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Impairments in speech and nonspeech sound categorization in children with dyslexia are driven by temporal processing difficulties

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ABSTRACT

Auditory processing problems in persons with dyslexia are still subject to debate, and one central issue concerns the specific nature of the deficit. In particular, it is questioned whether the deficit is specific to speech and/or specific to temporal processing. To resolve this issue, a categorical perception identification task was administered in thirteen 11-year old dyslexic readers and 25 matched normal readers using 4 sound continua: (1) a speech contrast exploiting temporal cues (/bA/-/dA/), (2) a speech contrast defined by nontemporal spectral cues (/u/-/y/), (3) a nonspeech temporal contrast (spectrally rotated/bA/-/da/), and (4) a nonspeech nontemporal contrast (spectrally rotated/u/-/y/). Results indicate that children with dyslexia are less consistent in classifying speech and nonspeech sounds on the basis of rapidly changing (i.e., temporal) information whereas they are unimpaired in steady-state speech and nonspeech sounds. The deficit is thus restricted to categorizing sounds on the basis of temporal cues and is independent of the speech status of the stimuli. The finding of a temporal-specific but not speech-specific deficit in children with dyslexia is in line with findings obtained in adults using the same paradigm (Vandermosten et al., 2010, *Proceedings of the National Academy of Sciences of the United States of America*, 107: 10389–10394). Comparison of the child and adult data indicates that the consistency of categorization considerably improves between late childhood and adulthood, particularly for the continua with temporal cues. Dyslexic and normal readers show a similar developmental progress with the dyslexic readers lagging behind both in late childhood and in adulthood.

1. Introduction

Developmental dyslexia is a frequent hereditary reading disability (e.g., Olson, 2002) which manifests itself despite normal intelligence and adequate schooling. It is well established that persons with dyslexia show impairments on a range of tasks probing phonological processing and it is assumed that this is due to their poorly specified phonological representations (e.g., Elbro & Jensen, 2005; Boada & Pennington, 2006). In line with these impoverished phonological

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Table 1
Psychophysical studies investigating categorical perception of stop consonants on the basis of temporal cues in reading disabled (RD) and normal reading subjects matched for chronological age (RN), or for reading age (RA).

