle of the consonant letters) as well as by letters. They provide complete, sometimes redundant, phonemic information. This version is used in reading and writing instruction in first grade, in children's books, in texts for immigrants, and in Biblical and poetic texts. Another version, *unpointed* orthography, represents all consonants, while vowels are partially and ambiguously represented by four letters

(AHWY). Unpointed orthography is the default version of written Hebrew, used across the board for most purposes, including school instruction (Ravid, 2001). When words are presented in context, Hebrew speaking readers read pointed and unpointed Hebrew words with the same speed and accuracy (Navon & Shimron, 1985).

Thus, reliance on consonants while reading in a primarily consonantal orthography such as Hebrew (Share & Levin, 1999) may be stronger in comparison with other languages where both vowels and consonants have an orthography representation. As such, Hebrew orthography may rely more on auditory temporal processing of brief and rapidly changing acoustic cues that represent consonants.

In the present study, we required children with and without RD to discriminate auditorily between pairs of syllables (i.e., /ba/ & /pa/) that can be differentiated on the basis of a brief temporal cue, the VOT. We also used two separate paradigms, one with a short interstimulus interval (ISI) (50 ms) and one with a long ISI (500 ms). These paradigms allowed us to explore to what extent the intrasyllabic differences between the consonants versus the rate of the presentation of the syllables differ between groups of readers. This question was raised because previous studies have shown that the slow-rate condition improves the performance of individuals with RD on a temporal order judgment task using a succession of syllables (Read, 1989; Rey et al., 2002).

Finally, behavioral data provide information about cognitive processes that are involved in the completion of sensory, cognitive, and motor tasks, but only at the conclusion of the processing sequence (Bentin, 1989). As such, they cannot specify all covert processing operations that contribute to a particular cognitive sequence, nor determine the relative processing times required for each individual stage (Brandeis & Lehmann, 1994; Johnson, 1995). Given these limitations, the present study included event-related potential (ERP) measures in an attempt to track the continuity of online cognitive activity during temporal processing. ERP methodology is based on electroencephalogram (EEG) data. It provides real-time imaging of neural system responses to sensory stimulation (Bentin, 1989). The data obtained from behavioral and electrophysiological measures are complementary, as each provides separate information about the same cognitive activity.

A number of studies have used ERP measures to distinguish between RD and control groups at various levels of information processing. Several studies have found evidence of delayed latencies of several ERP components among individuals with dyslexia when performing visual and auditory linguistic and nonlinguistic tasks (Barnea, Lamm, Epstein, & Pratt, 1994; Breznitz, 2001, 2002; Erez & Pratt, 1992; Fawcett et al., 1993; Neville, Coffey, Holcomb, & Tallal, 1993; Taylor & Keenan, 1990, 1999). These results have been obtained for the P300 (P3), which occurs in response to rare relevant events, and is associated with stimulus classification and working-memory processing (Barnea et al., 1994; Donchin, 1981). Previous work has shown that the latencies of the P3 covary with task difficulty (e.g., Goodin, Squires, & Starr, 1983). The more complex the task, the later the latency of the ERP components (Breznitz & Meyler, 2003).

Several studies have used ERP measures to test the temporal processing hypothesis. For instance, Neville et al. (1993) have reported comparatively longer N140 latencies and lower amplitudes among children with language and reading impairments who were assigned auditory tasks with short ISIs. Renvall and Hari (2002) found that auditory cortical responses of both hemispheres to speechlike stimuli were less reactive to acoustical changes in adults with dyslexia than in controls, as was evident from the weaker responses to the noise/square-wave transitions. These results suggested that adults with dyslexia may be deficient in processing acoustic changes presented in rapid succession within tens to hundreds of milliseconds. Moreover, Guttorm, Leppanen, Richardson, and Lyytinen (2001) showed that cortical activation evoked by consonant sounds varying in brief transitions was different already in infants at familial risk for dyslexia compared with the control group. The use of electrophysiologic methods is of special importance given that significant changes in brain activity associated with central auditory processing may not necessarily be perceptible (Allen, Kraus, & Bradlow, 2000).

