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Auditory temporal structure processing in dyslexia: processing of prosodic phrase boundaries is not impaired in children with dyslexia

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Abstract Reading disability in children with dyslexia has been proposed to reflect impairment in auditory timing perception. We investigated one aspect of timing perception—*temporal grouping*—as present in prosodic phrase boundaries of natural speech, in age-matched groups of children, ages 6–8 years, with and without dyslexia. Prosodic phrase boundaries are characterized by temporal grouping of functionally related speech elements and can facilitate syntactic processing of speech. For example, temporary syntactic ambiguities, such as early-closure structures, are processed faster when prosodic phrase boundaries are present. We examined children's prosodic facilitation by measuring their efficiency of sentence processing for temporary syntactic ambiguities spoken with (facilitating) versus without (neutral) prosodic phrase boundaries. Both groups of children benefited similarly from prosodic facilitation, displaying faster reaction times in facilitating compared to neutral prosody. These findings indicate that the use of prosodic phrase boundaries for speech processing is not impaired in children with dyslexia.

Keywords Children · Dyslexia · Grouping · Phrase boundary · Prosody · Rhythm · Syntax · Timing

Introduction

Developmental dyslexia is a neurobiological disorder characterized by significant difficulty with reading and spelling despite adequate educational environment and intelligence.

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Prevalence rates ranging from 3 to 10 % have been reported (Pennington, 1990; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). It is widely accepted that a core deficit in developmental dyslexia is inadequate phonological awareness defined as an individual's awareness for the constituent sounds of words in speech (Bishop & Snowling, 2004; Bradley & Bryant, 1978; Savage, 2004; Snowling, 2000). In turn, impaired phonological awareness has been linked to a range of basic auditory and motor temporal-processing deficits (Corriveau & Goswami, 2009; Gaab, Gabrieli, Deutsch, Tallal, & Temple, 2007; Holliman, Wood, & Sheehy, 2010; Holliman, Wood, & Sheehy, 2012a; Huss, Verney, Fosker, Mead, & Goswami, 2011; Overy, 2000; Overy, 2003; Stein & McAnally, 1995; Tallal, 1984; Thomson, Freyer, Maltby, & Goswami, 2006; Wolff, 2002). Temporal processing influences many levels of language processing from segmental analysis of words to suprasegmental processing of sentence structure. For example, in natural speech, prosodic structure helps listeners to constrain syntactic interpretation (Beach, 1991; Cooper & Paccia-Cooper, 1980; Lehiste, 1973; Price, Ostendorf, Shattuck-Hufnagel, & Fong, 1991; Snedeker & Casserly, 2010). The present study examined the possibility that impaired temporal processing in children with dyslexia could result in a deficit in prosody processing that hinders syntactic interpretation and comprehension.

In general, prosody is defined as the "organizational structure" of speech (Beckman, 1996). This refers to its pattern of intensity and intonation changes as well as its temporal pattern (Beckman & Ayers, 1997; Pierrehumbert & Hirschberg, 1990; Speer & Ito, 2009). One characteristic of temporal patterns crucial in speech is *temporal grouping*, the perceptual association of auditory units due to their temporal proximity. In natural speech, temporal grouping is an element of *prosodic phrase boundaries* and links sentence elements into functionally related groups, resulting in perceptual breaks in the speech stream. Acoustically, this can be measured by the presence of a pause between groups of words and by the lengthening and change in spectral information of a pre-boundary word (Lee & Watson, 2011; Morgan, 1996).

Adults use prosodic phrase boundaries to parse syntactic sentence structure (Carlson, Clifton, & Frazier, 2001; Isel, Alter & Friederici, 2005; Kjelgaard & Speer, 1999; Nakamura, Arai, & Mazuka, 2012; Snedeker & Trueswell, 2003; Steinhauer, Alter, & Friederici, 1999; Steinhauer, Abada, Pauker, Itzhak, & Baum, 2010; for a review see Wagner & Watson, 2010). Furthermore, it is likely that early-school-aged children may already take advantage of this kind of prosodic structuring of syntax because it is well established that children rely heavily on prosody from birth on, e.g., to identify their native languages (Jusczyk, Cutler, & Redanz, 1993; Mehler et al., 1988; Nazzi, Kemler-Nelson, Jusczyk, & Jusczyk, 2000; Zhou, Crain, & Zhan, 2012) and to segment words from a speech stream (Johnson & Jusczyk, 2001a; Jusczyk, 1999). Moreover, language production and perception studies indicate that toddlers and young preschoolers already demonstrate an understanding of the syntactic function of prosody (Snedeker & Yuan, 2008a; Snow, 1994; Trueswell, Sekerina, Hill, & Logrip, 1999). However, children with dyslexia might show an impaired ability to disambiguate speech structures on the basis of prosodic phrase boundaries (Marshall, Harcourt-Brown, Ramus, & van der Lely, 2009).

The present experiment tested whether prosody would facilitate the interpretation of syntactic ambiguities in early-school-aged children with a diagnosis of dyslexia compared to typical developing (TD) readers. We tested children's efficiency in processing syntactic ambiguities when encountering prosodic phrase boundaries (facilitating) versus neutral prosody (baseline). To ensure that a potential facilitation of prosody was specific to syntactic processing, early- and late-closure sentences were presented (Fig. 1). Both early- and late-closure sentences comprise two noun–verb combinations for which adult listeners expect the second noun to be the object of the first verb (Frazier, 1987; Frazier, & Rayner, 1982). In the late-closure structure, this expectation is met and, independent of the prosodic rendition of the sentence, late-closure syntactic structures are processed quickly. However, in the early-closure structure, the noun

[When Patrick eats] [the peperoni pizza is very hot]

[When Patrick eats the peperoni pizza][it's very hot]

Fig. 1 Examples of early-closure (*above*) and late-closure (*below*) syntactic structures with relevant temporal grouping of constituents indicated by brackets. As the listener encounters "the pizza," two syntactic attachment options are possible; "the pizza" could be the object of the verb "eats" or of the later encountered verb "is." In early closure structure, a reanalysis of the sentence takes place at the point of encountering disambiguating syntactic information ("is"). This reanalysis is reflected in longer reaction times when processing early closure sentences compared with late closure sentences

following the verb violates the listener's prediction. Without prosodic facilitation, listeners can only disambiguate the syntactic structure at the end of the sentence, resulting in longer processing for early-closure structures. However, facilitating prosody, indicating the correct syntactic structure by a prosodic phrase boundary after the verb, reduces processing times for early-closure sentences (Kjelgaard & Speer, 1999). We hypothesized that TD children would display faster reaction times in the facilitating condition compared to the baseline condition for early-closure sentences but not for late-closure sentences, and that children with dyslexia may not show this facilitation effect due to their potential impairment in temporal processing.

