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Special issue: Research report

Auditory temporal processing and dyslexia in an orthographically consistent language

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ARTICLE INFO

Article history:
Received 20 September 2008
Reviewed 17 November 2008
Revised 24 December 2008
Accepted 14 April 2009
Published online 30 June 2010

Keywords:
Auditory temporal processing
Beat detection
Dyslexia
Frequency discrimination
Orthographically consistent language

ABSTRACT

We examined two hypotheses relating auditory processing to dyslexia in Greek, an orthographically consistent language. Study I examined the "P-center" or "beat detection" hypothesis (Goswami et al., 2002) in a sample of Grade 6 dyslexics, Grade 6 chronological age (CA) controls, and Grade 4 reading age (RA) controls. Study II examined the "temporal processing," or "rapid auditory processing" hypothesis (Tallal, 1980) in a sample of Grade 7 dyslexics, CA controls, and in two groups of CA matched children with low frequency discrimination or low tone sequencing performance. Both studies indicate that (a) as a group, dyslexic children did not perform significantly worse on auditory processing measures than the control groups; (b) measures of auditory processing mostly did not account for unique amount of variance in phonological processing, reading, or spelling; and (c) at an individual level of analysis, some of the dyslexic children experienced auditory temporal processing deficits. Implications on the importance of auditory processing in reading in orthographically consistent languages are discussed.

1. Introduction

Dyslexia is commonly described as a disorder manifested by difficulties in learning to read and spell despite adequate intelligence and conventional instruction (Snowling, 2000). Although there are several competing explanations for dyslexia, perhaps the most widely accepted causal factor is a deficit in the representation or processing of phonological information, typically referred to as phonological processing deficit (Catts et al., 2005; Vellutino et al., 2004). Phonological processing deficits are reflected in poor performance in tasks requiring the participant to isolate, blend, or manipulate speech sounds (phonemes), as well as in reading nonwords (a task requiring knowledge of grapheme-to-phoneme mappings). These deficits may stem from limitations in verbal short-term memory (Share and Stanovich, 1995; Snowling et al., 1997)

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doi:10.1016/j.cortex.2010.06.006

or poorly specified phonological representations (Elbro and Jensen, 2005; Griffiths and Snowling, 2002). Alternatively, phonological deficits may be secondary to a more basic auditory impairment or part of a general sensorimotor deficit (Goswami et al., 2002; Hari and Renvall, 2001; Ramus, 2003; Tallal, 1980).

The notion of an auditory perceptual deficit at the root of dyslexia goes back at least to the work of Ingram (1963), who suggested that children with dyslexia have difficulty in the identification and discrimination of auditory stimuli, including speech and nonspeech sounds. More recently, two major hypotheses have been put forward regarding the underlying mechanisms relating auditory processing to reading difficulties and dyslexia. The first one is known as the "temporal processing," or "rapid auditory processing" hypothesis (Tallal, 1980; Tallal and Gaab, 2006). According to this hypothesis, difficulties in phonological processing at the phoneme level result from a general auditory deficit in the perception and processing of stimuli that are of brief duration and/or presented in rapid succession. The second hypothesis refers to "P-center" or "beat detection" and concerns the ability to utilize amplitude and frequency modulation cues to the rhythmic structure of speech needed for the segregation of syllable onsets and rimes (Goswami et al., 2002). According to this hypothesis, failure to process syllable-level information about speech based on amplitude cues results in poorly specified phonological representations (Richardson et al., 2004). Both of these approaches suggest a deficit at a general level of auditory perception, not specific to speech sounds, and are typically investigated with tasks using nonspeech stimuli. More recently, Ahissar (2007) posited the "anchoring deficit hypothesis", according to which dyslexics "fail to benefit from stimulus-specific repetitions".

In the present study we are concerned with the applicability of these hypotheses to Greek, which is a transparent orthography (Seymour et al., 2003). More specifically, we focus on the potential of auditory processing skills to account for individual differences in reading.

1.1. *Rapid auditory processing and dyslexia*

Tallal (1980) suggested that children with reading difficulties are characterized by impaired processing of rapid auditory stimuli, which limits their phonological processing development and contributes to their reading problems. Much of this line of work has employed the "repetition test", a time-order-judgment (TOJ) task in which participants are first familiarized with two distinct sounds and are then asked to report the order in which the two sounds are presented. The critical variable is the interstimulus interval (ISI), which is the time interval between the two sounds, the brevity of which (no more than a few tens of msec) controls whether the task tests "rapid" or slow auditory processing.

Since then, poor performance on the repetition test has been repeatedly found for experimental groups broadly defined as reading-impaired, ranging from children (Cohen-Mimran and Sapir, 2006) and college students (Watson, 1992; Watson and Miller, 1993) with a diagnosed specific reading disability to adults with a history of reading problems (Ahissar et al., 2000). Performance on the repetition test has been found to be positively correlated with reading, phonological awareness, and receptive language from childhood through adulthood (Walker et al., 2006). A variant of this task (requiring report of the first of two sounds only) administered at preschool was found to significantly predict Grade 1 word reading accuracy after controlling for age, environment, memory, attentional vigilance, nonverbal ability, and speech/language problems (Hood and Conlon, 2004). Other measures of "dynamic" or "rapid" auditory processing, such as frequency modulation detection or binaural click integration, have also been found to differ between children (Boets et al., 2007) and adults (Hari and Kiesilä, 1996) with and without dyslexia.

However, a number of studies have failed to replicate these findings in at least some respect (Bretherton and Holmes, 2003; Gibson et al., 2006; Mody et al., 1997; Waber et al., 2001), leading to the conclusion that nonverbal auditory perception is not systematically related to reading ability, and that deficits in the repetition test are not a universal feature of individuals with dyslexia and do not cause their phonological problems. The relation between performance on phonological tasks or reading ability and auditory temporal processing is not always reliable (Heiervang et al., 2002; Kronbichler et al., 2002) and may only be found when children have language problems additional to their reading difficulties (Tallal and Stark, 1982). Nittrouer (1999) found only marginally significant differences between "poor" and "normal phonological processing" groups of children, and, importantly, the differences were not larger at shorter ISIs. Snowling (2001) found that some, but not all, children with dyslexia showed difficulties in auditory processing tests. In a more recent review of this literature, Rosen (2003) noted that only a proportion of the individuals with reading impairment consistently present nonverbal auditory processing deficits (this was the case even in the early studies of Tallal, 1980, and Reed, 1989). This proportion has been estimated by Ramus (2003) to be about 40%, consistent with a more recent estimate of "about one third" by Boets et al. (2007, p. 1614).

Moreover, the nonverbal auditory deficits apparently do not account for concurrent impairments in the perception of speech. Rosen and Manganari (2001) tested children with dyslexia using speech (consonant-vowel – CV, and vowel-consonant – VC) syllables and nonspeech analogues in which a brief sound was forward or backward masked by a longer sound preceding or following it, respectively. They found increased backward masking by the children with dyslexia and no difference in forward masking, but no corresponding asymmetry in the perception of CV/VC speech stimuli. Thus, it seems that auditory deficits often co-occur with the reading disorder and "may aggravate the phonological deficit" while "the nature of the phonological deficit and its relationship to auditory processing difficulties remain to be established" (Ramus et al., 2003, p. 681).

Despite the aforementioned inconsistencies, the repetition test remains one of the most robust indexes of nonverbal auditory processing that is associated with reading difficulties, "distinguishing [specific language impairment/specific reading disability] populations from controls in many studies" (Rosen, 2003, p. 520). However, the repetition test is a complex task. It requires participants to memorize and label two sounds, to perceive them and to retain their correct order, and then to respond with the appropriate sequence. A number of approaches have attempted to disentangle purported individual perceptual components, such as the identification of stimuli and the discrimination of different frequencies under masking conditions, while relaxing the memory demands posed by the sequencing. These studies have suggested that the temporal dimension is not the sole limitation of poor readers with auditory processing deficits. That is, while a “higher incidence of auditory processing problems in people with language disorders” is acknowledged (Rosen, 2003, p. 524), these problems cannot be characterized as resulting from a deficit in rapid auditory processing.