Based on the above, the purpose of the present study was to test the following hypotheses: (1) Hebrew speaking children with RD will show an impaired ability to process rapid temporal stimuli at different levels of cognitive analysis (i.e., lower accuracy, longer reaction time, and prolonged ERP responses), (2) this impairment will be highly correlated with phonologic processing deficits, and (3) this impairment will be larger in the short ISI condition as compared with the long ISI condition.

Method

Participants

Twenty-two children participated in this study. Of these participants, 11 had been diagnosed with an RD; 2 children were girls and 9 were boys, ages 129–157 months (M = 141.2, SD = 8.32). The other group of 11 children had regular reading skills and served as controls; this group included 4 girls and 7 boys, ages 123–154 months (M = 140.3, SD = 8.19).

All participants were native speakers of Hebrew, from middle-class families. None had a history of neurological or mental illness. As per parental and teacher reports, none of the children had language development problems (i.e., SLI) or attention/hyperactivity problems. None received speech-language treatment. The two groups were matched on nonverbal IQ scores (Wechsler Intelligence Scale for Children—Third Edition [WISC-III]; Wechsler, 1991). The hearing level of all participants from the RD group was within normal limits (<20 dB HL at 250 Hz, 500 Hz, 1, 2, and 4 kHz). No audiometric testing was done on the control group as these children most likely did not have a hearing loss, based on their medical history, observation by a speech-language pathologist (the author), and parental reports. Participants were considered reading disabled if their achievement on the Battery of Reading test fell below the 16^{th} percentile. The Battery of Reading test, containing real-word and pseudoword decoding tasks, is widely used in Israel for reading diagnostic purposes. The real-word decoding test (Shalem & Lachman, 1998) comprises a list of 22 words and provides norms for children in fifth and sixth grades. The pseudoword decoding test (Deustch, 1994) includes 24 words and has preliminary norm results on relatively small groups of children from fifth and sixth grades. On both tests, participants were required to read aloud each word separately. The scores on these tests represent the number of real words or pseudowords read correctly.

In addition to the reading tests, all participants were given a phonological awareness test (Ben-Dror & Shany, 1996). In this test, the experimenter reads 20 words aloud and the participant has to produce a pseudoword, which is obtained by omitting a specified phoneme at the beginning, middle, or end of the word. The scores on this test represent the number of pseudowords correctly obtained.

Mean and standard deviation scores on the reading, phonological, and nonverbal IQ tests for each group are summarized in Table 1. As illustrated in the table, the RD group differed significantly from the controls on all tests except the nonverbal IQ test.

The temporal processing tasks. The test included two syllables, /pa/ and /ba/. We chose these syllables because they differ by one phonetic feature, voicing. VOT was measured with the Kay Elemetrics Computerized Speech Lab spectrograph analysis software. The VOT value of the voiced stimulus /ba/ was –105 ms and +15 ms for the unvoiced stimuli. Single syllable duration was 230 ms. These two syllables were recorded in a studio by a professional male announcer, whose average voice basic frequency was 115 Hz (sampling rate: 44 kHz; resolution: 16 bits; mode: stereo). The stimuli were presented at 75 dB SPL over an IBM-PC hi-fi speaker, which was situated 1 m behind the participant.