Methods

Stimuli

We constructed sentences comprising *temporary syntactic ambiguities*, specifically early-closure and late-closure syntactic structures (Clifton, Frazier, & Carlson, 2006; Frazier, Carlson, & Clifton, 2006). These sentences comprise two noun–verb combinations in which the second noun is either the object of the first verb or the subject of the second verb (Fig. 1). A definite interpretation of the syntactic structure can only be done after encountering the second verb. In the absence of prosodic information, both early- and late-closure structures are initially analyzed as late-closure sentences reflected in longer reaction times for the processing of early-closure sentences compared to late-closure sentences. This parsing preference is referred to as the "late-closure principle" (Frazier, 1987; Frazier & Rayner, 1982). However, when prosodic information consistent with the syntax is present, the late-closure preference is eliminated and reaction times for early-closure sentences are decreased (Kjelgaard & Speer, 1999).

A set of 18 sentence pairs was constructed containing both an early-closure and a late-closure syntax variant. All sentences were recorded with two different prosodic renditions: facilitating prosody and baseline (neutral) prosody (Fig. 2). The validity of the intended prosodic characteristics in these natural speech stimuli is documented by acoustic analyses and by an experimental validation on adult participants (see below).

Sentences contained verbs that were subjectively transitive to the experimenters in order to further bias the listener toward late-closure interpretation. Both early-closure and late-closure sentences had equal numbers of syllables to keep the prosodic timing similar aside from the boundary location. Facilitating prosody contained a prosodic boundary congruent with its syntax (Fig. 2). The baseline condition contained no prosodic boundary in the syntactically ambiguous region for either the early- or late-closure syntax; instead, stress was placed on the subject of the sentence in order to keep the rhythm (timing) consistent

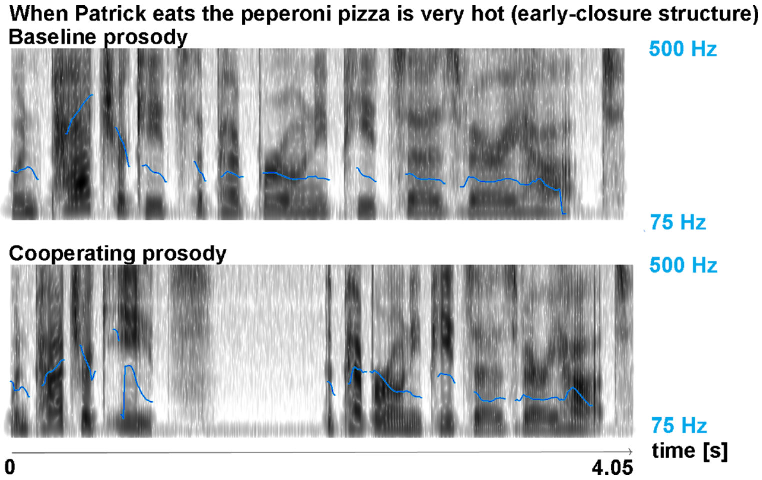

Fig. 2 The figure shows a spectrogram and pitch contour for an early-closure syntax sentence in baseline prosody (*top*), facilitating prosody (*bottom*)

across both early- and late-closure versions. In addition, 18 control sentences comprising a statement with differing syntactic forms were constructed to reduce the possibility that participants would become aware of the experimental prosodic or syntactic forms.

For each sentence, a comprehension question with two forced-response answer choices was recorded. The false answer was a foil of the same syntactic form and of related semantic content. For the sentence example indicated in Figs. 1 and 2 the question was: "What did Patrick eat?" The question was followed by the two answers: "Pizza–Hotdog". All experimental stimuli were normalized to a root-mean-square amplitude of 20 dB. The sentences were recorded by a professional female actress who was also a graduate student in a Department of Communication Sciences and Disorders; she was trained on the exact nature of the prosodic manipulations. The prosodic stimulus characteristics were validated by acoustic analysis as indicated in the next section. All experimental and control sentences and comprehension questions are found in supplementary material. The content of the sentences was geared toward children in early elementary school by relying on vocabulary familiar to this age range. Subjects of the sentences were TV characters known to be familiar to this age group in the USA.

Each child listened to 30 sentences. Six sentences were spoken with facilitating prosody (early-closure syntax, three; late-closure syntax, three). Six sentences were spoken with baseline prosody (early-closure syntax, three; late-closure syntax, three), and 18 were control sentences. No two selected sentences were drawn from the same sentence pair. A Latin square rotation was used to create lists of sentences for presentation.

Acoustic validation of the prosodic stimulus characteristics

To demonstrate the different prosodic manipulations, waveforms of the facilitating and baseline prosodies for the early-closure syntax structures are shown. We validated the prosodic stimulus characteristics by analyzing the two main acoustic elements of prosodic boundaries (Lee & Watson, 2011; Wagner & Watson, 2010). Using the PRAAT speech editor (www.fon.hum.uva.nl/praat), we analyzed the *duration* and maximum mean *pitch* of the sentence constituents that ended the syntactic phrase in the experimental conditions. In the early-closure sentences, the constituents were the duration and pitch of the verb and duration of the following pause. In the late-closure sentences, constituents were the duration and pitch of the noun phrase and the duration of the following pause. Repeated-measure ANOVAs, with the factors “prosody” (facilitating; baseline) and “syntax” (early-closure; late-closure), were used to confirm the acoustic characteristics of the prosodic manipulation. The full statistics are reported in Tables 1 and 2.