1.2. *Frequency discrimination (FD)*

The discrimination of simple tone stimuli that differ only in frequency has emerged as another aspect of poor auditory processing performance for some individuals with dyslexia. FD is typically measured as a “just noticeable difference” in frequency between two simple tones presented in succession. The duration of each tone and the ISI between them are beyond the “brief” or “rapid” range typically seen in the repetition task, on the order of a few hundred msec. Participants are asked to decide whether the two tones are “the same” or “different”. Therefore, some auditory memory requirements are posed by this task, in addition to the comparison of the auditory images of the two tones. However, there is no requirement to order, identify, or label the stimuli, making this a simpler task than the repetition test. More demanding task formats require participants to identify the “higher” or “lower” tone, or to select the frequency-matching tone from a pair, relative to a reference tone.

Deficits in FD for individuals with dyslexia were reported by de Weirdt (1988) and have been replicated several times (Amitay et al., 2002a; Halliday and Bishop, 2006; Heath et al., 2006). Young “poor readers” (Talcott et al., 2002) and adults with a history of reading problems (Ahissar et al., 2000) were also impaired in FD. Such deficits may account for difficulties in the perception of vowels, in contrast to rapid processing difficulties thought to affect the perception of stop consonants. According to Halliday and Bishop (2006), “[w]hile a variety of auditory perceptual deficits have been linked to low reading ability in both normal and reading-impaired populations…, deficits in [FD] are the most well attested” (p. 214). However, a number of studies have failed to replicate the findings for poorer FD of poor readers or individuals with dyslexia (Watson, 1992; Watson and Miller, 1993) or have found impaired FD only in a subset of individuals with dyslexia (Amitay et al., 2002b), particularly those who exhibited working memory deficits (Banai and Ahissar, 2004), or only when a “high”/“low” response format was required (Banai and Ahissar, 2006), or only for brief ISIs (Ben-Yehuda et al., 2004). Discrepancies in FD data have recently been re-interpreted in the light of task demands concerning the availability of a constant reference stimulus, which allow the general population to form an internal reference and forgo interstimulus comparison, in contrast to dyslexics, who appear unable to benefit from the repetition (Ahissar, 2007).

1.3. *Perceptual centers and rise time in dyslexia*

The second major hypothesis of lower level perceptual deficits in dyslexia is known as the “Perceptual center” or “P-center” hypothesis. P-centers are perceptual ‘moments of occurrence’ in speech that are points in time at which discrete perceptual events are felt to occur (Morton et al., 1976), and are determined by the rate of change of the amplitude envelope in lower frequency regions. Efficient P-center perception is considered to be crucial for representing two segments of any given syllable, namely the onset and the rime. If onset-rime awareness predicts reading acquisition, then a perceptual deficit in P-center processing may contribute to literacy problems.

To test this hypothesis, Goswami et al. (2002) developed a nonspeech task (called beat detection task) requiring children to decide whether an amplitude-modulated (AM) sound was comprised one element fluctuating in loudness, or of two different elements, a distinct beat and a background sound. In line with their prediction, dyslexic children performed significantly poorer than normally developing children, and precocious readers showed superior detection of AM beats. In addition, Goswami et al. (2002) reported that the beat detection task accounted for 25% of unique variance in reading and spelling, and 8–13% of unique variance in phonological processing tasks (rime oddity, RAN, and phonological short-term memory). Prompted by these findings, Goswami et al. argued that “the ability to process amplitude envelope onsets accurately may constitute the primary deficit in developmental dyslexia” (p. 10915).

Several follow-up studies have replicated Goswami et al. (2002) findings in different languages (*English*: Richardson et al., 2004; *French*: Muneaux et al., 2004; *Hungarian*: Surányi et al., 2009), with participants of different ages (*children*: Richardson et al., 2004; *adults*: Thomson et al., 2006), and with different AM tasks (*intensity*: Richardson et al., 2004; Thomson et al., 2006; *duration*: Richardson et al., 2004; Thomson et al., 2006; *rise time*: Halliday and Bishop, 2006; Hämäläinen et al., 2005; Richardson et al., 2004). Likewise, previous studies have examined the role of frequency modulation (at different rates, namely, 2–10 Hz) and speech perception in good and poor readers concluding that children with dyslexia tend to show difficulties in these types of tasks (Talcott et al., 2000; Witton et al., 1998).

However, other studies have also indicated that dyslexics may differ in some, but not all, beat detection tasks (Richardson et al., 2004), may not differ at all from their controls (see the Finnish data in Thomson et al., 2007), or differences may appear only when dyslexics are tested at a specific age (Halliday et al., 2008). In addition, Rosen (2003) re-analyzed Goswami et al.’s (2002) data and found that when groups were analyzed separately, there was no longer a significant relationship between beat detection and reading in the dyslexic group. In fact, significant correlations were found only in the age-matched control group, despite a highly significant difference in beat detection performance between the dyslexic and the age-matched control group. According to Rosen (2003), “the drawback of analyzing disparate groups of subjects as a single group is that any trait associated differentially with the groups (but not necessarily causally related to the main attribute of interest) will lead to significant correlations” (p. 519).

1.4. *The present study*

Auditory temporal processing continues to attract interest because it is conceived as a valid avenue to explore potential physiological causes underlying the phonological and reading deficits observed in dyslexia. As with most reading skills and difficulties, studies have been conducted mostly with English-speaking participants, with the exception of FD, which has been extensively studied with Hebrew-speaking children by Ahissar and her colleagues (Amitay et al., 2002a; Banai and Ahissar, 2004). Nonverbal auditory perception is by definition language independent, and therefore there should be no difference between languages in the profiles of persons with poor auditory skills. However, there may be differences between languages in the relation of auditory skills to reading skills or in the reliability of auditory skills as indicators of reading problems and dyslexia. Such differences may arise from different demands on auditory perception posed by the phonological properties of languages (e.g., vowel space density, consonant distinctions etc.) and from different demands on phonological representations in the process of forming graphophonemic mappings (Hadjibeganovic et al., 2010, this issue). Therefore, it is instructive to examine the relations between auditory and reading skills and the potential of auditory skills as indicators of dyslexia in languages with different phonological structures and orthographic transparency.

In contrast to English, Greek has a simple syllable structure and high orthographic transparency (Seymour et al., 2003). Therefore, it is of interest to examine (a) whether Greek children with dyslexia are impaired in the auditory processing skills that have been found to be poor in at least some English-speaking dyslexic children, (b) whether auditory skills correlate with reading skills in the general Greek student population and in children with dyslexia, and (c) whether the cognitive and reading profiles of children with low-auditory skills resemble the profiles of children with dyslexia. We report below two studies that were carried out in different student populations at middle school level when both auditory and reading skills are expected to be substantially developed. Study I focuses on the perceptual center hypothesis and compares rise time processing in children with dyslexia to that of chronological age (CA) and reading age (RA) matched controls. Study II is concerned with the rapid auditory processing hypothesis and examines temporal order judgment and FD for simple tones in children with and without dyslexia.

2. Study I

2.1. *Method*

2.1.1. *Participants*

Sixty-eight children who were native Greek speakers with no reported history of speech, language, attention, neurological, or hearing difficulties participated in this study. Grade 6 teachers were first asked to nominate children in their classroom experiencing reading and/or spelling difficulties. The children were then tested on two measures of reading fluency [word reading efficiency (WRE) and phonemic decoding efficiency (PDE)] and on a measure of nonverbal IQ (Block Design; WISC-III-R; *Greek adaptation*; Georgas et al., 1997). Children ($n = 20$, 17 males) scoring below the 25th percentile on both reading fluency tasks and within average (standard score of 7 or higher) on the nonverbal IQ task were included in the "dyslexic" group. Next, 24 Grade 6 children (seven males) with no known educational difficulties and no history of hearing or behavior problems, were roughly matched to the dyslexic group on CA, and 24 normally developing Grade 4 children (11 males) were matched to the dyslexic group on reading ability. The participants were also tested on verbal IQ (Expressive Vocabulary; WISC-III-R; *Greek adaptation*; Georgas et al., 1997) with no statistically significant differences being observed among the three groups, $F(2, 65) = 2.67$, $p = .077$. Participant characteristics are summarized in Table 1.