The temporal processing tasks were computerized. Two separate paradigms were used, one with a short ISI (50 ms) and one with a long ISI (500 ms). Each paradigm contained four pairs of stimuli: /ba-ba/, /pa-pa/, /ba-pa/, and /pa-ba/. Each pair was presented 20 times; thus, 80 pairs were presented in a random order in each paradigm ($4 \times 20 = 80$). The participant was required to make a same–different decision for each stimulus pair by pressing the right green key of a joystick if the syllables were identical, and the left red key if they were different. Prior to data collection on each task, participants were instructed to respond as quickly as possible after stimulus occurrence. In each experiment, 1,200 ms passed from the time the participant pressed the left or right key until the appearance of the next stimulus, with a maximum interval of 2,500 ms between pairs. The single stimulus duration and the short and long ISI were selected from various temporal processing studies (e.g., Heath, Hogben, & Clark, 1999; Merzenich et al., 1996; Tallal, Stark, Kallman, & Mellits, 1981; Tallal, Stark, & Mellits, 1985a, 1985b). The same–different decision task was based on Tallal's Repetition Test (Tallal, 1980). Reaction time measured from the onset of the second syllable in each pair until button press response and accuracy measured as the number of correct responses were automatically recorded by the computer program.

The oddball paradigm task. In this task, a series of 120 stimuli were randomly presented with an ISI of 2 s. The low-probability target was /ba/ and the high-probability target was /pa/ (we used the same stimuli as in the behavioral task). The low-probability target stimuli

Table 1. Baseline measures.

	RD (n = 11)		Control (n = 11)			
	M	*SD*	*M*	*SD*	*t*	Effect size
Reading measures						
Real words	9.58	1.98	17.91	2.07	9.49***	0.85
Pseudowords	9.45	4.37	20.73	2.19	7.65***	0.73
Phoneme awareness	12.00	2.52	18.54	1.29	7.64***	0.79
Performance IQ	104.80	9.96	110.45	17.99	0.90	0.03

***$p < .001$.

occurred 30 times and the high-probability target stimuli occurred 90 times. The participants were asked to press a joystick button as quickly as possible whenever they heard the sound /ba/.

Instrumentation

Twenty-two channels of EEG activity were recorded using a Bio-Logic Brain Atlas III computer system with brain-mapping capabilities. This system used a bandpass of 0.1–70 Hz, interfaced with a 20-channel 12-bit A/D converter. The EEG signals were sampled at a rate of 250 Hz (dwell time = 4.0 ms) beginning 100 ms before stimulus 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 within). Electrode impedance was kept under 5K, during data collection, by first prepping scalp areas with a mildly abrasive cleanser (Omni-Prep) and then using an electrolyte gel (Electro-Gel). Nineteen scalp electrodes were used: PF1, PF2, F7, F3, FZ, F4, F8, T3, C3, CZ, C4, T4, T5, P3, PZ, P4, T6, O1, and O2. All were referenced to an electrode on the left mastoid and grounded to the right mastoid. In addition, 1 electrode was applied diagonally below the left eye to monitor eye movements. Trial onset was marked on the EEG Oz channel via a positive polarity 5 mv pulse, delivered from an IBM-PC 386 computer. The stimuli were randomized using a commercial pseudorandomization software program. Each stimulus (i.e., each syllable) was coded by a different code, thus completely controlling the stimuli contributing to the signal average. The stimulus code was marked on the continuous EEG signal concurrently with stimulus presentation.

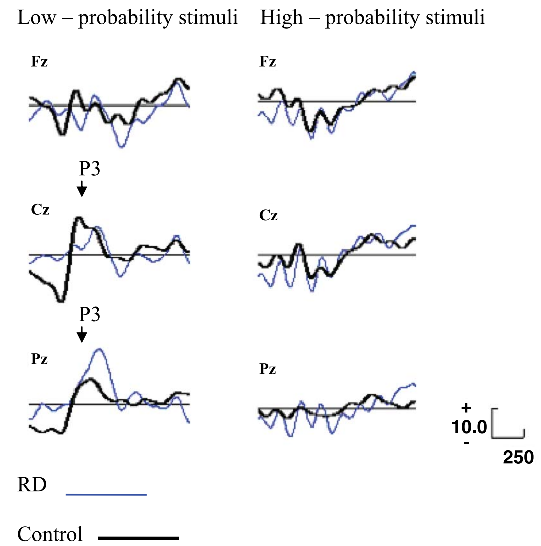
Signal averaging of the raw EEG data was performed off-line, and EEG data were separated into discrete trials. The recording window included a 100 ms prestimulus period, and poststimulus epoch length was 1500 ms. Stimuli were presented over the IBM-PC speaker, situated 1 m behind the participant played at 75 dB SPL.