Study	Subjects	Stimulus	Identification: Slope or Stimulus × group interaction	Discrimination scores
Gerrits and De Bree (2009)	$34_{\text{at risk}}$ RD (3.10y.) $23_{\text{low risk}}$ RD (3.10y.)	Place: pop-kop	$_{\text{at risk}}$RD < $_{\text{lowrisk}}$RD	
Gerrits (2003)	$15_{\text{at risk}}$ RD (3.11y.) $19_{\text{low risk}}$ RD (3.11y.)	Place: pop-kop	$_{\text{at risk}}$RD < $_{\text{low risk}}$RD**	
Boets, De Smedt, et al. (2010)	16 DR (5.6y.) 46 NR (5.6y.) 16 DR (6.6y.) 46 NR (6.6y.)	Place: bak-dak	RD < RN** RD < RN**	
Chiappe, Chiappe, and Siegel (2001)	26 RD (6y.) 36 RN (6y.)	VOT: bif-pif bis-pis	RD < RN***	
Breier, Fletcher, Denton, and Gray (2004)	$24_{\text{at risk}}$ RD (6.6y.) $13_{\text{low risk}}$ RD (6.4y.)	VOT: ga-ka		*Across category*: $_{\text{at risk}}$RD < $_{\text{low risk}}$RD*** *Within category*: n.s.
Joanisse, Manis, Keating, and Seidenberg (2000)	61 RD (8.7y.) 52 RN (8.5y.) 37 RA (6.11y.)	VOT: dug-tug Place: spy-sky	RD vs. RN: **(in language impaired subgroup)	
Maassen et al. (2001)	8 RD (8.9y.) 12 RN (8.9y.) 8 RA (7y.)	VOT: bak-pak Place: bak-dak	VOT: RD < RN: * RD vs. RA: n.s. Place: n.s.	VOT: RD < RN: * RD < RA: * Place: RD < RN: * RD < RA: *
Serniclaes, Van Heghe, Mousty, Carré, and Sprenger-Charolles (2004)	18 RD (9y.) 23 RN (9y.)	VOT: ba-pa ga-ka		*Across category*: RD < RN*** (3-step pair) *Within category*: RD > RN*** (3-step pair)
Reed (1989)	23 RD (9y.) 23 RN (8.11y.)	Place: ba-da	RD < RN*	n.s.
Blomert and Mitterer (2004)	10 RD (9y.) 12 RN (9.3y.)	Place: ba-da (synthetic)	n.s.	
Blomert, Mitterer, and Paffen (2004)	14 RD (9.1y.) 28 RN (8.6y.)	Place: tart-kart (natural)	n.s.	
Paul, Bott, Heim, Wienbruch, and Elbert (2006)	58 RD (9.1y.) 21 RN (9.2y.)	Place: ba-da	RD < RN***	
De Weirdt (1988)	10 RD (9.4y.) 10 RN	Place: pe-te	n.s.	RD < RN (no statistics)
Bogliotti, Serniclaes, Messaoud-Galusi, and Sprenger-Charolles (2008)	10 RD (10y.) 11 RN (10y.) 10 RA (7.6y.)	VOT: do-to	RD vs. RN: n.s. RD vs. RA: n.s.	*Across category*: RD < RN*; RD < RA (*) *Within category*: RD > RN**; RD > RA***
Nittrouer (1999)	17 RD (8–10y.) 93 NR (8–10y.)	VOT: da-ta Gap: sei-stei	VOT: n.s. GAP: n.s.	
Werker and Tees (1987)	14 RD (10.3y.) 14 RN (10.5y.)	Place: ba-da	RD < RN (*)	RD < RN*** (2-step-pair)
Adlard and Hazan (1998)	13 RD (10.4y.) 12 RN (10.1y.) 12 RA (8.2y.)	Place: date-gate	n.s.	
Liu, Shu, and Yang (2009)	25 $\text{RD}_{\text{phonologically impaired}}$ (10.4y.) 25 RN (10.2y.)	VOT:/pa/-/p^{h}a/	RD < $\text{RN}_{(\text{slope})}$ RD < $\text{RN}^{*}_{(\text{interaction})}$	
Godfrey, Syrdal-Lasky, Millay, and Knox (1981)	17 RD (10.5y.) 17 RN (10.5y.)	Place: ba-da da-ga	RD < RN(*)$_{(\text{slope})}$ RD < $\text{RN}^{***}_{(\text{interaction})}$	Within category: RD > RN*
Cheung et al. (2009)	30 RD (10.5y.) 30 RN (10.5y.) 30 RA (8.11y.)	VOT: /gi/-/ki/	RD < $\text{RN*}_{(\text{slope})}$ RD < $\text{RN*}_{\text{Endpoint}}$ RD vs. RA: n.s.	
McArthur et al. (2008)	65 RD (10.6y.) 37 NR (10.2y.)	Place: ba-da		n.s.
White et al. (2006)	23 RD (8–12y.) 22 RN (8–12y.)	VOT: coat-goat Place: ba-da	Place: n.s. VOT: n.s.	
Rosen and Manganari (2001)	8 RD (13y.) 8 RN (13y.)	Place: ba-da ab-ad	n.s.	RD < RN**
Manis et al. (1997)	25 RD (13.3y.) 25 RN (12y.) 24 RA (8.5y.)	VOT: b-*p*	RD < RN**(especially in phonological impaired subgroup) RD vs. RA: n.s.	
Kraus et al. (1996)	91 learning disabled (6–15y.) 90 RN (6–15y.)	Place: da-ga Duration: ba-wa		Learning disabled < RN***

Table 1 (*Continued*)

Study	Subjects	Stimulus	Identification: Slope or Stimulus × group interaction	Discrimination scores
Breier et al. (2002)	38 $RD_{no\ ADHD}$ 32 $RD_{with\ ADHD}$ 43 $RN_{no\ ADHD}$ 29 $ADHD_{no\ RD}$ (all: 7.3–14.5y.)	Place: ba-da		$RD < RN^{**}$ (independent of ADHD)
Breier et al. (2001)	21 $RD_{no\ ADHD}$ 26 $RD_{with\ ADHD}$ 26 $RN_{no\ ADHD}$ 22 $ADHD_{no\ RD}$ (all: 7.5–15.9y.)	VOT: ga-ka	$RD < RN^{***}$	
de Gelder and Vroomen (1998)	14 RD (9.4–14.2y.) 14 RN (9.4–14.2y.) 14 RA (7.7–11.5y.)	Place: ba-da	$RD < RN^{*}$ $RD < RA^{*}$	
Steffens et al. (1992)	18 RD (adults) 18 NR (adults)	Place: ba-da Gap: sa-sta	Place: $RD < RN^{*}$	Place: n.s. Gap: n.s.
Ramus et al. (2003)	16 RD (adults) 16 RN (adults)	VOT: coat-goat Place: ba-da, date-gate	VOT: n.s. Place: n.s.	Place (only ba-da): n.s.
van Beinum, Schwippert, Been, van Leeuwen, and Kuijpers (2005)	12 RD (adults) 12 RN (adults)	Place: bak-dak	$RD < RN^{***}$	$RD < RN^{***}$
Dufor, Serniclaes, Sprenger-Charolles, and Démonet (2007)	14 RD (adults) 16 RN (adults)	Place: ba-da (sinewave)		Accuracy: $RD < RN^{*}$ (no interaction with within-across category)