2.1.2. *Measures*

2.1.2.1. Auditory processing. *Amplitude rise time discrimination* (*ARTD*). In this task, children were presented with two AM sounds of equal modulation frequency and duration, but with different rise times. The children were asked to decide which of the two sounds had a sharper beat (shorter rise time). Forty stimuli of 3570 msec duration were used for this task. Within each trial sounds were presented with an ISI of 500 msec. The two-interval-forced-choice (2IFC) task was administered by a custom software program developed by Dorothy Bishop at Oxford University. In this program the children were introduced to a pair of cartoon dinosaurs. It was explained that each dinosaur would make a sound and that the child's task was to decide which dinosaur made a sound with a sharper beat. Prior the beginning of the experimental trials, the children participated in five practice trials in which they heard sound pairs and were asked to judge which dinosaur sound had the sharper beat. The children were asked to respond verbally by telling the researcher the colour of the chosen dinosaur. Feedback on performance accuracy was provided by the software after every trial. Feedback was accompanied by further verbal explanation and reinforcement by the researcher during the practice period. The children then proceeded to the main task, in which stimulus presentation followed the adaptive More Virulent PEST procedure (Findlay, 1978) to track the child's performance. The standard reference stimuli always had the longest rise time value (300 msec). The maximum trial number was 40. Upon task completion a threshold value was calculated, indicating the smallest difference in rise time that could be discriminated by the child with 75% accuracy. Test–retest reliability with a subsample of students ($n = 23$) participating in an ongoing

Table 1 – Mean participant characteristics for Study I.

Group	Dyslexic $n = 20$		CA match $n = 24$		RA match $n = 24$	
	M	SD	M	SD	M	SD
Age in months	143.80	4.34	142.92	3.05	116.21	3.62
Block design[a]	10.25	1.80	11.12	1.96	10.38	2.10
Vocabulary[a]	5.15	2.80	6.29	3.04	7.12	2.61
WRE	41.30	9.29	77.04	10.14	42.92	4.86
PDE	26.55	4.72	46.96	7.01	26.62	2.60
TRF	91.35	28.69	43.56	7.59	96.58	17.00

a Standard score.

research project (from whom four children were also included in the present study) was .63. The interval between the testing times was approximately 1 month.

FD, fixed standard. Using the same adaptive procedure as above, children were presented with two-tone sequences in a 2IFC format. In each sequence, five 200 msec long simple tones were presented with a 50 msec ISI. Each tone had a 50 msec rise and fall time. One sequence in the pair consisted of tones with a constant frequency of 500 Hz (‘AAAAA’); the other sequence consisted of five tones alternating between the standard (500 Hz) frequency and a higher frequency (‘ABABA’). The task used a logarithmic continuum of 40 stimuli in which the maximum frequency difference between A and B was three semitones (Hz). The task was introduced by explaining to the child that each dinosaur would make a series of sounds and that his/her task was to decide which dinosaur made the sounds that went up and down. Test–retest reliability was .65 in the aforementioned retest sample ($n = 23$).

Simple auditory reaction time (*SART*). In this task the children were instructed to press a button on a laptop computer every time they heard a ding sound through their headphones. The test consisted of 15 ding sounds. Time to respond was automatically registered by the experiment programming software (Direct RT), and was used as the participant’s score. Test–retest reliability was .81.

2.1.2.2. Phonological processing.

Phoneme elision. There were three practice items and 29 test items: Two test items were compound words and required the participant to say the word without saying one of the constituent parts, six test items required the participant to say the word without saying one of the syllables (e.g., *λεμόνι*/lemoni/(lemon) without the /le/ is *μόνη*/moni/“alone”), and the remaining 21 items required the participant to say a word without saying a designated sound in the word. The position of the phoneme to be removed varied across those 21 items: Seven test items required the participant to delete the initial phoneme (e.g., *πόλη*/’poli/“town” without the /p/ is *όλη*/’oli/“all”); seven test items required deletion of the medial phoneme (e.g., *δίνω*/’ðino/“give” without the /n/ is δύο/’ðio/“two”), and seven the final phoneme (e.g., ζώα/’zoa/“animals” without the /a/ is *ζω*/’zo/“I live”). Testing was discontinued after three consecutive errors. A participant’s score was the number of correct items. Cronbach’s alpha reliability coefficient in our sample was .87.

RAN-Digits. This task required participants to name as quickly as possible a sequence of 50 digits from the set [2, 4, 5, 7, 9]. The digits were presented on a laptop computer screen and were arranged randomly in five rows with ten digits per row. Before the timed naming, each participant was asked to name the five individual digits in a practice trial to ensure familiarity. The corresponding names of digits in Greek are δύο (/’ðio/) for two, τέσσερα (/’tesera/) for four, πέντε (/’pede/) for five, επτά (/e’pta/) for seven, and εννιά (/e’ɲa/) for nine.

Word series. This task was adapted in Greek from the Word Series task in the Cognitive Assessment System (CAS; Naglieri and Das, 1997; *Greek standardization*: Papadopoulos et al., 2007). This task required the children to repeat a series of words in the same order that the examiner used. The series increased in length from two to nine words (e.g., μαμά-γάτα-δώρο /ma’ma/-/’γata/-/’ðoro/; “*mother*”–“*cat*”–“*gift*”). All nine words used were highly familiar and phonetically dissimilar. The number of word series recalled correctly constituted the score of the participant. The task contains 27 items. Testing was discontinued after four consecutive incorrect responses. Cronbach’s alpha reliability coefficient in our sample was .78.

2.1.2.3. Reading fluency.

WRE. The children were given a list of 104 words, divided into four columns of 26 words each, and were asked to read them as quickly as possible. A short, eight-word practice list was presented first. The number of words read correctly and the number of errors made within a 45-sec time limit was recorded.

PDE. The children were given a list of 63 nonwords, divided into three columns of 21 items each, and were asked to read them as quickly as possible. A short, eight-item practice list was presented first. The number of nonwords read correctly and the number of errors made within a 45-sec time limit was recorded.

Text reading fluency (*TRF*). The children were asked to read as quickly and as accurately as possible two short passages. The passages were selected so that one was well within the reading ability of almost all children, and the other was more challenging. The individual’s score was the total time to read both passages.

2.1.3. *Procedure*

Participants were examined in April/May of their 4th or 6th school year. Children were assessed in a quiet room in the schools during school hours by trained experimenters. Testing was divided into two sessions lasting roughly 40 min each. Session A consisted of block design, vocabulary, WRE, PDE and TRF. Session B consisted of digit naming, SART, elision, ARTD, word series, and FD. All participants received Session A first, followed by Session B. The order of the tasks within each session was fixed.

2.2. *Results*

Descriptive statistics for all variables, broken down by group, are shown in Table 2. A MANOVA with the three auditory processing tasks as dependent measures and Group (3) as a fixed factor showed no significant main effect of group (Wilks’ $\lambda = .896$, $F(6, 126) = 1.18$, ns). In contrast, a MANOVA with the three phonological processing tasks as dependent measures and Group (3) as a fixed factor showed a significant main effect of group (Wilks’ $\lambda = .676$, $F(4, 128) = 6.93$, $p < .001$).[1] Subsequent ANOVAs showed significant differences between the groups only in elision and RAN-Digits, with the CA group performing significantly better than the other two groups (see Table 2 for *F* values, significance levels, and effect sizes).

To explore the relationship between the three auditory processing tasks, phonological processing and reading

[1] We also ran the analyses specifying orthogonal contrasts (DYS + RA *vs* CA and DYS *vs* CA) in order to increase power. The results were identical to the ones reported for MANOVA.

Table 2 – Descriptive statistics for all the tasks used in Study I.

Group	Dyslexic $n = 20$		CA match $n = 24$		RA match $n = 24$		F	η^2	Group differences
	M	SD	M	SD	M	SD			
ARTD	24.84	12.05	20.01	11.54	19.76	11.09	1.31	.039	DYS = CA = RA
FD	19.98	10.25	16.13	10.34	21.82	11.61	1.73	.051	DYS = CA = RA
SART	365.50	190.55	350.34	138.56	383.51	149.46	.26	.008	DYS = CA = RA
Elision	22.40	4.04	26.96	1.82	22.29	4.36	13.02^{***}	.286	CA > DYS = RA
RAN-Digits	29.03	5.53	20.24	2.20	28.82	4.81	30.93^{***}	.488	CA > DYS = RA
Word Span	8.45	2.03	9.04	2.44	9.96	3.01	1.96	.057	DYS = CA = RA

Note. $^{***}p < .001$.

fluency, both zero-order and partial correlations controlling for age and IQ (average standard score of the two IQ tasks) were calculated using the data from children in all three groups pooled together ($n = 68$). The correlations are presented in Table 3. The analysis with the zero-order correlations yielded significant results only between FD, TRF, and elision. In the case of partial correlations, significant results were observed between TRF and ARTD. When the analysis was repeated with the dyslexic group alone ($n = 20$), the only significant correlations that emerged were between ARTD, PDE, and TRF.