Event-Related Potentials

ERPs were obtained for each participant. Only single trials that were free from eye movements and artifacts were averaged to obtain the evoked potentials. Eye movement corrections were done relative to the X1 and Fp1 electrodes. Averaging rejection rate was set at 20% relative to baseline.

Evoked responses elicited by low-probability stimuli and high-probability stimuli were averaged separately. After rejection of those trials that contained eye movements and artifacts, averages of individual trials for each participant were determined. The P3 component was well identified among all participants only for the low probability stimuli (see Figure 1). Twenty-five to thirty artifact-free trials were averaged for each participant. However, in a few cases only 16–25 artifact-free trials were obtained. These cases were included because their ERP peaks were well identified. Grand averages over participant were then performed for each of the 19 scalp electrodes.

Figure 1. ERP waves for low- and high-probability stimuli: A comparison between children with reading disabilities (RD) and controls.



A positive peak between 300 ms and 650 ms was identified as the P3 peak that was typically elicited within an oddball paradigm (Donchin, 1981). Latencies were measured from stimuli's onset to the first component peak. Amplitudes were measured relative to the mean voltage in each channel during prestimulus baseline.

Testing Sessions

Each participant was administered the experimental measures over two testing sessions of about 2 hr each at the Laboratory for Neurocognitive Research at the University of Haifa. During the first session, behavioral baseline measures were taken, and in the second session, the actual experimental tasks were delivered. All testing was conducted individually. Test presentation order was random across participants. When performing the behavioral tests, participants sat in a quiet room. During collection of electrophysiological data, participants were seated in a sound-attenuated room on an adjustable chair so that their heads could be positioned roughly parallel to the IBM-PC computer screen. Participants were connected to an Electro-cap, which required about 30 min of preparation and were instructed to remain quiet during

Table 2. Accuracy and reaction time (in milliseconds) on the temporal processing tasks.

	RD		Control			
	M	*SD*	*M*	*SD*	*t*	Effect size
Short ISI accuracy	67.40	8.75	76.63	2.25	3.24**	0.39
Short ISI reaction time	964.16	179.02	737.27	126.88	2.82*	0.38
Long ISI accuracy	65.90	12.46	76.09	2.24	2.54*	0.27
Long ISI reaction time	955.54	165.63	774.37	126.76	2.45*	0.29

*$p < .05$. **$p < .01$.

testing sessions, refrain from moving, avoid excessive eye movements, and avoid blinking as much as possible.

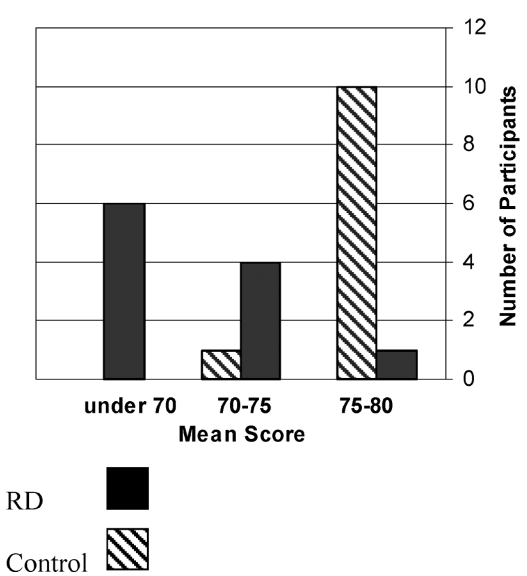
Results

Behavioral Measures

Comparing between the groups. The means and standard deviations of the scores and reaction times on the auditory task for the two groups are presented in Table 2. The RD group scored significantly below the controls on both the short ISI task, $t(20) = 3.24$, $p < .01$, $\eta^2 = 0.39$, and the long ISI task, $t(20) = 2.54$, $p < .05$, $\eta^2 = 0.27$. Also, the RD group had significantly longer reaction times than controls on both the short ISI task, $t(20) = -3.37$, $p < .01$, $\eta^2 = 0.38$, and the long ISI task, $t(20) = -2.83$, $p < .05$, $\eta^2 = 0.29$.