(*)$p < .10$.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

representations, one may expect deficits in tasks where individuals have to assign speech sounds to phonemic categories or where they have to determine whether acoustically-similar speech sounds belong to the same category. Inspection of the literature on categorical perception in dyslexia confirms that individuals with dyslexia compared to normally reading peers show a less consistent identification and discrimination of stop consonants in 64% of the reported experiments (32 out of 50 experiments, described in 32 studies, for more details see Table 1). Yet, these studies are inconclusive to whether these problems are specific to the perception of speech sounds or whether they can be reduced to basal auditory problems. Indeed, building up well-specified phonological representations requires an accurate perception of subtle auditory cues which are important to analyze the speech stream into its phonetic components. In this regard, Tallal (1980) proposed that individuals with dyslexia have a particular deficit in processing nonspeech temporal auditory cues, which subsequently causes problems in the accurate processing of rapid acoustic changes in speech (such as in stop consonants). This speech perception deficit is hypothesized to result in impoverished phonological representations, which consequently provoke problems in learning to read and spell. A large body of literature has supported this hypothesis by demonstrating deficits in low-level auditory perception of nonspeech sounds in individuals with dyslexia (for review see Habib, 2000 and Hämäläinen, Salminen, and Läppanen, in press) and associations between temporal auditory processing, speech perception and reading-related skills (e.g., Boets, Wouters, van Wieringen, De Smedt, & Ghesquiere, 2008; McBride-Chang, 1996). However, some studies could not demonstrate auditory temporal processing problems in individuals with dyslexia or demonstrated auditory problems with stimuli that cannot be specifically categorized as temporal in nature (e.g., frequency discrimination and backward notched-noise conditions) (for a critical review see Rosen, 2003).

Thus, despite substantial research efforts on auditory processing and speech perception in dyslexia, two important issues remain unsolved: (1) is the processing problem specific to the perception of speech sounds or does it also include basic acoustic processing more generally and (2) is the auditory problem specific to rapid temporal processing or does it encompass a broader range of spectro-temporal processing abilities. In order to unequivocally answer these speech-specific and temporal-specific questions, it is necessary to control for acoustical complexity of the stimuli across the speech and temporal dimension and to administer tasks that adopt identical paradigms. If not, presence of specific group differences may be related to stimulus complexity and/or to the use of specific task paradigms, instead of reflecting true difficulties with certain linguistic and/or temporal characteristics (e.g., Banai & Ahissar, 2006). Some studies have addressed the speech-specific question by applying identical test paradigms, but stimulus complexity was not controlled for across the speech and nonspeech stimuli (Mody, Studdert-kennedy, & Brady, 1997; Ramus et al., 2003; Rosen & Manganari, 2001; White et al., 2006; Breier et al., 2001). The observed group differences, which were mainly found in the speech condition, can thus either be explained by the speech factor or by the higher acoustic complexity of the speech stimuli. With respect to the temporal-specific question, categorical speech perception studies on steady-state phonemes (i.e., vowels) versus dynamic phonemes (i.e., stop consonants that differ by place of articulation) are mostly in favor of a specific temporal deficit (Gerrits, 2003;

Rosen & Manganari, 2001; Steffens, Eilers, Gross-Glenn, & Jallad, 1992). Though, one study was not able to show a specific deficit (McArthur, Ellis, Atkinson, & Coltheart, 2008).

Mixing up the speech and temporal dimension, by contrasting nontemporal nonspeech sounds (tones) versus temporal speech sounds (stop consonants), confounds the interpretation of the results as the observed specific deficit for stop consonants can indicate a speech-specific deficit, a temporal-specific deficit or a combination of both (e.g., Breier, Gray, Fletcher, Foorman, & Klaas, 2002). Thus in order to disentangle the precise nature of a possible auditory deficit in persons with dyslexia, integrating both dimensions (speech vs. nonspeech and temporal vs. nontemporal) within one test paradigm with stimuli adequately controlled for acoustic complexity seems the best option. Recently, such a design was applied by Vandermosten et al. (2010) who tested 31 adults with dyslexia and 31 matched normal readers on an identification task using four continua with equal spectro-temporal complexity: (1) a speech contrast exploiting temporal cues (/bA/-/dA/), (2) a speech contrast defined by nontemporal spectral cues (/u/-/y/), (3) a nonspeech temporal contrast (spectrally rotated/bA/-/dA/), and (4) a nonspeech nontemporal contrast (spectrally rotated/u/-/y/). The results showed that, relative to normal readers, adults with dyslexia had problems labeling sounds on the basis of rapidly changing information, irrespective whether speech or nonspeech sounds were used. This finding suggests that the auditory deficit in persons with dyslexia is temporal-specific but not speech-specific. Although this adult study provides a solid answer on the specific nature of the perceptual problems in dyslexia, it remains unclear whether the observed deficits in categorization on the basis of temporal cues result from a lifetime of reading difficulties or whether they constituted a more fundamental problem instrumental in producing reading failure. A first step towards elucidating this issue is investigating whether the same pattern of results can be found in children who are less experienced in reading.