To examine if auditory processing measures predict phonological processing and reading, a series of three-step fixed-entry multiple regressions were computed on the entire dataset. Reading fluency measures, phoneme elision, RAN-Digits, and Word Span were the dependent variables. The independent variables were (in a fixed order) (1) age,[2] (2) IQ, and (3) an auditory processing measure. The results of the hierarchical regression analyses are presented in Table 4. ARTD accounted for a significant 5% of unique variance in TRF. The other two basic auditory processing tasks did not explain any unique variance in any dependent variable. When these analyses were replicated with only the dyslexic participants ($n = 20$), ARTD accounted for 31% of the PDE variance and 33% of the TRF variance.

Next, to test the possibility that auditory processing deficits may only characterize a subgroup of dyslexics (Gibson et al., 2006; Hämäläinen et al., 2005; Ramus, 2003), we plotted the performance of each participant on ARTD and FD tasks relative to the CA group's mean and one standard deviation. Fig. 1 shows the results for each group (higher scores indicate poorer performance). The two graphs are similar and consistent with the idea that a small subgroup of dyslexic children presents deficits in basic auditory processing. However, subgroups of children from the CA and the RA groups also perform poorly in these auditory processing tasks, and, a subgroup of DYS children (three in ARTD and one in FD) performed better than 1 SD from the CA group's mean. These results suggest that auditory temporal processing deficit is not associated with dyslexia status in our sample.

[2] We also ran the analyses with group membership (dummy variable) entered in the place of age. Because the results were identical, we present in Table 3 only those with age as a control variable.

2.3. *Discussion*

Study I examined the P-center hypothesis in relation to dyslexia in a group of Grade 6 dyslexic children, CA matched controls, and RA matched controls. In contrast to the majority of studies conducted in English (e.g., Goswami et al., 2002; Richardson et al., 2004; Thomson et al., 2006) our results suggest that, as a group, dyslexic children do not exhibit a beat perception deficit. However, while measures of beat perception were mostly not unique predictors of phonological processing or reading in our whole sample (after controlling for the effects of age and IQ), ARTD did account for unique variance in decoding efficiency and TRF in the dyslexic sample. Individual level data indicated further that 45% of the dyslexic children performed worse than 1 SD from the CA's mean on ARTD and 35% on FD, percentages that are very similar to the 40% reported by Ramus (2003). When compared to RA controls performance, the first number was essentially the same, but the second dropped to 10%. These numbers suggest that a subgroup of dyslexics experiences problems with auditory rise time discrimination, but less so with FD, and that these problems may be associated with some measures of reading fluency.

These results are difficult to reconcile with the P-center hypothesis. First, beat perception measures were not significantly associated with the more direct measure of phonological representations, elision,[3] used in this study. If beat detection underlies phonological awareness, and phonological awareness is necessary for reading, then beat detection should be related to reading via phonological awareness which clearly was not the case in Study I. The majority of studies conducted in orthographically consistent languages, such as Finnish, Italian, or German have shown that phonological awareness may be important for reading, but only during the first 1 or 2 years of schooling (e.g., Georgiou et al., 2008; Leppänen et al., 2006; Papadopoulos et al., 2009). Researchers have hypothesized that the effect of consistent spelling-sound correspondences is sufficiently powerful to secure children's phonological recoding skills after a few months of reading experience regardless of their levels of phonological awareness (Papadopoulos et al., 2009). Why beat detection would then be

[3] Although elision is used as a measure of phonological awareness, it is possible that the children are using orthographic information to perform this task. This, in turn, may explain why ARTD correlated significantly with TRF and PDE in the dyslexic group.

Table 3 – Pearson zero-order correlations and partial correlations (in Parenthesis) between the auditory processing measures and the experimental variables in Study I for the entire sample.

	ARTD	FD	SART
WRE	−.12 (−.15)	−.23 (−.15)	−.11 (−.04)
PDE	−.05 (−.07)	−.15 (−.06)	−.09 (−.02)
TRF	.19 (.25*)	.29* (.23)	.12 (.08)
Elision	−.21 (−.23)	−.25* (−.20)	−.23 (−.15)
RAN-Digits	.05 (.07)	.22 (.16)	.12 (.09)
Word Span	−.06 (.04)	−.03 (.01)	.06 (.07)

Note. *$p < .05$.
$N = 68$.

Table 4 – Proportion of variance in reading fluency, Elision, RAN, and Word Span explained by the different independent variables in fixed-entry multiple-regression analyses (Study I).

Step	Variables	WRE	PDE	TRF	Elision	RAN	Word Span
		ΔR^2	ΔR^2	ΔR^2	ΔR^2	ΔR^2	ΔR^2
1.	Age	.17***	.19***	.20***	.10**	.12***	.03
2.	IQ	.05*	.05*	.01	.14***	.00	.00
3.	ARTD	.02	.00	.05*	.04+	.00	.00
3.	FD	.02	.00	.04+	.03	.02	.00
3.	SART	.00	.00	.00	.02	.01	.00

Note. +$p = .06$; *$p < .05$; **$p < .01$; ***$p < .001$.
$N = 68$.

related to reading when phonological awareness is not is difficult to explain within current theoretical models.

It is possible that the selection of the reading measures has affected the contribution of beat detection on reading in the normally reading sample. The dependent variables in the study were all fluency measures because even dyslexic readers reach high level of accuracy in consistent orthographies (Landerl, 1997). In contrast, previous studies in English used mainly accuracy measures (Word Identification, Nonword Reading). If reading fluency relies more heavily on orthographic processing (Barker et al., 1992) which, in turn, is more influence by visual temporal processing (Klein, 2002; McLean et al., 2010, this issue), then deficits in the auditory domain will not influence reading fluency.

3. Study II

3.1. Method

3.1.1. Participants

Two groups of children participated in this study. An unselected sample (93 males and 92 females, 136–167 months old) was recruited from eight public secondary schools, covering a wide socioeconomic range. Information about the study was given to the entire 7th-grade cohort in each school and all children whose parents signed the consent form were tested, without applying any additional inclusion or exclusion criteria.

A second group of 7th-grade children (18 males and 8 females, 143–159 months old) was recruited at a special diagnostic center operated by the Ministry of Health at the time of the study. Children in this group had at least average intelligence and were officially diagnosed with dyslexia on the basis of slow reading and poor spelling. No children with neurological, psychiatric, emotional, or behavior problems were included in the dyslexic sample.

3.1.2. Materials

All children were tested with a learning assessment scale (KLIMA) including reading, spelling, and cognitive ability tests as described in detail by Protopapas and Skaloumbakas (2007). Briefly, the measures included:

3.1.2.1. Nonverbal intelligence. The complete 60-item Raven's Standard Progressive Matrices test (Raven, 1976) was administered, noting the number of correct responses (raw score).