Group and task effect. Two factor repeated measures multivariate analyses of variance (MANOVAs) examined main effects of Group (RD × Control) × Task (Short ISI × Long ISI) for both accuracy and reaction time. Results of this analysis showed a significant main effect of group. For both conditions, the RD group showed significantly lower scores, $F(1, 20) = 13.47$, $p < .01$, and longer reaction times, $F(1, 20) = 12.32$, $p < .01$, as compared with the control group. However, no other significant main effects of task or interactions were found.

Figure 2. The distribution of the mean scores: A comparison between children with RD and controls.



Individual differences. In order to characterize an overall parameter of temporal processing performance for each participant individually, we computed a new mean score. Since there was no significant difference between scores of the short and long ISI tasks, we computed a mean score of both tasks. Figure 2 shows the distribution of mean scores in the two groups. At the two lower points of the distribution there are 10 participants from the RD group and only 1 from the control group. In contrast, at the highest points of the distribution there are 10 participants from the control group and only 1 from the RD group. These differences were statistically significant (Yates $\chi^2 = 11.64$, $p < .001$).

Electrophysiological Measures

ERP latencies. The RD and control groups were compared on latencies and amplitudes of the P3 component for the low-probability target stimuli in the oddball paradigm task, using general linear model MANOVAs. No main effect of group was obtained for the P3 latency. However, univariate analyses revealed significant between-group effects across all scalp sites (e.g., at electrode Cz for P3: $F[1, 20] = 12.46$, $p < .01$, $\eta^2 = 0.38$); see Table 3. P3 latencies occurred significantly later for the RD group than for the control group.

ERP amplitudes. No significant differences between groups were found for P3 amplitudes. See Table 3.

The Relationship Between Temporal Processing Tasks and the Reading and Phonological Tasks

As the present study aimed to investigate the relationships between temporal processing tasks and phonological skills, Spearman correlations were conducted between each one of the experiment tasks and

Table 3. ERP latency (in milliseconds) and amplitude (Cz electrode).

	RD		Control			
	M	*SD*	*M*	*SD*	*F*(1, 20)	Effect size
P3 latency	434.30	75.92	323.51	71.19	12.46**	0.38
P3 amplitude	8.83	11.29	9.56	10.28	0.24	0.001

**$p < .01$.

Table 4. Spearman correlation coefficients between temporal processing tasks and baseline measures.

	Phonological awareness	Reading pseudowords	Performance IQ
Short ISI accuracy	.71**	.66**	.06
Short ISI reaction time	−.59**	−.59**	.05
Long ISI accuracy	.36	.41	−.15
Long ISI reaction time	−.42	−.51*	.06
P3 latency at Cz	−.69**	−.42	−.39

*$p < .05$. **$p < .01$

the phonological awareness and reading pseudowords measures. P3 latencies at electrode Cz were selected to represent the ERP results in these analyses. Spearman correlations were also performed between the temporal processing tasks and the IQ measure. Results of these correlations are displayed in Table 4. Across all participants, significant correlations were found between both accuracy and reaction time of the short ISI task and both phonological awareness tasks ($r = .71$, $p < .001$; $r = -.59$, $p < .01$, respectively) and reading pseudowords ($r = .66$, $p < .01$; $r = -.58$, $p < .01$, respectively) tasks. A significant correlation was also found between reaction time of the long ISI task and reading pseudowords. Finally, significant negative correlations were found between the P3 latency and the phonological awareness task ($r = -.69$, $p < .001$). It appears that delayed P3 latencies, longer reaction times, and lower scores for the short ISI task were associated with more errors in both reading and phonological tests.