The *duration component* of the facilitating prosodic boundary in the *early-closure* sentences was a lengthened verb and a pause after the verb of the relative phrase. Neither was present in the baseline prosody sentences as confirmed by an acoustic analysis. Both the verb (M=0.68, SE=0.13 s) and the pause (M=0.54, SE=0.17 s) were significantly longer in the early-closure, facilitating prosody sentences compared to the verb (M=0.324, SE=0.11 s) and the pause (<0.05 s) in the baseline prosody early-closure sentences [verb, $F(1,17)=415.94$, $p<0.001$, pause, $F(1,17)=160.70$, $p<0.001$].

The *duration component* of the facilitating prosodic boundary in the *late-closure* structure was a lengthened noun phrase and a pause after the noun phrase. Neither was present in the baseline prosody sentences. Both the noun phrase (M=0.80, SE=0.16 s) and the pause (M=0.59, SE=0.18 s) were significantly longer in the facilitating prosody sentences compared to the verb (M=0.57, SE=0.17 s) and the pause (<0.05 s) in the baseline prosody late-closure sentences [noun phrase, $F(1,17)=159.42$, $p<0.001$; pause, $F(1,17=56.46$, $p<0.001$]. The duration analysis is shown in Table 1.

The *pitch component* of the facilitating prosodic boundary in the *early-closure* structure is a higher mean pitch at the prosodic boundary in the facilitating prosody sentences compared to the baseline sentences. That is, the verb (M=293.89, SE =27.8 Hz) was significantly higher in pitch in the facilitating prosody sentences compared to the verb (M=217.94, SE=18.8 Hz) in the baseline prosody early-closure sentences [verb, $F(1,17)= 87.1$, $p<0.001$].

The *pitch component* of the facilitating prosodic boundary in the *late-closure* structure included a higher pitch on the noun phrase in the facilitating prosody sentences compared to the baseline sentences. To that end, the noun phrase (M=290.19, SE=28.9 Hz) was significantly higher in pitch in the facilitating prosody late-closure sentences compared to the noun phrase (M=207.78, SE=11.1 Hz) in the baseline prosody late-closure sentences [noun phrase, $F(1,17)=178.74$, $p<0.001$]. The pitch analysis is shown in Table 2.

Experimental stimulus validation was done on 37 healthy adults. They responded more quickly to stimuli with facilitating prosodies (M=266.1, SE=32.3 ms) compared to stimuli with baseline prosodies (M=467.7, SE=541.8 ms) [$F(1,34)=49.97$, $p<0.001$] indicating a facilitation effect of prosody. Furthermore, they responded more quickly to the late-closure (M=339.0, SE=394.8 ms) compared to the early-closure (M=394.8, SE=40.4 ms) [$F1(34)=4.47$, $p<0.05$] syntactic condition. The significant interaction between prosody and syntax [$F(1,34)=15.53$, $p<0.001$] revealed that the difference in reaction times between baseline prosody and facilitating prosody was significantly greater in the early-closure syntax condition compared to the late-closure syntax condition (Fig. 3).

Taken together, these analyses indicate that the prosodic phrase boundary in sentences with facilitating prosody was comprised of prosodic boundaries through the use of temporal grouping and pitch variations, inseparable in natural stimuli. The baseline prosody, however, has no such temporal grouping of the syntactic constituents. This validates the intended prosodic characteristic of our stimulus material.

Table 1 Prosodic stimulus characteristics—duration component of prosodic phrase boundary

	Verb	Pause	Noun phrase	Pause
Prosody	$p<0.001$, $F(1, 17)=478.4$	$p<0.001$, $F(1,17)=16{,}970$	$p<0.001$, $F(1, 17)=191.69$	$p<0.001$, $F1{,}17=180.30$
Syntax	$p<0.001$, $F(1, 17)=209.8$	$p>0.05$	$p<0.001$, $F(1, 17)=44.42$	$p>0.05$
Interaction	$p<0.001$, $F(1, 17)=535.85$	$p>0.05$	$p<0.001$, $F(1, 17)=57.24$	$p>0.05$
Condition	Verb (eats)	Pause (silence)	NP (the pepperoni pizza)	Pause (silence)
EC cooperating	.675 (.13)	.536 (.17)	.623 (.20)	
LC cooperating	.305 (.10)		.800 (.16)	.587 (.18)
EC baseline	.324 (.11)	<.05	.576 (.17)	<.05
LC baseline	.319 (.11)	<.05	.571 (.15)	<.05

Table 2 Prosodic stimulus characteristics—pitch component of prosodic phrase boundary

	Verb	Noun phrase
Prosody	$p<0.001$, $F(1, 17)=56.027$	$p<0.001$, $F(1, 17)=65.54$
Syntax	$p<0.01$, $F(1, 17)=11$	$p>0.05$
Interaction	$p<0.05$, $F(1, 17)=5.08$	$p=0.06$, $F(1, 17)=3.89$
Condition	Verb (eats)	NP (the pepperoni pizza)
EC cooperating	293.89 (27.8)	259.9 (58.5)
LC cooperating	248.57 (50.8)	290.19 (28.9)
EC baseline	217.94 (18.8)	210.177 (11.9)
LC baseline	211.64 (21.4)	207.78 (11.1)