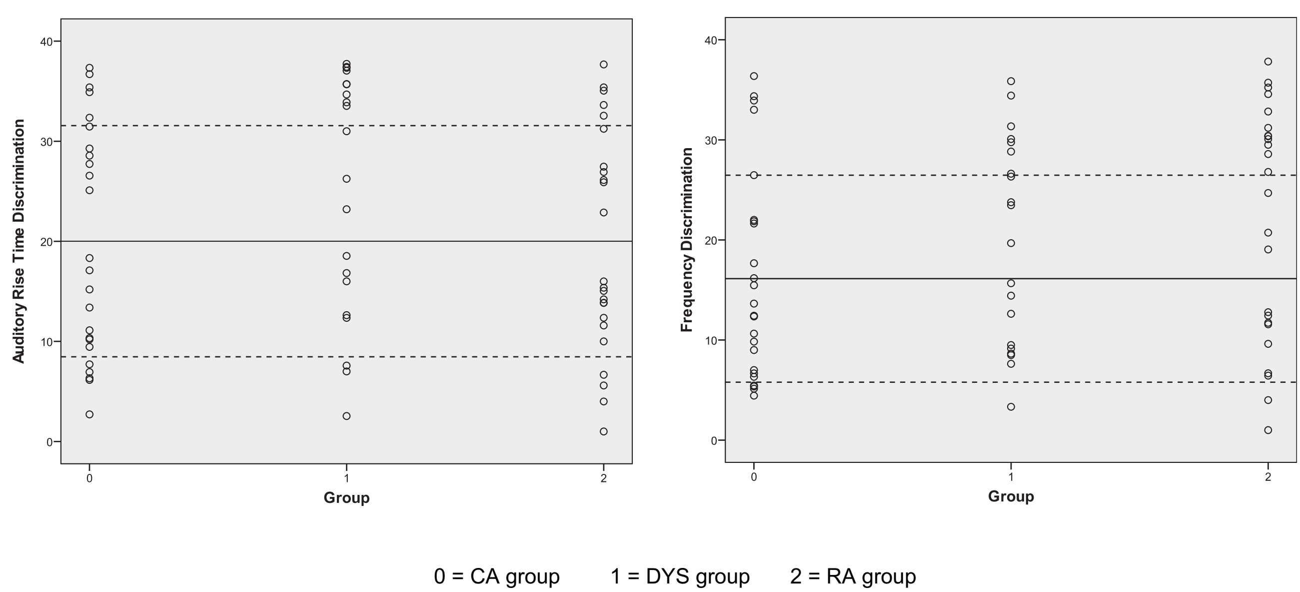

Fig. 1 – Scatterplots of the performance of the three groups on ARTD and FD in Study I.

3.1.2.2. Reading ability.

Pseudoword reading. Twenty pseudowords from Maridaki-Kassotaki (1998), 3–5 syllables long, were printed on a sheet of paper and the child was asked to read them. The number of incorrectly pronounced items and the total reading time were noted.

Word reading. Eighty-four words, 1–6 syllables long, spanning a wide range of printed frequency, were printed on a sheet of paper and the child was asked to read them. The number of incorrectly pronounced items and the total reading time were noted.

Text reading. Three age-appropriate passages, 72–90 words long, were read aloud by the child, then (for the last two only) read silently for 1 more min. Each passage was withdrawn and followed by 3–4 open-ended comprehension questions, the answers to which contributed predetermined points towards a comprehension score. The number of incorrectly pronounced words, the total reading time, and the total comprehension score were noted.

3.1.2.3. Spelling.

Word spelling. Twenty-two words, selected to provide a wide range of opportunities for grammatical and thematic spelling errors, were dictated individually for the child to write. The number of spelling errors was noted.

Text spelling. A 49-word age-appropriate passage, from Zahos and Zahos (1998), was dictated at a child-determined pace. The total number of spelling errors was noted.

3.1.2.4. Phonological processing.

Pseudoword repetition. Twenty pseudowords from Maridaki-Kassotaki (1998), 3–5 syllables long, different from those used in the pseudoword reading task, were pronounced individually by the experimenter for the child to repeat. The number of incorrectly repeated items was noted.

Phoneme elision. Each of 22 pseudowords was pronounced by the experimenter for the child to repeat, then a single target phoneme was presented and the child was asked to repeat the pseudoword with this phoneme removed. The number of incorrectly responded items was noted.

Speech discrimination. A subscale from AthenaTest (Paraskevopoulos et al., 1999). Thirty-six pairs of pseudowords were presented, 24 of which differed by a single phoneme while the others were identical. The child should respond to each pair by saying "same" or "different." The number of incorrectly classified pairs was noted.

Digit span (*DS*). From the Greek standardized version of the WISC-III (Georgas et al., 1997), noting the total number of correctly repeated sequences (raw score).

In addition to KLIMA, children were administered three psychoacoustic tasks to determine their temporal processing and spectral resolution thresholds. In each of these tasks an adaptive procedure was implemented, based on the accelerated stochastic approximation (ASA; Treutwein, 1995), to track the participant's performance and converge onto a 75% correct threshold. The ASA method was slightly modified to accelerate convergence in cases of inattention or lucky streaks. The procedure terminated after nine reversals, the last six of which were averaged to calculate the threshold.

The psychoacoustic tasks were modeled after Ahissar et al. (2000), and included:

FD, roving standard. Two 250-msec long pure tones with 2.5-msec square-sine on- and off-ramps were presented in each trial, at a constant amplitude (75 dB in the 16-bit waveform), separated by 500 msec of silence. The two tones were of the same frequency in 40% of the trials ("catch trials"), in which case the response did not affect the subsequent trial. In the remaining 60% of the trials ("test trials"), the two tones differed in frequency by an adaptively adjusted amount starting at 500 Hz and allowed to vary between 0 and 600 Hz. Individual tone frequencies ranged between 600 and 1400 Hz, and the mean frequency of each presented pair ranged between 900 and 1100 Hz, thus keeping the task around 1 kHz, but roving so as to prevent participants' forming strong auditory images for specific frequencies. The participant had to indicate, after presentation of each tone pair, whether the two tones were the "same" or "different."

Tone sequencing. There were two components to this "temporal processing" task. In the first component, "two-tone sequencing" (TP2), two 20-msec long tones with 2.5-msec square-sine on- and off-ramps were presented in each trial, at a constant amplitude (80 dB in the 16-bit waveform). The frequency of each tone was either 800 Hz ("low" or L) or 1200 Hz ("high" or H), randomly determined. The temporal distance between the two tones (ISI) was adaptively adjusted starting at 500 msec and allowed to vary between 0 and 600 msec. The task was to reproduce the auditory sequence (LL, LH, HL, or HH) by clicking on two displayed buttons, one of which produced a low (800 Hz) tone and the other a high (1200 Hz) tone. Two clicks were required for each trial, one corresponding to each presented tone. A response was considered correct when both tones were reproduced correctly, in the right order.

In the second component of this task, "three-tone sequencing" (TP3), there were three tones per trial and the child had to respond with three clicks, each corresponding to one tone, in the correct order. Tone parameters were identical to those used in the two-tone component, and temporal separation (the same in both ISIs) was adjusted in the same way within the same range.

3.1.3. *Procedure*

KLIMA was administered individually by trained research assistants in a quiet space at school for the school sample, and by a special education specialist at the diagnostic center for the dyslexic sample. Brief breaks were offered as needed. Testing lasted 60–80 min, typically spanning two successive class periods. Administration of the psychoacoustic tasks took place in the school computer laboratory, when available, or using laptops in other quiet spaces provided by the school, or the diagnostic center, always on a different day from KLIMA.

3.1.4. *Group analysis*

For the purposes of the present study, subgroups of children were formed meeting special criteria. The clinical sample ($n = 26$, 18 males) made up the "dyslexic" group (DYS). Three special groups were formed out of the school sample. The 15th percentile was identified in FD performance and in mean standardized tone sequencing performance. Children below these cutoff points formed the “low-FD” (LFD) and “low-TP” (LTP) groups, respectively, each with $n = 27$, of which 11 were males. Nine children belonged to both of these groups. Of the remaining 140 children in the school sample, expert clinical judgments were available for 86 (44 males) children, on the basis of their KLIMA performance (see Protopapas and Skaloumbakas, 2007, for details), that they were free from any learning difficulties. These children constituted the “nondyslexic” (ND) group.

3.2. *Results*

Table 5 shows the means (standard deviations in parenthesis) for the four groups on the learning assessment scale as well as the average psychoacoustic thresholds. Table 6 lists the results from between-group ANOVAs. As expected from previous studies of Greek Grade 7 (Protopapas & Skaloumbakas, 2007) and Grades 3–4 children (Protopapas et al., 2008), dyslexic children differed from ND children primarily on the reading and spelling measures and did not differ in psychoacoustic performance.

Fig. 2 shows the scatterplots of performance in the two most important components of the Greek dyslexic profile and the two auditory processing tasks for the entire school sample and the DYS group. In all four graphs, performance of the children with dyslexia occupies the entire range of the general population performance. There is no evidence for a bimodal distribution, as might be expected if some individuals were particularly impaired in their auditory skills while others were unimpaired.

It is, however, possible that children with auditory processing difficulties may present a poor reading performance profile even though they may not meet the diagnostic criteria of dyslexia. To test this hypothesis, we compared the ND and dyslexic children with the groups of low-auditory skills, to determine whether the low-FD and low-TP groups resemble ND or dyslexic children. The low-auditory groups differed from both DYS and ND in the psychoacoustic thresholds, with moderate to high effect sizes. However, many differences between ND and the low-auditory groups concern measures of little relevance to dyslexia. Both the low-FD and low-TP groups differed more from DYS than they differ from ND in the measures of reading speed, which are the most critical indicators of reading problems in Greek and most reliable diagnostic measures for dyslexia from early grades through secondary education (Papadopoulos, 2001; Porpodas, 1999; Protopapas and Skaloumbakas, 2007; Protopapas et al., 2008).