The goal of the present study is twofold. First, we aim to consolidate our previous findings in adults by investigating the speech-specific and/or temporal-specific nature of the auditory processing problems in school-aged children with dyslexia versus matched controls. Second, we aim to compare and integrate the current categorical perception data of the 11-year-old children with those of the adults (Vandermosten et al., 2010) in order to construct a more comprehensive developmental framework.

2. Methods

2.1. Participants

Thirty-eight 11-year-old children participated in the study. Children attended sixth grade of primary school and were selected from a sample that was longitudinally followed up from kindergarten. The original sample consisted of children at high family risk of dyslexia and a matched low-level control group (Boets, Vandermosten, et al., 2010). Children's literacy performance was assessed in first, third and sixth grade by standardized tests for word reading, pseudoword reading (van den Bos, Spelberg, Scheepstra, & De Vries, 1994) and spelling (Dudal, 1997), which resulted in nine literacy scores for each participant (3 tests at 3 time points). In line with current practice in Belgium and Netherlands (Gersons-Wolfensberger & Ruijssenaars, 1997), the criterion we used for the diagnosis of dyslexia took into account both the severity and the persistence of children's literacy problems. Specifically, children of the dyslexic group scored below the 10th percentile on the same standardized reading and spelling task on at least 2 successive test moments. In addition, children had to score below percentile 50 on each literacy task at each test moment. The normal reading group consisted of the original low-risk children who presented no reading or spelling problems throughout primary school (i.e., above percentile 10 on all literacy measures).[2] This classification resulted in a group of 13 dyslexic readers (DR) and 25 normal readers (NR). All participants had adequate nonverbal intelligence, defined by a standard score above 85 on the Raven's Coloured Progressive Matrices test (Raven, Court, & Raven, 1984), and normal hearing, defined by an audiometric pure-tone average (0.5, 1 and 2 kHz) better than 25 dB HL in the test ear. All participants were native Dutch speakers without a history of brain damage, psychiatric disorder, visual problems or long term hearing loss. Table 2 displays descriptive statistics for the two groups. Both groups did not differ in gender ratio, age, nonverbal intelligence or parental educational level (as assessed with the International Standard Classification of Education scale; OECD, 1999). As expected, reading and spelling achievement in sixth grade was significantly poorer in the dyslexic reading group than the normal reading group.

2.2. Stimuli and design

The experimental design, stimuli and procedure are identical to those reported in the adult study by Vandermosten et al. (2010). The intensity level (RMS), duration and cut-off frequency of the spectra (<4 kHz) were identical for the four stimulus types. The endpoints, or 'prototypes', of each of the four continua are displayed in Fig. 1.

[2] The high-risk normal reading children of the study of Boets, Vandermosten, et al. (2010) and Boets, De Smedt, et al. (2010) were excluded because of unbalanced number of normal versus dyslexic readers, but the pattern of results was identical when the high-risk and low-risk normal reading groups were collapsed.

Table 2
Characteristics of the participants.

Characteristics	Dyslexic readers ($n = 13$)	Normal readers ($n = 25$)	Test statistics
	M (*SD*)	*M* (*SD*)	
Subject characteristics			
Sex (male/female)	8/5	14/11	χ^2 (1) = 0.10, $p = .75$
Maternal educational level	2.6 (0.7)	2.7 (0.5)	Fisher's exact test: $p = .51$
Paternal educational level	2.3 (0.5)	2.4 (0.6)	Fisher's exact test: $p = .31$
Age (years)	11.6 (0.3)	11.7 (0.3)	$t(36) = -0.97$, $p = .34$
Non-verbal IQ (Raven)	108.1 (8.2)	112 (13.5)	$t(36) = -0.94$, $p = .35$
Defining literacy measures in grade 6			
Word reading	68.1 (13.3)	98.0 (12.2)	$t(36) = -6.94$, $p < .0001$
Pseudoword reading	76.9 (14.8)	102.4 (9.5)	$t(36) = -6.46$, $p < .0001$
Spelling	84.7 (14.7)	107.9 (7.3)	$t(36) = -6.67$, $p < .0001$

Note. The scores of the defining literacy measures and non-verbal IQ are standardized scores with population average $M = 100$ and $SD = 15$.