Participants

Twenty-one typically developing readers (seven girls, age, $M=7.4$ years, SD=0.5, 0 left handed) were recruited from a local public school to participate in the study. All children were normally developing and displayed no developmental disorders as confirmed by school special education personnel. In addition, 21 children with dyslexia (seven girls, age, $M=7.4$ years, SD=0.6, 6 left handed) were recruited from a reading intervention study and therefore well characterized with regard to their behavioral profiles. Children qualified for participation in that intervention study and met criteria for dyslexia based on the following: history of reading difficulty or current diagnosis of reading disability or dyslexia; scoring below the 25th percentile on at least two measures of word reading or related sub-skills; scoring at least in the average range (16th–84th percentile) on a measure of non-verbal cognitive ability. The test battery included measures of: non-verbal cognitive ability ("Matrices", *Kaufman Brief Intelligence Test, 2nd Edition* (KBIT): Kaufman & Kaufman, 1997); receptive vocabulary (*Peabody Picture Vocabulary Test* (PPVT-4): Dunn & Dunn, 2007); untimed real word ("Word Identification") and pseudoword reading ("Word Attack," Woodcock Reading Mastery Test, 3rd Edition (WRMT-III): Woodcock, 2011);

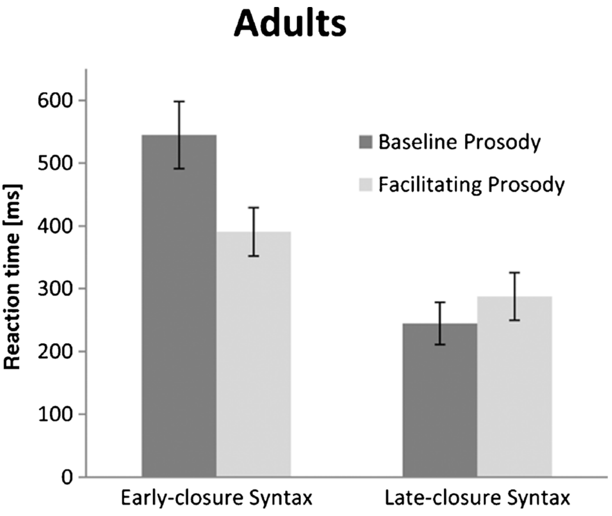

Fig. 3 The figure displays mean reaction times for adults. Error bars indicate standard errors

timed real word ("Sight Word Efficiency") and pseudoword reading ("Phonemic Decoding Efficiency," *Test of Word Reading Efficiency*, *2nd Edition* (TOWRE-2): Torgesen, Wagner & Rashotte, 2012); text comprehension ("Passage Comprehension," WRMT-III: Woodcock, 2011); spelling (*Test of Written Spelling*, *4th Edition* (TWS): Larsen, Hammill, & Moats, 1999); phonological awareness ("Elision," Comprehensive Test of Phonological Processing (CTOPP): Wagner, Torgesen, & Rashotte, 1999); phonological working memory ("Non-word Repetition," CTOPP); and rapid naming ("Objects," "Letters," and "2-Set," *Rapid Automatized Naming and Rapid Alternating Stimulus Tests* (RAN and RAS): Wolf & Denckla, 2005). (Standardized scores are reported in Table 3.) Experimental stimulus validation was done on 37 healthy adults (25 women; age: *M*=24 years, SD=4.9), primarily graduate students.

Adults and caregivers gave written informed consent in accordance with the procedures approved by the local ethics committee. Adults were given payment for the time they and their child shared to participate, and children received a small toy after the experiment. All methods of recruitment and experimental procedure were approved by the local Institutional Review Board.

Procedure and experimental task

The stimuli were presented over headphones using Presentation software (http://www.neurobs.com/) while participants were seated comfortably in front of a laptop computer. The TD children were tested in a quiet conference room at a local school. The children with dyslexia and the adults were tested in quiet testing rooms at the university.

All participants were instructed to listen carefully to the sentences and press a button on the keyboard as quickly as possible as soon as they had understood the sentence (response 1). To ensure that subjects had processed the sentences, they were presented with the comprehension question and two response choices after every sentence. Participants responded by pressing one

Table 3 Characteristics of children with dyslexia (*N*=21)

	Mean (standard deviation)
Non- Verbal Cognitive Abilities: KBIT-2 Matrices	105.4 (12.3)
Receptive Vocabulary: PPVT-4	112.8 (10.5)
Rapid Automatized Naming:	
RAN Objects	87.6 (11.9)
RAN Letters	90.3 (9.5)
RAS (2-set)	96.3 (14.4)
Phonological Processing: (CTOPP)	
Elision	8.0 (1.56)
Nonword Repetition	8.2 (1.6)
Real Word Reading: Word Identification, WRMT-III	83.6 (11.6)
Pseudoword Reading: Word Attack, WRMT-III	86.4 (11.2)
Timed Word Reading: Sight Word Efficiency, TOWRE-2	82.2 (11.2)
Timed Pseudoword Reading: Phonemic Decoding Efficiency, TOWRE-2	78.9 (10.0)
Comprehension: Passage Comprehension, WRMT-III	89.0 (13.2)
Expressive Spelling: TWS-4	83.4 (4.5)

Standard score values are based on a scale of 100±15 for all measures except CTOPP subtests, which are based on a scale of 10+3 of two buttons (response 2). Prior to the presentation of the sentence and the comprehension question, a drawing of an ear was presented on the screen to draw attention to the auditory stimulus to follow. After every button press, colorful stars flashed on the screen to further motivate participants.

Data analysis

Data analysis was performed using MATLAB and SPSS. For both groups of subjects, the reaction time of response 1 and number of correct responses for response 2 were analyzed. Response 1 was measured from the offset of the sentence to control for sentence length and was only included when subsequent response 2 was correct. Any button (1, 2, or 3) was considered a correct button press for response 1. Responses above 6 s duration from the offset of the sentence were treated as outliers and excluded from the analysis for both adults and children. No more than three slow responses (0.3 on average for kids and 0 for adults) were removed. This procedure eliminated the trials in which the children were likely distracted or missed the trial. As behavioral data are naturally skewed, no additional correction for individual outliers was performed. Instead, as a measure of central tendency, median reaction times for correctly identified trials per condition and participant were subjected to a group analysis. A repeated-measure ANOVA including the between subject factor "groups" (typically developing readers; children with dyslexia) and the within-subject factors "prosody" (facilitating; baseline) and "syntax" (early-closure; late-closure) was performed.