Because of differences in nonverbal intelligence between the two low-auditory groups and both the DYS and the ND groups, comparisons were repeated with the Raven score as a covariate (bottom part of Table 6). The differences between the DYS and the ND groups remained essentially the same. The effect sizes of the differences between DYS and the two low-auditory groups were not reduced by the introduction of the covariate. In contrast, effect sizes of the differences between ND and low-TP for the reading and spelling measures were substantially reduced, several comparisons failing to reach significance. In sum, the general effect of introducing the nonverbal intelligence as a covariate was that both low-auditory groups became more like the ND group than like the DYS group, especially in terms of the reading and spelling measures that are related to reading difficulties and dyslexia.

Table 7 presents the partial correlation coefficients (controlling for age and Raven score) between the psychoacoustic thresholds and all measures of the learning assessment scale, in order to examine whether auditory processing skills are related to poor reading and spelling performance only for some groups of children and not for the entire population. Most correlation coefficients are low and not statistically significant.

3.3. *Discussion*

The most important finding of Study II is the lack of a significant difference between children with and without dyslexia in

Table 5 – Task range and reliability information, and mean performance for each subgroup (standard deviation in parentheses) in Study II.

	Internal consistency (Cronbach’s α)	ND ($n = 86$)	Dyslexic ($n = 26$)	Low-TP ($n = 27$)	Low-FD ($n = 27$)
Age (months)		150.0 (3.9)	149.6 (4.1)	150.6 (5.5)	149.5 (4.8)
Nonword repetition errors	.64	4.2 (2.4)	4.5 (2.9)	6.1 (3.3)	5.4 (2.9)
Nonword reading errors	.84	3.2 (2.5)	7.6 (3.4)	5.8 (4.5)	5.4 (4.5)
Nonword reading time (sec)		40.6 (10.3)	74.8 (30.1)	49.0 (21.9)	47.1 (27.4)
Word reading errors	.95	1.2 (1.6)	9.2 (6.5)	6.4 (8.6)	4.4 (7.0)
Word reading time (sec)		85.6 (18.0)	154.1 (55.8)	106.4 (48.3)	102.9 (52.7)
Text reading errors		3.4 (2.5)	9.8 (5.9)	8.9 (10.6)	4.9 (4.7)
Text reading time (sec)		99.5 (16.5)	203.9 (71.9)	123.6 (66.2)	123.4 (54.3)
Reading comprehension score	.43	11.3 (3.3)	8.7 (2.3)	8.6 (3.3)	9.9 (2.9)
Text spelling errors		2.5 (2.7)	14.6 (8.4)	9.7 (13.2)	8.2 (12.1)
Word spelling errors	.87	1.0 (1.5)	5.9 (4.3)	5.1 (7.4)	4.1 (6.3)
Phoneme deletion errors	.79	4.4 (3.1)	7.5 (3.6)	7.1 (4.2)	7.0 (4.6)
Speech discrimination errors	.72	4.4 (2.4)	5.8 (3.4)	7.9 (5.0)	7.0 (4.3)
Raven raw score	.92	40.0 (8.3)	37.4 (7.2)	31.0 (10.4)	34.5 (9.2)
DS raw score		14.2 (2.8)	11.8 (2.0)	11.9 (2.5)	12.1 (2.7)
FD (Hz)		60.8 (39.7)	75.7 (69.6)	160.4 (121.1)	257.1 (78.6)
TP2 ISI (msec)		87.5 (85.7)	126.9 (132.9)	482.9 (105.1)	275.4 (193.1)
TP3 ISI (msec)		172.6 (127.1)	219.5 (125.7)	527.4 (84.4)	358.2 (176.5)

Table 6 – Group comparisons by ANOVA and ANCOVA (controlling for Raven) in the tasks of Study II.

	ND-DYS			ND-LFD			DYS-LFD			ND-LTP			DYS-LTP		
	$F(1, 110)$	p	η^2	$F(1, 111)$	p	η^2	$F(1, 51)$	p	η^2	$F(1, 111)$	p	η^2	$F(1, 51)$	p	η^2
Age (months)	.2	.653	.00	.3	.617	.00	.0	.962	.00	.4	.522	.00	.6	.448	.01
Nonword repetition errors	.3	.597	.00	4.4	.038	.04	1.2	.285	.02	10.0	.002	**.08**	3.2	.080	.06
Nonword reading errors	52.6	.000	**.32**	10.8	.001	**.09**	3.9	.054	.07	15.4	.000	**.12**	2.6	.111	.05
Nonword reading time (sec)	81.0	.000	**.42**	3.4	.069	.03	12.3	.001	**.19**	7.5	.007	.06	12.8	.001	**.20**
Word reading errors	111.1	.000	**.50**	15.5	.000	**.12**	6.8	.012	.12	29.5	.000	**.21**	1.7	.196	.03
Word reading time (sec)	97.5	.000	**.47**	6.8	.010	.06	11.8	.001	**.19**	11.2	.001	**.09**	11.1	.002	**.18**
Text reading errors	62.1	.000	**.36**	4.4	.039	.04	11.1	.002	**.18**	20.0	.000	**.15**	.1	.723	.00
Text reading time (sec)	157.3	.000	**.59**	13.1	.000	**.11**	21.3	.000	**.29**	9.7	.002	**.08**	17.9	.000	**.26**
Reading comprehension score	14.6	.000	**.12**	4.1	.044	.04	2.8	.102	.05	13.8	.000	**.11**	.0	.938	.00
Text spelling errors	135.6	.000	**.55**	16.5	.000	**.13**	5.1	.029	.09	22.9	.000	**.17**	2.6	.115	.05
Word spelling errors	80.6	.000	**.42**	18.0	.000	**.14**	1.5	.231	.03	22.9	.000	**.17**	.2	.624	.01
Phoneme deletion errors	18.1	.000	**.14**	11.4	.001	**.09**	.2	.686	.00	12.5	.001	**.10**	.2	.685	.00
Speech discrimination errors	5.4	.022	.05	15.5	.000	**.12**	1.2	.271	.02	23.8	.000	**.18**	3.1	.085	.06
Raven raw score	2.2	.144	.02	8.6	.004	.07	1.6	.216	.03	21.4	.000	**.16**	6.7	.013	.12
DS raw score	16.7	.000	**.13**	12.0	.001	**.10**	.2	.668	.00	15.4	.000	**.12**	.0	.918	.00
FD (Hz)	1.9	.170	.02	298.6	.000	**.73**	79.0	.000	**.61**	43.9	.000	**.28**	9.6	.003	.16
TP2 ISI (msec)	3.2	.076	.03	50.6	.000	**.31**	10.6	.002	**.17**	391.6	.000	**.78**	117.4	.000	**.70**
TP3 ISI (msec)	2.7	.101	.02	36.0	.000	**.25**	10.8	.002	**.18**	184.3	.000	**.62**	110.3	.000	**.68**
	$F(1, 109)$	p	η^2	$F(1, 110)$	p	η^2	$F(1, 50)$	p	η^2	$F(1, 110)$	p	η^2	$F(1, 50)$	p	η^2
Age (months)	.1	.780	.00	.0	.933	.00	.0	.918	.00	.8	.385	.01	.1	.742	.00
Nonword repetition errors	.1	.767	.00	2.5	.116	.02	.8	.377	.02	4.4	.039	.04	1.4	.240	.03
Nonword reading errors	49.4	.000	**.31**	9.1	.003	.08	4.9	.032	.09	8.2	.005	.07	7.4	.009	.13
Nonword reading time (sec)	80.6	.000	**.43**	4.4	.038	.04	11.6	.001	**.19**	7.0	.009	.06	12.7	.001	**.20**
Word reading errors	106.4	.000	**.49**	12.6	.001	**.10**	8.2	.006	.14	16.3	.000	**.13**	5.5	.023	.10
Word reading time (sec)	96.1	.000	**.47**	7.4	.008	.06	11.3	.002	**.18**	5.9	.017	.05	15.2	.000	**.23**
Text reading errors	58.6	.000	**.35**	3.1	.083	.03	11.3	.001	**.19**	8.2	.005	.07	2.3	.140	.04
Text reading time (sec)	152.0	.000	**.58**	12.9	.000	**.11**	21.0	.000	**.30**	5.2	.025	.05	21.8	.000	**.30**
Reading comprehension score	12.2	.001	**.10**	1.1	.287	.01	3.2	.079	.06	4.8	.031	.04	.0	.880	.00
Text spelling errors	134.9	.000	**.55**	12.4	.001	**.10**	7.2	.010	.13	10.7	.001	**.09**	9.0	.004	.15
Word spelling errors	76.7	.000	**.41**	13.5	.000	**.11**	2.7	.109	.05	12.0	.001	**.10**	2.3	.133	.05
Phoneme deletion errors	15.5	.000	**.13**	6.8	.010	.06	.5	.465	.01	3.9	.051	.03	2.0	.163	.04
Speech discrimination errors	4.6	.034	.04	12.4	.001	**.10**	.3	.563	.01	14.1	.000	**.11**	.2	.693	.00
DS raw score	15.4	.000	**.12**	10.7	.001	**.09**	.1	.725	.00	9.3	.003	.08	.5	.506	.01
FD (Hz)	1.9	.173	.02	284.6	.000	**.72**	76.1	.000	**.60**	42.4	.000	**.28**	9.7	.003	.16
TP2 ISI (msec)	2.8	.095	.03	44.9	.000	**.29**	10.6	.002	**.17**	309.0	.000	**.74**	97.9	.000	**.66**
TP3 ISI (msec)	2.4	.127	.02	29.4	.000	**.21**	10.2	.002	**.17**	138.6	.000	**.56**	91.3	.000	**.65**