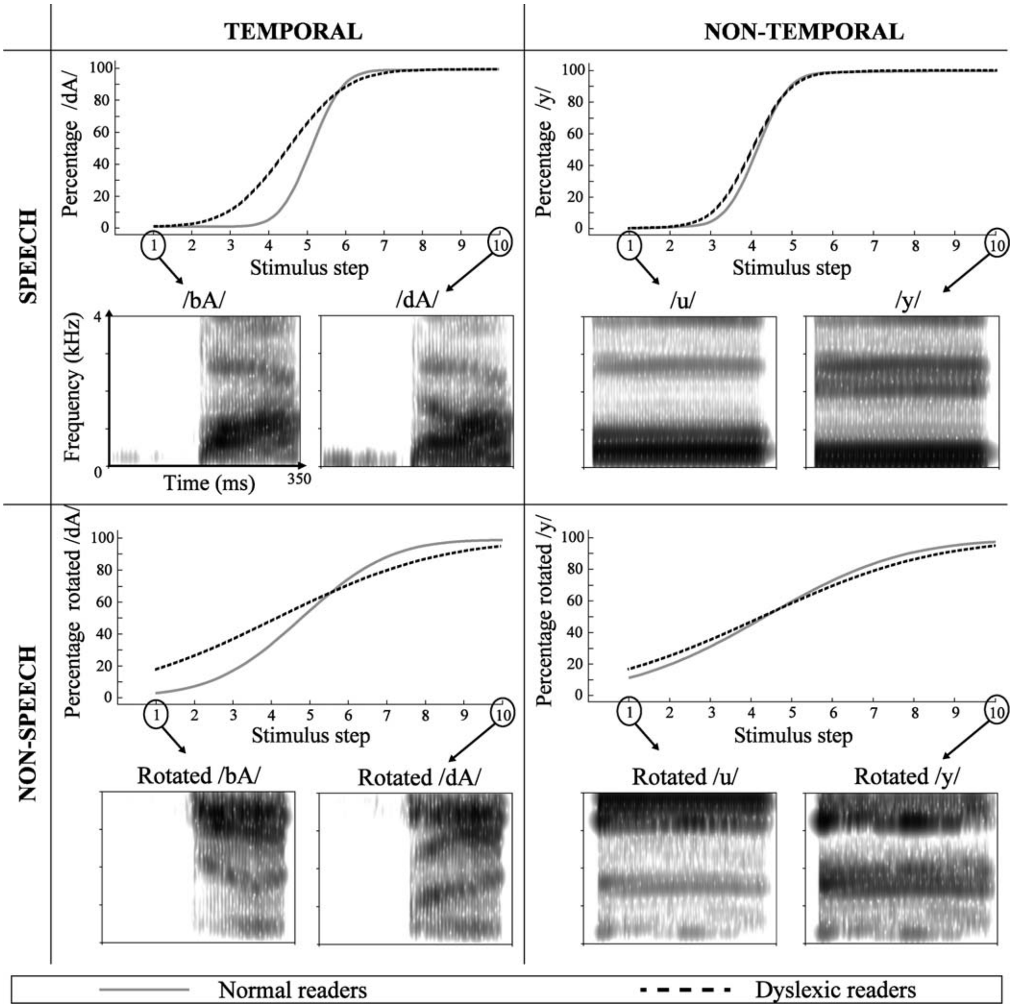

Fig. 1. For each of the four conditions, the spectrograms of the two endpoint stimuli and the estimated identification curves are shown. The estimated identification curves are based on the averaged slope and category boundary parameters per group. Dotted gray lines depict the dyslexic reading group and full black lines depict the normal reading group. Percentage of/dA/,/y/, rotated/dA/and rotated/y/responses (*y*-axis) is shown along the 10 stimulus steps (*x*-axis). On the spectrograms, the *x*-axis represents time (350 ms), the *y*-axis represents frequency (4 kHz), and the intensity of the gray-scale represents the amplitude.

2.2.1. Speech continua

Two 10-step phonetic continua were created using Praat (Boersma & Weenink, 2000): one started from a naturalistic spoken/bA/and was extrapolated to/dA/and one started from a naturalistic spoken/u/and was extrapolated to/y/. The signals were down-sampled to 11,025 Hz for Linear Predictive Coding (LPC) analyses of the formant frequencies. The LPC-analysis was done with 10 linear prediction parameters, a window width of 25 ms, a time step of 5 ms, and pre-emphasis of +6 dB/octave starting at 50 Hz.

Speech temporal: The acoustic difference between/bA/and/dA/lies within the transition of the second formant (F2), which is rising for/bA/and falling for/dA/. Since the F2-transition is rapidly changing over time, this contrast is defined as 'temporal'. To create a speech continuum that gradually moves from/bA/to/dA/in 10 acoustically identical steps, the transition of F2 was linearly interpolated from/b/to/d/. The manipulated part of the signal was a 100 ms interval at the beginning of the sound. The F2 onset ranged from 830 Hz to 1906 Hz, while the steady-state part of the vowel was kept at 1100 Hz. F1 and F3 were constant for all 10 stimuli at 680 Hz and 2620 Hz, respectively. Each item of the resulting 10-step continuum had a total length of 350 ms.