Results

Reaction times for TD readers and children with dyslexia are indicated in Fig. 4. Overall, children processed sentences with facilitating prosody faster (M=961.1, SE=102.9) than sentences with baseline prosody (M=1,183.8, SE=91.6) [$F(1,40)=10.73$, $p<0.01$]. No difference between the processing of the two syntactic conditions was observed [$F(1,40)=0.49$, $p=0.49$]. There was a significant interaction between the factors "prosody" and "syntax" [$F(1,40)=6.52$, $p<0.05$]. Post hoc tests revealed that prosody facilitated early-closure syntax processing [baseline, M=1,299.7, SE=102.0; facilitating, M =889.4, SE=123.3, $F(1,40)=$

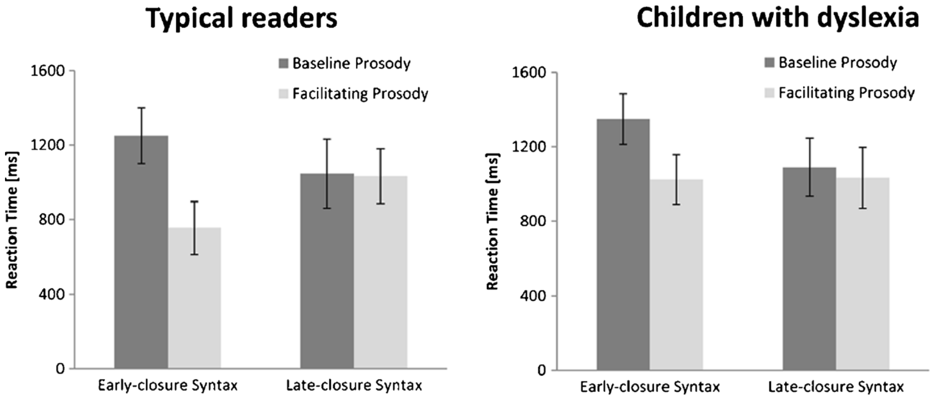

Fig. 4 The figure displays mean reaction times for typical readers (*left*) and children with dyslexia (*right*). Error bars indicate standard errors

21.56, $p<0.001$], but did not facilitate late-closure syntax processing [baseline, $M=1{,}447.7$, SE=96.7; facilitating, $M=1{,}032.8$, SE=110.1, $F(1{,}40)=0.10$, $p=0.75$].

No significant difference between TD and dyslexic groups was observed [$F(1{,}40)=0.30$, $p=0.59$]. There was no interaction between the factors group and syntax [$F(1{,}40)=1.65$, $p=0.21$] and between the factors group and prosody [$F(1{,}40)=0.22$, $p=0.65$]. In the critical syntactic condition, the early-closure syntax, both groups processed sentences in the facilitating condition significantly faster than in the baseline condition [TD children, $t(20)=3.28$, $p<0.01$; children with dyslexia, $t(20)=3.54$, $p<0.01$]. Children's answers to the comprehension questions were correct at a rate that was significantly above chance ($M=88.6$, SE=1.4 % correct). No group differences were observed in comprehension accuracy [$F(1{,}40)=0.000$, $p=1.00$].

Discussion

This study investigated the efficiency of children aged 6–8 in using prosodic boundaries that comprise temporal grouping for syntactic processing. Children exhibited significantly shorter reaction times for early-closure sentence structures when there was facilitating prosody. Such facilitating prosody eliminated the advantage in processing time for late-closure versus early-closure sentence structures that occurred for neutral sentences. Critically, children with dyslexia exhibited prosodic facilitation that was similar to TD readers, indicating that children with dyslexia use prosodic phrase boundaries to disambiguate syntactic structure in speech in a similar way than TD readers do.

In the baseline condition, a syntactic late-closure preference was found. That is, children processed late-closure sentences faster than early-closure sentences when they were presented with baseline prosody. Slower processing of early-closure sentence is expected because the anticipated late-closure structure is not encountered and re-analysis of the syntactic structure is required (Kjelgaard & Speer, 1999). This effect was previously documented in speech perception and in reading with adult listeners (Clifton et al., 2006; Frazier et al., 2006; Kjelgaard & Speer, 1999; Warren, Grabe, & Nolan, 1995) and in a self-paced reading task with children (Traxler, 2002). Thus, our study converges with previous research and shows for the first time that the late-closure preference is present not only in reading but also in speech processing in young children.

Prosodic facilitation of syntactic processing was expected for TD readers. Children process prosody from birth on, which may drive infants' preferences for their native language (Jusczyk et al., 1993; Mehler et al., 1988; Nazzi et al., 2000) and aid in speech segmentation necessary to learn words (Johnson & Jusczyk, 2001b; Jusczyk, 1999). Children's ability to use prosody for syntactic parsing has also been demonstrated, although it is yet unclear whether prosody is required for syntax acquisition as suggested in the prosodic bootstrapping theory (Bedore & Leonard, 1995; Snedeker & Casserly, 2010; Speer & Ito, 2009). There is evidence that young children show an understanding of the syntactic function of prosodic phrasing, for example, in ambiguous prepositional phrases or ambiguous transitive and intransitive verb structures (Snedeker & Yuan, 2008b; Snow, 1994; Wells, Peppe, & Goulandris, 2004). All studies above used speech in which prosody comprised some form of distinctive temporal information that was used for syntactic disambiguation. The specific syntactic ambiguity used in our speech stimuli had never been investigated in young children. Our results show for the first time that early-school-aged children use prosody to interpret early-closure temporary syntactic ambiguities.

In contrast to our hypothesis, children with dyslexia displayed behavioral outcomes similar to TD readers. The group comparison revealed no significant differences between the reaction times of TD readers and children with dyslexia. Thus, children with dyslexia were able to use prosodic phrase boundaries comprising temporal grouping for syntactic processing. Because various other aspects of timing perception are affected in children with dyslexia (Corriveau & Goswami, 2009; Holliman et al., 2010; Holliman et al., 2012a; Holliman, Wood & Sheehy, 2012b; Holliman et al., 2013; Huss et al., 2011; Overy, 2000; Overy, 2003; Thomson et al., 2006; Wolff, 2002) we had hypothesized that temporal grouping might be impaired as well.