Note. Effect sizes are shown in bold when $p < .0025$. Results of univariate ANOVA are presented in the top part of the Table and results of ANCOVA (with Raven raw score as a covariate) are presented in the bottom part of the Table.
DYS = Dyslexic.

either tone sequencing (a test of rapid auditory processing) or FD (a test of spectral resolution). This finding does not support an auditory processing deficit theory as a causal or contributing factor to dyslexia. It is a strong finding because the ND group excluded children already assigned to the LFD and LTP groups, to maximize sensitivity for the detection of differences.

Poor reliability of auditory processing measures is an unlikely cause of our failure to detect significant group differences. Test–retest reliability (Pearson's r between successive thresholds) in this age group has been previously reported on the basis of an independent retest sample ($n = 49$) at .49, .78, and .52 for FD, TP2, and TP3, respectively (Protopapas and Skaloumbakas, 2007). Moreover, the correlation between TP2 and TP3 in our school sample was .70, further attesting to at least half of the variance being reliable.

One possible explanation for the lack of a group effect might be that only some children with dyslexia present auditory deficits, while different skills are impaired in the other children. However, as noted above, no support for this hypothesis is seen in the distributions shown in Fig. 2. A more specific possibility has been raised by Banai and Ahissar (2004), namely that only dyslexic children with working memory deficits show auditory processing deficits. However, as seen in Table 7, there is no evidence for a significant correlation between DS and either auditory measure in the dyslexic (or in any other) group. Additional analyses, testing separately for auditory measure correlations with forward and backward DS in the DYS group also failed to uncover evidence for a significant relation (Spearman's ρ ranged between −.013 and .157 for DS forward and between −.025 and .152 for DS backward, $n = 20$, ns).

We observed some weak correlations between the auditory processing measures and reading *error* measures in the dyslexic group. Thus, it remains plausible that there is some specific relation between these skill domains, broadly consistent with a weak version of an auditory processing

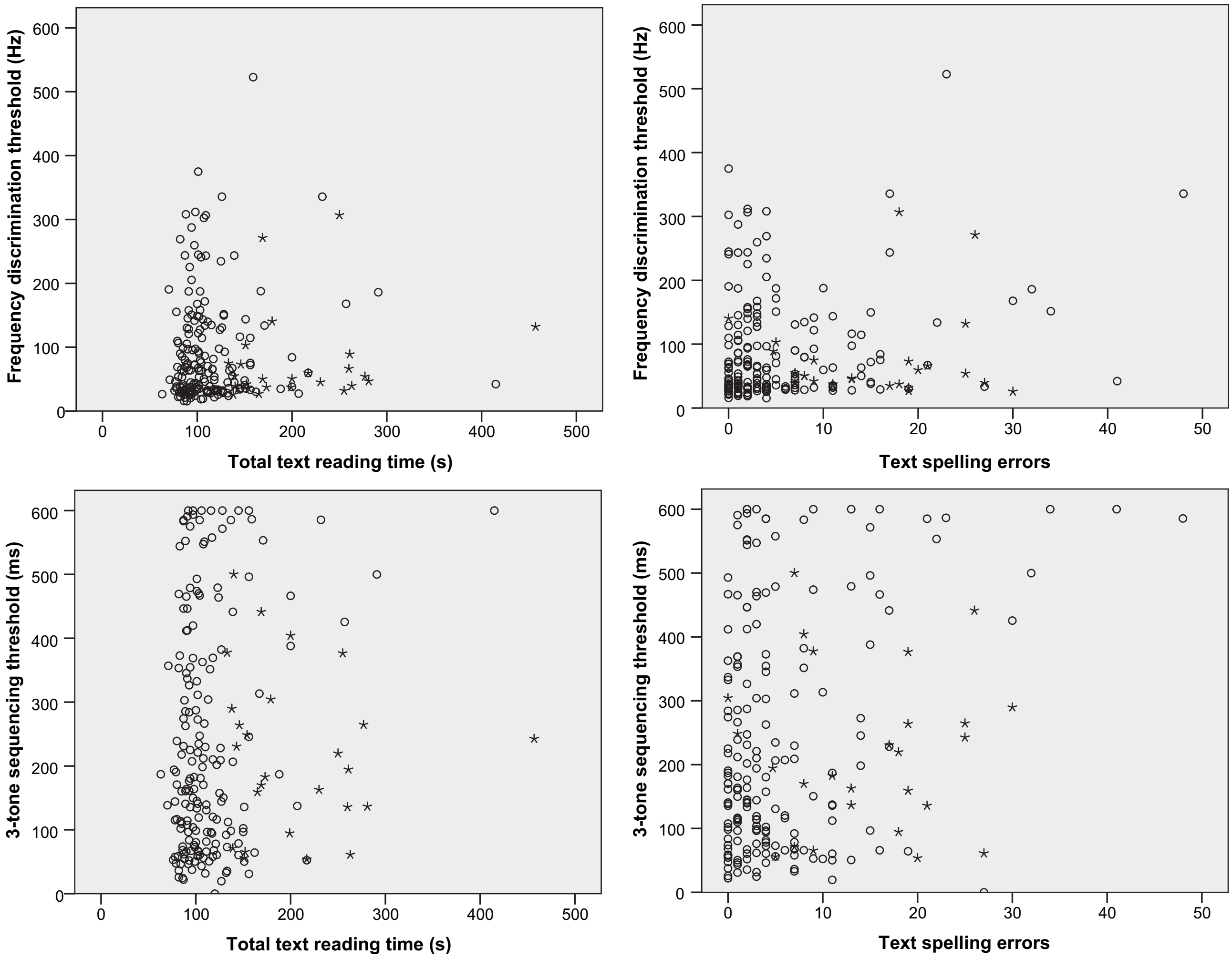

Fig. 2 – Scatterplots of text reading time and text spelling errors against FD and TP3 ISI thresholds in Study II. Children from the school sample (N = 185) are indicated with circles; children from the clinical sample (DYS, N = 26) are indicated with asterisks.

Table 7 – Partial correlations (controlling for age and Raven) between psychoacoustic thresholds and measures of the learning assessment scale, separately for each subgroup of children in Study II.