Speech nontemporal: The acoustic difference between/u/and/y/lies within the frequency of F2. During the total length of the phonemes, F2 stays relatively stable but is at a lower frequency in/u/than in/y/. Since the F2 remains constant over time, this contrast is defined as 'nontemporal'. To create a gradual vowel continuum, the frequency of F2 was linearly interpolated from/u/to/y/in 10 acoustically identical steps ranging from 800 Hz to 2100 Hz across the 10 stimuli, and remaining constant throughout the vowel within each stimulus. F1 and F3 were kept stable at 680 Hz and 2620 Hz, respectively. Stimuli were once again 350 ms in duration.

2.2.2. Nonspeech continua

Non-phonetic contrasts with the same spectro-temporal complexity as the speech continua were obtained by flipping both the/bA/-/dA/and the/u/-/y/continua along a frequency axis of 2 kHz (Blesser, 1972; Scott, Blank, Rosen, & Wise, 2000) (see Fig. 1). In addition, the spectra of the rotated stimuli were filtered to the long-term average spectra of the unrotated original speech stimuli in order to equalize the overall spectral cues of the continua.

Nonspeech temporal: In order to minimize the effects of nonspecific performance factors like attention and effort, we ensured that performance levels on the endpoint stimuli were identical across the four stimulus types. For this reason, and based on behavioral pilot data, the discriminability of the rotated/bA/-/dA/continuum was enhanced by additionally manipulating, in 10 equal steps, the onset of F2 of the rotated continuum (i.e., corresponding to F3 in the non-rotated continuum). This resulted in a falling F2 for the rotated/bA/and a rising F2 for the rotated/dA/. The distances from the onset of this formant transition to its steady-state part were equal to those in the non-rotated/bA/-/dA/-continuum (see Liebenthal, Binder, Spitzer, Possing, & Medler, 2005 for a similar approach). Using spectral rotation of the/bA/-/dA/-continuum, temporal characteristics were preserved.

Nonspeech nontemporal: For the rotated/u/-/y/continuum, no additional manipulation was needed to obtain similar performance levels as in the speech condition. Using spectral rotation of the/u/-/y/-continuum, nontemporal characteristics were preserved.

2.3. Procedure

Besides controlling the acoustic complexity of the stimuli across the four conditions, test procedures were also kept constant. Participants performed a two-alternative forced-choice ABX identification task where they had to indicate whether the third presented stimulus (X) was most similar to the first (A) or second (B) stimulus, by pressing '1' or '2' respectively. Reference stimuli (A and B) were always the endpoints of the tested continuum. Each of the 10 stimuli was presented eight times in a random sequence, for a total of 80 trials. There was an unlimited time to respond and no direct feedback was given. Stimuli were presented monaurally to the right ear over calibrated TDH-39 headphones using the integrated audio card of a PC routed to an audiometer (Madsen OB622). The presentation order of the continua was counterbalanced, with the restriction that participants always started with one of the two speech continua. A pre-test, in which each of the two endpoints of the continuum were presented five times, preceded the administration of the experimental trials.

3. Results

The parameter of interest in this study was the slope of the identification curve at the category boundary. A high slope value indicates a small uncertainty range and suggests a highly consistent ability to categorize sounds, whereas a low slope value indicates a large range of uncertainty and suggests difficulties in identifying the sounds (Maassen, Groenen, Crul, Assman-Hulsmans, & Gabreels, 2001). To calculate the slope, individual identification data were submitted to a logistic fitting using Psignifit toolbox, a software package that implements the maximum-likelihood method reported by Wichmann and Hill (2001a). Confidence intervals were determined using a bootstrap method based on Monte–Carlo simulations (Wichmann & Hill, 2001b). If the goodness of fit was unsatisfactory (i.e., if confidence intervals could not be estimated), data were excluded from the analyses. This was the case for 7 out of the 152 estimated slopes, which were equally spread over the 4 conditions and the 2 groups. Prior to analysis, the obtained slope parameters were log10-transformed to obtain normally distributed data.

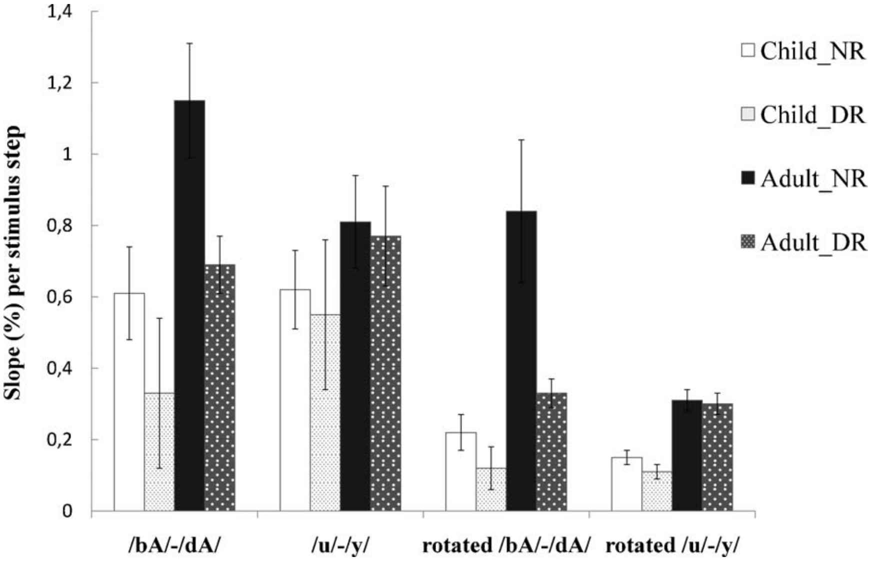

Fig. 2. Average identification slopes of the four stimulus continua for DR and NR children and DR and NR adults. Error bars indicate plus and minus one standard error of the mean per group.