Two interpretations of the typical performance in children with dyslexia are possible. The absence of a difference in performance between TD readers and children with dyslexia might be speech specific. Natural speech carries inherently redundant information that facilitates processing (Aylett & Turk, 2004; Patel, Xu, & Wang, 2010), and in the case of prosodic phrase boundaries, a pitch modulation is present as well (Lee & Watson, 2011; Wagner & Watson, 2010). Consequently, a potential underlying impairment in temporal grouping perception could have been compensated by children with dyslexia by relying on the pitch modulations in the speech signal. This interpretation is partially supported by one earlier study that compared children with dyslexia to children with both dyslexia and SLI (Marshall et al., 2009). In that study, children with a double diagnosis were impaired in prosodic phrase processing when it was presented both in speech as well as in speech-derived non-linguistic sound sequences. Children with dyslexia and no SLI, however, were impaired in non-lingustic sound processing only. Together with our result, these findings support the interpretation that children with dyslexia, although potentially impaired in non-linguistic temporal grouping, can compensate for this deficit when temporal grouping is presented in a natural speech stimulus.

Alternatively, it is possible that temporal grouping perception is one of the temporal aspects of auditory signals not impaired in children with dyslexia. To our knowledge, impairment in non-linguistic temporal grouping perception in dyslexic children has not been reported. This may appear to contradict reports that suggested a relationship between "auditory rhythm sensitivity" and literacy in adult individuals with dyslexia (Thomson et al., 2006; Wolff, 2002), as temporal grouping is one aspect of auditory rhythm. However, these authors refer to rhythm in a more musical sense in which rhythmic refers to a temporal pattern that comprises periodicity, also referred to as beat. Reproduction of speech rhythm although already impaired in children with dyslexia further deteriorated when synchronization to an external regular cue was required (Wolff, 2002), and manual tapping to a metronome was impaired as well in children with dyslexia (Thomson et al., 2006). It is likely that temporal grouping and beat processing, although functionally interacting, rely at least partially on distinct mechanisms (Geiser, Ziegler, Jancke, & Meyer, 2009). Thus, it is possible that impairment in non-linguistic rhythm processing is mainly an effect of impaired temporal regularity perception while grouping perception is intact. Future studies should use manipulated speech material and non-linguistic temporal processing paradigms to further investigate this temporal-processing abilities in dyslexic readers and, furthermore, investigate the specific contribution of temporal regularity and temporal grouping perception to reading abilities both in typically developing readers and in children with dyslexia.

Temporal processing, as investigated in our study, is a suprasegmental aspect of speech. Segmental aspects of speech also rely on temporal processing and have been associated with reading impairment. Specifically, the processing of temporal intervals in the range of 20–50 ms, which is in the temporal range of segmental aspects of speech, has been linked to developmental dyslexia or SLI (Benasich & Tallal, 2002; Gaab et al., 2007; Tallal, 1984; Temple et al., 2000; Waber et al., 2001). Several ideas about parallel processing in the auditory system proposed that the left hemisphere tunes in to rapid temporal cues present in speech, while the right hemisphere focuses on "musical" aspects such as spectral processing and longer temporal processing windows (Poeppel, 2003; Zatorre & Belin, 2001; Zatorre, Belin, & Penhune, 2002). Although left and right hemispheric mechanisms most likely interact depending on the task at hand, one might speculate that children with dyslexia have segmental temporal-processing deficits associated with the left hemisphere, but not a suprasegmental temporal-processing deficit associated with the right hemisphere. In conclusion, our study shows that early-school-aged children with dyslexia show processing of prosodic phrasing in speech similar to children with typical reading abilities.

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References

Aylett, M., & Turk, A. (2004). The smooth signal redundancy hypothesis: A functional explanation for relationships between redundancy, prosodic prominence, and duration in spontaneous speech. *Language and Speech, 47*(1), 31–56.

Beach, C. M. (1991). The interpretation of prosodic patterns at points of syntactic structure ambiguity: Evidence for cue trading relations. *Journal of Memory and Language, 30*(644), 663.

Beckman, M. E., & Ayers, G. E. (1997). *Guidlines for ToBI labelling*, *vers 3.0* [*manuscript*]. Ohio State University: The Ohio State University Research Foundation.

Beckman, M. E. (1996). The parsing of prosody. *Language and Cognitive Processes, 11*(1–2), 17–67.

Bedore, L. M., & Leonard, L. B. (1995). Prosodic and syntactic bootstrapping and their clinical applications. *American Journal of Speech-Language Pathology, 4*, 66–72.

Benasich, A. A., & Tallal, P. (2002). Infant discrimination of rapid auditory cues predicts later language impairment. *Behavioural Brain Research, 136*(1), 31–49.

Bishop, D. V., & Snowling, M. J. (2004). Developmental dyslexia and specific language impairment: Same or different? *Psychological Bulletin, 130*(6), 858–886. doi:10.1037/0033-2909.130.6.858.

Bradley, L., & Bryant, P. E. (1978). Difficulties in auditory organisation as a possible cause of reading backwardness. *Nature, 271*, 746–747.

Carlson, K., Clifton, C., & Frazier, L. (2001). Prosodic boundaries in adjunct attachment. *Journal of Memory and Language, 45*(1), 58–81. doi:10.1006/jmla.2000.2762.

Clifton, C. J., Frazier, L., & Carlson, K. (2006). Tracking the what and why of speakers' choices: Prosodic boundaries and the length of constituents. *Psychonomic Bulletin and Review, 13*, 854–861.

Cooper, W. E., & Paccia-Cooper, J. (1980). *Syntax and speech*. Cambridge: Harvard University Press.

Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex, 45*(1), 119–130. doi:10.1016/j.cortex.2007.09.008.