	ND (N = 86)			Dyslexic (N = 26)			Low-FD (N = 27)			Low-TP (N = 27)		
	FD	TP2	TP3	FD	TP2	TP3	FD	TP2	TP3	FD	TP2	TP3
Nonword repetition errors	.08	.07	−.05	.00	.10	.05	.02	.49	.32	.14	.33	.34
Nonword reading errors	−.02	.15	.05	.11	.34	.24	.34	.10	.38	.24	−.19	.30
Nonword reading time (sec)	.06	−.06	.14	.50	−.09	−.03	.10	−.22	.25	.17	.00	−.24
Word reading errors	.09	−.07	−.02	.36	.54	.25	.32	.32	.40	.28	.01	.10
Word reading time (sec)	.07	−.05	−.08	.41	.19	−.01	−.14	−.16	.20	−.02	.12	−.14
Text reading errors	.00	.06	.08	.45	**.75**	.57	.15	.02	.33	−.15	.12	.09
Text reading time (sec)	−.03	−.05	.01	.35	.16	−.07	−.06	−.02	.30	−.01	.02	−.12
Reading comprehension score	.08	−.01	−.04	−.08	.08	.22	−.11	−.38	−.10	.07	−.26	−.11
Text spelling errors	−.05	.03	−.09	.29	.11	.17	.07	.03	.30	.22	.05	.04
Word spelling errors	−.04	.06	−.15	.09	.05	.18	−.01	.12	.35	.07	.14	.18
Phoneme deletion errors	.07	.07	.24	−.17	.06	−.10	.11	.14	.25	.17	.10	.04
Speech discrimination errors	.32	.08	.19	−.03	.14	.27	.23	.53	.32	.28	.30	.09
DS raw score	.15	.20	.05	.08	−.13	.02	−.05	−.22	.00	.01	−.25	.31
FD (Hz)		.23	**.33**		.13	.27		.37	.41		.01	−.15
TP2 ISI (msec)	.23		**.43**	.13		**.63**	.37		**.58**	.01		−.23
TP3 ISI (msec)	**.33**	**.43**		.27	**.63**		.41	**.58**		−.15	−.23	

Note. Correlations in bold are significant to $p < .0025$.

hypothesis. The fact that correlations emerge across two reading measures (word and text reading errors) and all three auditory processing measures (FD, TP2, and TP3), surviving control for Raven, suggests that this pattern warrants further investigation. It is difficult to interpret why this should hold for accuracy and not fluency – however, taking this into account it is perhaps possible to understand why it is seen most clearly in the dyslexic group: The reading accuracy of the other groups is so high that there is little variance left to be accounted for by the auditory measures.

A second potentially interesting pattern concerns the relationship between the auditory measures and speech discrimination, broadly in line with the hypothesis that speech discrimination may be limited by spectral resolution. There is a corresponding correlation with nonword repetition as well, but not with DS, indicating that the effect, if it turns out to be robust in future studies with larger sample sizes, most likely concerns phonological processing of the speech input and not the retention of phonological information in working memory.

The characteristics of the "low-auditory" groups, in comparison to the dyslexic and ND groups, suggest that there is some weak relationship between auditory processing and reading beyond what is mediated by general cognitive ability. Some measures distinguishing low-FD and low-TP from ND are among those distinguishing children with dyslexia from those without dyslexia. Thus, there is some sense in which poor auditory processing performance is related to the dyslexic profile. On the other hand, both low-auditory groups differ from the dyslexic group in about the same measures, and, for most pairwise comparisons, the effect size between low-auditory and dyslexic group is larger than the effect size between low-auditory and ND group. Therefore, the low-auditory groups are decidedly ND, even though they seem to differ from NDs towards the dyslexic profile. In sum, we may tentatively conclude that although Greek 7th-grade children with dyslexia do not have poor auditory skills, children with relatively poor tone sequencing or FD do have somewhat poor reading skills warranting further investigation.

4. General conclusions

Auditory processing difficulties have been frequently reported in the literature for children and adults, yet the evidence to date remains inconclusive. In the present study, we have examined whether auditory processing deficits are related to dyslexia in two different cohorts of Greek school-age children with dyslexia. The findings from both studies support neither the "P-center" nor the "rapid auditory processing" hypothesis. Our findings also fail to support the "anchoring deficit hypothesis" because there were no group differences in fixed-standard FD (Study I) and tone sequencing (Study II), both of which are "reference paradigms" (Ahissar, 2007).

The failure to detect significant differences in auditory processing cannot be attributed to poor sample selection or atypical cases of dyslexic children. Our dyslexic groups showed significantly slower reading, poorer phonological processing, and poorer spelling or PDE than their same-age ND peers. These group differences accounted for more than half of the corresponding measure variance, attesting to good separation of the groups. The children with dyslexia did not differ from the ND control group in nonverbal intelligence, and any differences in vocabulary or comprehension were substantially smaller than their WRE differences. The profiles of the children in the two studies are similar to those of children with dyslexia previously reported for Greek (Porpodas, 1999) and English (see Vellutino et al., 2004, for a review).

Our auditory measures were selected to match those producing the most reliable and consistent results in the literature. This makes our findings somewhat surprising, as we did not observe group differences despite using identical stimulus and procedure configurations. The rise time measures that we adapted carefully in Greek for Study I have been developed and used by Goswami et al. (2002) and Richardson et al. (2004), and have reliably distinguished dyslexic groups from control groups in the past. Similarly, the FD and TOJ measures in Study II closely matched those employed by Ahissar et al. (2000), which revealed impaired performance in adults with a history of reading problems.

Despite the lack of between-group differences, it remains possible that auditory processing performance is related to reading skills, presumably via phonological processing, at least for a subgroup of the dyslexic children. A continuous relation between two variables does not imply that all individuals performing poorly on one of the two tasks are expected to perform poorly on the other as well. A weak or moderate correlation between reading and auditory processing is consistent with the latter being a causal contributing factor in the development of the former as long as it is not the only (or the dominant) factor. A direct causal relation between auditory processing, phonological processing, and reading skill may exist in the general population, but if alternative routes to reading failure are possible, this relation may not lead to significant group differences.

Reading is a complex cognitive achievement with many subskills and component processes contributing to its development. Consequently, students with dyslexia are likely to demonstrate many difficulties in skills that are necessary for successful reading. If some poor readers are deficient in auditory skills, others in visual skills, and yet others in different domains, there may be no group generalizability of any one of these particular deficits, hence no significant differences in between-groups comparisons such as presented in this paper. This idea is consistent with the pervasive finding that, when group differences exist, they typically arise primarily because of a subgroup of dyslexic participants performing particularly poorly, while others score well within the normal (even above average) range (Gibson et al., 2006; Ramus et al., 2003).

In sum, it is not at all clear theoretically how impaired auditory processing skills are associated with reading difficulties. The current examinations of auditory processing are clouded by seemingly conflicting findings, a result that could be attributed to at least three reasons. First, there are several methodological and statistical shortcomings in current and past research. Specifically, studies with children and adults alike have been limited by small sample sizes, floor or ceiling effects, or by use of auditory processing skill measures that confound task type with psychoacoustic domain. Future methodological and statistical improvements may help clarify the relations among potentially different types of auditory processing impairments and reading skills.

Second, the developmental courses of both auditory processing and reading must be examined longitudinally as developmental disorders require developmental explanations (Goswami, 2003; Karmiloff-Smith, 1998). An infant brain processing auditory signals differently may wire itself up differently for phonological processing later on, even though it may eventually overcome, or compensate for, any auditory processing deficit. Only a longitudinal design can reveal whether auditory processing affects speech perception and phonetic learning in such a way that the resulting phonological representations will or will not facilitate learning to read. Longitudinal studies have already begun to reveal relevant patterns that need to be explored in more detail in the future, focusing on specific critical aspects of auditory processing and phonological development (Benasich and Tallal, 2002; Leppänen et al., 2010, this issue; Lyytinen et al., 2004).

Third, the nature of auditory processing skills ought to be studied systematically and longitudinally across languages. Although it remains possible that both the “rapid auditory processing” hypothesis and the “P-center” hypothesis are on the right track as alternative developmental accounts of reading problems for possibly distinct subgroups of children, there is a need for convergent validity evidence with other non-English-speaking populations.

To conclude, our findings seem broadly congruent with the overall picture in the literature, which on the one hand includes a variety of inconsistent findings but on the other hand remains dominated by a pervasive link between reading and auditory skills. This link still defies a coherent theoretical explanation, as all specific hypotheses tested so far fail to account for the many contradictory findings of variable strength and locus. It remains unclear how and under what circumstances people with dyslexia also show auditory processing deficits. At present, it seems that the role of auditory processing in explaining reading problems is limited.

Acknowledgement

The authors would like to thank the children, teachers, and principals who were involved in the two studies. We would also like to thank Dr. Jenny M. Thomson for providing us the beat detection tasks used in Study I and for her comments on an earlier version of this manuscript.

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