Discussion

The purpose of this study was to examine to what extent the temporal processing deficit (TPD) that was found in poor readers of English (e.g., Farmer & Klein, 1995) could be demonstrated in a sample of Hebrew speaking children with RD. Our interest in Hebrew readers stemmed from the assumption that the variability we find between studies may well have to do with differences between orthographies and specific speech characteristics. We predicted that Hebrew speaking children with RD would show difficulty discriminating auditorily between pairs of syllables that can be differentiated only on the basis of a brief temporal cue, namely, the VOT. We also predicted that the TPD would correlate strongly with phonologic processing deficits. Finally, we assumed that if the task were made harder by speeding up the presentation rate, an additional decrement in performance would be seen.

In general, both behavioral as well as electrophysiological data supported our predictions. At least half of the children from the RD group showed lowered accuracy, longer reaction times, and prolonged P3 latency when they were asked to differentiate between two CV syllables that were different in VOT of the consonant.

Our findings are consistent with other studies showing that children with RD have more difficulty than controls in processing rapidly changing speech stimuli (Breier et al., 2001; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Read, 1989; Rey et al., 2002). Our findings also extend those previous results by demonstrating that this deficit characterized Hebrew speaking children, thereby contributing further evidence for the assumption that TPD among individuals with RD appears in speakers of different languages (Talcott et al., 2003). Moreover, the present findings confirm our prediction of significant high correlations between the temporal processing tasks and reading and reading related tasks. These findings are consistent with other studies that demonstrated correlation between speech perception (Breier et al., 2001) or syllable discrimination (Rey et al., 2002) and reading related abilities. Although correlation does not imply causation, the significant correlations found between these tasks suggest that phonologic processing and reading skill development may be related to auditory processing of brief, rapidly changing auditory signals. The high correlations we found in the current study can also be attributed to the specific features of Hebrew. The temporal processing hypotheses specifically claimed that the TPD is more related to consonants, where there is a need to process rapid acoustic changes, than to speech sounds such as vowels that are more steady in nature (Tallal & Piercy, 1974). Thus, if the orthography of a language is primarily consonantal, as in Hebrew, it is not surprising to find significant correlations between the ability to distinguish between consonants and reading related skills. However, the present study of children with RD showed much higher correlations between TPD and phonological processing than those observed in Hebrew speaking adults with RD (Amitay, Ahissar, & Nelken, 2002). Thus, these findings suggest that higher correlations between TPD and phonological processing measures may best be found in younger individuals with RD. At the same time, such results emphasize the need for a cross-linguistic study that will use the same methods in order to assess the connections between TPD and reading in different orthographic systems in both children and adults.

The results from the current study showed that the TPD of some children with RD is expressed in slower neural activity underlying information update in working memory. These findings are in line with those of other studies (Breznitz, 2002; Breznitz & Meyler, 2003; Fawcett et al., 1993; Taylor & Keenan, 1990) reporting slow processing in the RD group beginning at the primary processing levels. A number of studies (Bradlow et al., 1999; Schulte-Korne, Deimel, Bartling, & Remschmidt, 2001) have shown significant preattentive deficit (i.e., lower amplitudes of the mismatch negativity [MMN] component) in processing of rapid temporal patterns among individuals with reading problems. In future studies it may well prove insightful to combine attentive and preattentive measures in order to trace the continuity of online brain activity during temporal processing. Combining our results with results from the MMN studies, we can assume, at least tentatively, that abnormalities in processing temporal information embedded in speech sounds, rather than phonetic information per se, may form the core deficit among individuals with RD (Schulte-Korne et al., 2001).