Dunn, L. M., & Dunn, D. M. (2007). *PPVT-4 manual*. Bloomington: NCS Perason, Inc.

Frazier, L. (1987). Sentence processing: A tutorial review. In M. Coltheart (Ed.), *Attention and performance XII* (pp. 559–586). Hillsdale: Erlbaum.

Frazier, L., Carlson, K., & Clifton, C. (2006). Prosodic phrasing is central to language comprehension. *Trends in Cognitive Sciences, 10*(6), 244–249.

Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye-movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology, 14*(2), 178–210. doi:10.1016/0010-0285(82)90008-1.

Gaab, N., Gabrieli, J. D., Deutsch, G. K., Tallal, P., & Temple, E. (2007). Neural correlates of rapid auditory processing are disrupted in children with developmental dyslexia and ameliorated with training: An fMRI study. *Restorative Neurology and Neuroscience, 25*(3–4), 295–310.

Geiser, E., Ziegler, E., Jancke, L., & Meyer, M. (2009). Early electrophysiological correlates of meter and rhythm processing in music perception. *Cortex, 45*(1), 93–102. doi:10.1016/j.cortex.2007.09.010.

Holliman, A. J., Williams, G. J., Mundy, I. R., Wood, C., Hart, L., & Waldron, S. (2013). Beginning to disentangle the prosody-literacy relationship: A multi-component measure of prosodic sensitivity. *Reading and Writing*. doi:10.1007/s11145-013-9443-6.

Holliman, A. J., Wood, C., & Sheehy, K. (2012a). The contribution of sensitivity to speech rhythm and non-speech rhythm to early reading development. *Educational Psychology, 35*(1), 32–48.

Holliman, A. J., Wood, C., & Sheehy, K. (2012b). A cross-sectional study of prosodic sensitivity and reading difficulties. *Journal of Research in Reading, 35*(1), 32–48.

Holliman, A. J., Wood, C., & Sheehy, K. (2010). Does speech rhythm sensitivity predict children's reading ability one year later? *Journal of Educational Psychology, 102*(2), 356–366.

Huss, M., Verney, J. P., Fosker, T., Mead, N., & Goswami, U. (2011). Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology. *Cortex, 47*(6), 674–689. doi:10.1016/j.cortex.2010.07.010.

Isel, F., Alter, K., & Friederici, A. D. (2005). Influence of prosodic information on the processing of split particles: ERP evidence from spoken German. *Journal of Cognitive Neuroscience, 17*(1), 154–167. doi:10.1162/0898929052880075.

Johnson, E., & Jusczyk, P. W. (2001a). Word segmentation by 8 month olds: When speech cues count more than statistics. *Journal of Memory and Language, 44*, 458–467.

Johnson, E., & Jusczyk, P. (2001b). Word segmentation by 8-month-olds: When speech cues count more than statistics. *Journal of Memory and Language, 44*(4), 548–567. doi:10.1006/jmla.2000.2755.

Jusczyk, P. W., Cutler, A., & Redanz, N. J. (1993). Infants' preference for the predominant stress patterns of English words. *Child Development, 64*, 675–687.

Jusczyk, P. W. (1999). How infants begin to extract words from speech. *Trends in Cognitive Sciences, 3*(9), 323–328.

Kaufman, A. S., & Kaufman, N. (1997). *Kaufman brief intelligence test* (2nd ed.). Minneapolis: Pearson Assessments.

Kjelgaard, M. M., & Speer, S. R. (1999). Prosodic facilitation and inhibition in the resolution of temporary syntactic ambiguity. *Journal of Memory and Language, 40*, 153–194.

Larsen, S., Hammill, D., & Moats, L. (1999). *Test of written spelling* (4th ed.). Austin,TX: Pro-Ed.

Lee, E. K., & Watson, D. G. (2011). Effects of pitch accents in attachment ambiguity resolution. *Language and Cognitive Processes, 26*(2), 262–297.

Lehiste, I. (1973). Phonetic disambiguation of syntactic ambiguity. *Glossa, 7*, 102–122.

Marshall, C. R., Harcourt-Brown, S., Ramus, F., & van der Lely, H. K. J. (2009). The link between prosody and language skills in children with specific language impairment (SLI) and/or dyslexia. *International Journal of Language & Communication Disorders, 44*(4), 466–488.

Mehler, J., Jusczyk, P., Lambertz, G., Halsted, N., Bertoncini, J., & Amiel-Tison, C. (1988). A precursor of language acquisition in young infants. *Cognition, 29*(2), 143–178.

Morgan, J. L. (1996). Prosody and the roots of parsing. *Language and Cognitive Processes, 11*(1–2), 69–106.

Nakamura, C., Arai, M., & Mazuka, R. (2012). Immediate use of prosody and context in predicting a syntactic structure. *Cognition, 125*(2), 317–323. doi:10.1016/j. cognition .2012.07.016.

Nazzi, T., Kemler-Nelson, D. G., Jusczyk, P. W., & Jusczyk, A. M. (2000). Six-month olds' detection of clauses embedded in continuous speech: Effects of prosodic well-formedness. *Infancy, 1*, 123–147.

Overy, K. (2003). Dyslexia and music—from timing deficits to musical intervention. *Neurosciences and Music, 999*, 497–505. doi:10.1196/annals.1284.060.

Overy, K. (2000). Dyslexia, temporal processing and music: The potential of music as an early learning aid for dyslexic children. *Psychology of Music, 28*, 218–229.

Patel, A. D., Xu, Y., & Wang, B. (2010). *The role of fo variation in the intelligibility of mandarin sentences*. Chicago, IL: Proceedings of Speech Prosody.

Pennington, B. F. (1990). The genetics of dyslexia. *Journal of Child Psychology and Psychiatry, and Allied Disciplines, 31*(2), 193–201. doi:10.1111/j.1469-7610.1990.tb01561.x.

Pierrehumbert, J., & Hirschberg, J. (1990). The meaning of intonational contours in the interpretation of discourse. In P. Cohen, J. Morgan, & M. E. Pollock (Eds.), *Intentions in communication* (pp. 345–365). Cambridge: MIT Press.