With regard to the specific nature of an auditory deficit, data are shown in Fig. 1. A 2 (Group-factor: DR vs. NR) $\times$ (Temporal-factor: temporal vs. nontemporal) $\times$ 2 (Speech-factor: speech vs. nonspeech) design was tested using a series of repeated Mixed Model Analyses with subject as random variable and group as fixed between-subject variable. The analysis of the slope, which indicates how consistent sounds are labeled, showed a main effect of Group [$F(1, 29.7) = 10.89$, $p = .003$], with shallower slopes in DR compared to NR. However, this poorer performance of DR should be interpreted in the light of the significant Group $\times$ Temporal interaction [$F(1, 95.5) = 3.95$, $p = .049$]. Post-hoc analyses showed that DR had a significantly shallower slope than NR on both temporal continua [$t(54.5) = -3.86$, $p = .003$] but not on the nontemporal ones [$t(54.3) = -1.81$, $p = .08$]. Thus, the imprecise categorization in children with dyslexia is primarily present for sounds that are distinguished on the basis of temporal cues. The latter is the case both in the speech (/bA/-/dA/) and in the nonspeech continuum (rotated/bA/-/dA/) since no significant interaction was observed with the Speech-factor [Group $\times$ Speech: $F(1, 92.4) = 1.95$, $p = .16$; Group $\times$ Speech $\times$ Temporal: $F(1, 92.7) = 0.01$, $p = .93$]. An important implication of the latter is that the categorization deficit in children with dyslexia is not speech-specific.

To examine the evolution from primary school to adulthood, the child data of the present study were integrated with the previously obtained adult data (Vandermosten et al., 2010). Data are shown in Fig. 2 and were analyzed by means of a 2 (Group-factor: DR vs. NR) $\times$ 2 (Temporal-factor: temporal vs. nontemporal) $\times$ 2 (Speech-factor: speech vs. nonspeech) $\times$ 2 (Age-factor: child vs. adult) factorial design. As expected from the results in adults (Vandermosten et al., 2010) and the current results in children, the integrated analysis confirmed the presence of a temporal-specific but not speech-specific categorization deficit in DR [(Group $\times$ Temporal interaction: $F(1, 279) = 9.37$, $p = .002$, and Group $\times$ Speech interaction: $F(1, 277) = 0.54$, $p = .46$)]. With regard to the developmental pattern, a highly significant difference in overall performance was found between children and adults [$F(1, 92.3) = 63.77$, $p < .0001$]. Thus labeling performance improves further after the age of 11. Interestingly, a significant Age-by-Temporal interaction was found [$F(1, 279) = 11.05$, $p = .001$]. Post-hoc analyses revealed significant improvement from childhood to adulthood for both temporal [$t(178) = 8.44$, $p < .0001$] and nontemporal conditions [$t(174) = 4.95$, $p = < .0001$], but the development was significantly larger for the temporal ones. Finally, there was no significant Group $\times$ Age interaction [$F(1, 87.3) = 3.24$, $p = .08$] which implies that both the DR and the NR group improved to a similar extent, with the DR group continuously lagging behind. No other interaction effects reached significance ($p > .05$).

4. Discussion

The present study was designed to examine the specific nature of auditory problems in 11-year olds with dyslexia: are the auditory problems in dyslexia temporal-specific and/or speech-specific. An identification task was administered for 4 stimulus types: a speech temporal contrast (/bA/-/dA/), a speech nontemporal contrast (/u/-/y/), a nonspeech temporal contrast (rotated/bA/-/dA/) and a nonspeech nontemporal contrast (rotated/u/-/y/). The first observation is that children with dyslexia display categorization problems which are not only limited to speech but also encompass nonspeech sounds. This finding is consistent with a variety of studies that demonstrated non-linguistic auditory deficits in individuals with dyslexia (e.g., for review see, Hämäläinen et al., in press). Yet, it contradicts most studies that explicitly aimed at targeting the speech-specific question and that yielded group differences only for the speech stimuli and not for the nonspeech counterparts. These studies, however, mainly used nonspeech sounds that consisted either of pure tones (Breier et al., 2002), sinewave-speech (Mody et al., 1997), or isolated formant transitions (Ramus et al., 2003; Rosen & Manganari, 2001; White et al., 2006), which all have a lower acoustical complexity than speech. In everyday natural speech, the acoustic cues relevant for identifying phonemes are embedded within a stream of acoustic information. Thus, in order to map the incoming acoustic signal to a phonological representation, the listener must be able to select the relevant cues (i.e., the signal) out of the variety of redundant acoustic information (i.e., noise). Given the evidence that individuals with dyslexia have problems excluding the noise from the signal (Sperling, Lu, Manis, & Seidenberg, 2006; Ziegler, Pech-Georgel, George, & Lorenzi, 2009), it may be that dyslexics' temporal processing problems are less likely to show up in isolation or in simplified acoustic environments, whereas they do emerge when the relevant cues are concealed in a complex sound. In the present study, in the adult study (Vandermosten et al., 2010), as well as in a recent study with specific language impaired children (Davids et al., 2011) the nonspeech sounds are acoustically as complex as natural speech, and in such a context nonspeech auditory problems are displayed.