Several explanations have been offered for the relation between TPD and reading disabilities. Some authors have linked temporal processing deficits to abnormalities in the magnocellular system (e.g., Galaburda, 1999; Renvall & Hari, 2002; Samar, Parasnis, & Berent, 2002; Stein, 2001). This system, which governs motion and transmits information about stimulus change and general shape, is well suited for transmitting sensory information associated with the process of reading (Lovegrove, 1993). Presumably, the magnocellular system is abnormal in individuals with developmental reading and language disabilities, and therefore it does not allow efficient information processing across sensory modalities. There is some evidence for anatomical and physiologic abnormality of the magnocellular system in individuals with dyslexia (e.g., Galaburda, Menard, & Rosen, 1994; Renvall & Hari, 2002; Samar, Parasnis, & Berent, 2002). Yet other physiologic studies have provided evidence against the magnocellular deficits hypothesis, indicating that they are neither necessarily present, nor a cause of, developmental dyslexia (e.g., Amitay, Ben-Yehudah, et al., 2002; Hill & Raymond, 2002; Kronbichler, Hutzler, & Wimmer, 2002).

One possible explanation for the inconsistent results in the literature is that only a subgroup of individuals with RD had difficulty in processing rapidly changing auditory signals (Heath et al., 1999; Heath & Hogben, 2004; Tallal, 1980). In line with these results in the present study, 6 of the 11 (55%) children with RD made more errors than the worst score among the control participants. It has been hypothesized that individuals with RD who have severe problems with processing rapidly changing auditory signals might be the ones that also have SLI (Heath et al., 1999). In the present study we purposefully excluded participants with documented comorbidities such as SLIs and low IQs. Thus, we can at least assume that TPDs that relate to speech sounds are not restricted to children with general language problems. This assumption leaves us with the unresolved question of why some individuals with RD do and others do not have those deficits that are presumed to be at the heart of phonologic and reading deficits (Bishop & Snowling, 2004).

Other explanations for the TPD and RD relationship have been offered, including impairments in perceptual memory (Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001), prolonged attentional dwell time (Hari, Valta, & Uutela, 1999), and extraneous noise within the auditory channel (Amitay, Ahissar, & Nelken, 2002). In any event, children in this study were not asked to categorize stimuli or judge the order of presentation, but merely to compare between stimuli (in behavioral tasks) or detect when a change in stimuli had occurred (in ERP tasks). Those procedures were relatively simple and provided the opportunity to minimize memory load effects and reduce the need for comprehensive attentional resources to be recruited.

Another important methodological issue relates to the nature of the stimuli used in differentiating between those with and without RD. Blomert and Mitterer (2004) have argued that differences in central auditory processing of speech signals between individuals with and without dyslexia might be present when the signals are synthetic but not when they are natural. They attributed this difference to the fragile nature of the perceptual system of individuals with dyslexia. In the present study we used natural speech stimuli, yet performance was nevertheless worse in the RD group compared to the controls.

Finally, although we assumed that the deficit is due primarily to a difficulty in perceiving the brief VOT cue intrasyllabically, we expected to see some additional decrement in performance when we speeded up the presentation rate. However, we did not find any significant differences between the short and the long ISI conditions. Nevertheless, two interesting trends were found. First, the effect size of the short ISI condition was larger than the effect size of the long ISI condition. In other words, the gap between the groups on the short ISI task tends to be larger than the gap between groups on the long ISI task. Second, only the accuracy in the short ISI task was significantly correlated with the phonological task. Thus, it could be that more differences between conditions and groups could not be picked up because of the features of the stimuli (syllable duration of 230 ms in combination with an ISI range of 50–500 ms).

In sum, the results obtained in the present study are quite consistent with other studies and provide additional support for the TPD as a significant correlate of reading and reading related skills in some of the children with RD. The presence of the TPD deficit is consistent with the hypotheses that children with RD have a low level deficit in the auditory system and that this deficit could account for observed difficulty in perception of speech stimuli (Tallal, 1980). However, while the cue for discriminating between syllables with different VOT is temporal in nature, the current study did not address the question of the specificity of the deficit to temporal cues because no nontemporal control stimuli were included. This important question should be a focus for further research.

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