Poeppel, D. (2003). The analysis of speech in different temporal integration windows: Cerebral lateralization as 'asymmetric sampling in time'. *Speech Communication, 41*(1), 245–255. doi:10.1016/S0167-6393(02)00107-3.

Price, P. J., Ostendorf, M., Shattuck-Hufnagel, S., & Fong, C. (1991). The use of prosody in syntactic disambiguation. *The Journal of the Acoustical Society of America, 90*(6), 2956–2970.

Savage, R. (2004). Motor skills, automaticity and developmental dyslexia: A review of the research literature. *Reading and Writing: An Interdisciplinary Journal, 17*, 301–324.

Shaywitz, S. E., Shaywitz, B. A., Fletcher, J. M., & Escobar, M. D. (1990). Prevalence of reading disability in boys and girls. *Journal of the American Medical Association, 264*, 998–1002.

Snedeker, J., & Casserly, E. (2010). Is it all relative? Effects of prosodic boundaries on the comprehension and production of attachment ambiguities. *Language and Cognitive Processes, 25*(7–9), 1234–1264.

Snedeker, J., & Yuan, S. (2008a). Effects of prosodic and lexical constraints on parsing in young children (and adults). *Journal of Memory and Language, 58*, 574–608.

Snedeker, J., & Trueswell, J. (2003). Using prosody to avoid ambuiguity: Effects of speaker awareness and referential context. *Journal of Memory and Language, 48*, 103–130.

Snedeker, J., & Yuan, S. (2008b). Effects of prosodic and lexical constraints on parsing in young children (and adults). *Journal of Memory and Language, 58*(2), 574–608. doi:10.1016/j.jml.2007.08.001.

Snow, D. (1994). Phrase-final syllable lengthening and intonation in early child speech. *Journal of Speech and Hearing Research, 37*, 831–840.

Snowling, M. (2000). *Dyslexia* (2nd ed.). Oxford: Blackwell.

Speer, S. R., & Ito, K. (2009). Prosody in first language acquisition—acquiring intonation as a tool to organize information in conversation. *Language and Linguistics Compass, 3*(1), 90–110.

Stein, J. F., & McAnally, K. (1995). Auditory temporal processing in developmental dyslexics. *Irish Journal of Psychology, 16*(3), 220–228.

Steinhauer, K., Alter, K., & Friederici, A. D. (1999). Brain potentials indicate immediate use of prosodic cues in natural speech processing. *Nature Neuroscience, 2*(2), 191–196. doi:10.1038/5757.

Steinhauer, K., Abada, S. H., Pauker, E., Itzhak, I., & Baum, S. R. (2010). Prosody–syntax interactions in aging: Event-related potentials reveal dissociations between on-line and off-line measures. *Neuroscience Letters, 472*, 133–138.

Tallal, P. (1984). Temporal or phonetic processing deficit in dyslexia—that is the question. *Applied Psycholinguistics, 5*(2), 167–169. doi:10.1017/S0142716400004963.

Temple, E., Poldrack, R. A., Protopapas, A., Nagarajan, S., Salz, T., Tallal, P., et al. (2000). Disruption of the neural response to rapid acoustic stimuli in dyslexia: Evidence from functional MRI. *Proceedings of the National Academy of Sciences of the United States of America, 97*(25), 13907–13912. doi:10.1073/pnas.240461697.

Thomson, J. M., Freyer, B., Maltby, J., & Goswami, U. (2006). Auditory and motor rhythm awareness in adults with dyslexia. *Journal of Research in Reading, 29*(3), 334–348. doi:10.1111/j.1467-9817.2006.00312.x.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (2012). *Test of word reading efficiency* (2nd ed.). Austin: Pro-ED, Inc.

Traxler, M. J. (2002). Plausibility and subcategorization preference in children's processing of temporarily ambiguous sentences: Evidence from self-paced reading. *Quarterly Journal of Experimental Psychology, 55*(1), 75–96.

Trueswell, J. C., Sekerina, I., Hill, N. M., & Logrip, M. L. (1999). The kindergarten-path effect: Studying on-line sentence processing in young children. *Cognition, 73*, 89–134.

Waber, D. P., Weiler, M. D., Wolff, P. H., Bellinger, D., Marcus, D. J., Ariel, R., et al. (2001). Processing of rapid auditory stimuli in school-age children referred for evaluation of learning disorders. *Child Development, 72*(1), 37–49.

Wagner, M., & Watson, D. G. (2010). Experimental and theoretical advances in prosody: A review. *Language and Cognitive Processes, 25*(7), 905–941.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999). *Comprehensive test of phonological processing*. Austin: Pro-ed.

Warren, P., Grabe, E., & Nolan, F. (1995). Prosody, phonology, and parsing in closure ambiguities. *Language and Cognitive Processes, 10*, 457–486.

Wells, B., Peppe, S., & Goulandris, N. (2004). Intonation development from five to thirteen. *Journal of Child Language, 31*, 749–778.

Wolf, M., & Denckla, M. B. (2005). *RAN/RAS: Rapid automatized naming and rapid alternating stimulus tests*. Austin: Pro-ed.

Wolff, P. H. (2002). Timing precision and rhythm in developmental dyslexia. *Reading and Writing: An Interdisciplinary Journal, 15*, 179–206.

Woodcock, R. W. (2011). *Woodcock reading mastery test (WRMT-III)* (3rd ed.). San Antonio: Pearson.

Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: Music and speech. *Trends in Cognitive Sciences, 6*(1), 37–46.

Zatorre, R. J., & Belin, P. (2001). Spectral and temporal processing in human auditory cortex. *Cerebral Cortex, 11*(10), 946–953.

Zhou, P., Crain, S., & Zhan, L. (2012). Sometimes children are as good as adults: The pragmatic use of prosody in children's on-line sentence processing. *Journal of Memory and Language, 67*(1), 149–164. doi:10.1016/j.jml.2012.03.005.