A second observation is that the poorer performance of the dyslexic children is primarily located in the/bA/-/dA/and the rotated/bA/-/dA/condition, which both are temporal conditions. We therefore conclude that the rapidly changing information of the sounds, rather than its speech character, constitutes the determining factor for observing group differences between dyslexic and normal readers. Other researchers (Roach, Edwards, & Hogben, 2004; Heath, Bishop, Hogben, & Roach, 2006; Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009) have disagreed to attribute the observed problems on auditory tasks to a specific perceptual processing deficit of certain stimulus characteristics (e.g., temporal cues), but have explained the deficit by task demands. Most auditory processing tasks, like the ABX-identification task used in this study, also rely on non-sensory factors such as attention and verbal short-term memory, which have been shown to be impaired in persons with dyslexia (Ramus & Szenkovits, 2008; Fletcher, Shaywitz, & Shaywitz, 1999). We agree that also in our study these non-sensory factors may have decreased the overall performance of the children with dyslexia, but these non-sensory factors cannot explain why the labeling problems in dyslexics were significantly worse in the temporal versus the nontemporal conditions since task demands were equal across conditions. Thus, although verbal short-term memory and attention may have deteriorated the overall performance, the significant interaction suggests that processing difficulties of certain (temporal) stimulus characteristics are at the basis of the temporal-specific deficit. Categorical perception studies that did control for task demands by including steady-state stimuli (i.e., vowels) as well as temporal stimuli (i.e., stop consonants) are largely in line with our finding of a temporal-specific deficit (Gerrits, 2003; Rosen & Manganari, 2001; Steffens et al., 1992); except for one study (McArthur et al., 2008).

Finally, the findings of the present study in children consolidate and extend the findings in adults (Vandermosten et al., 2010) where we applied the same test paradigm and stimuli. Both studies converge in finding a specific deficit for labeling speech and nonspeech sounds on the basis of temporal cues in individuals with dyslexia. The use of the same study design across different age groups enabled us to examine developmental changes between 11-year-olds and adults. We demonstrate that performance in labeling still improves from childhood to adulthood, and importantly, this developmental progress runs parallel in persons with and without dyslexia. This implies that the temporal processing deficit of an 11-year-old child with dyslexia does not enlarge or diminish over time. Wright and Zecker (2004) also compared auditory performance of dyslexic versus normal readers, across different age groups (from 6-year-olds to adults). They concluded that an auditory deficit can be observed in dyslexic readers in both childhood and adulthood, if the development of these auditory aspects continues into adolescence in the normal population. Accordingly, this conclusion is in line with our findings. Yet, Wright and Zecker hypothesized that the auditory development in persons with dyslexia is prematurely halted at puberty, which opposes to our finding of a continuing development in dyslexic children which parallels to one of the normal readers. It is difficult to pin-out the sources of these age-related improvements in sound categorization, but it is presumable that auditory maturation plays a key role. Behavioral studies on auditory processing (Neijenhuis, Snik, Priester, Van Kordenoordt, & Van Den Broek, 2002; Stollman, Van Velzen, Simkens, Snik, & Van Den Broek, 2004) as well as anatomical studies on the myelination of the human auditory cortex (Moore, 2002; Moore & Guan, 2001) have demonstrated a long-lasting development up to adolescence. However, not all acoustic aspects show a similar long-lasting development. Different acoustic aspects seem to follow different developmental time tables; e.g., the development of speech perception in quiet stops at 8 years, whereas the development of speech-in-noise-perception continues until after 11 years (Stuart, 2005). Our findings are in line with a cue-specific development by demonstrating a more protracted development for temporal than for nontemporal sounds. At the nonspeech level, this is in line with (1) physiological animal studies showing that neural coding for temporal aspects of the stimulus reaches maturity later than neural coding for frequency selectivity (Eggermont, 1996), and with (2) behavioral auditory studies in humans providing evidence for a more prolonged development of the sensitivity for temporal than for nontemporal auditory cues (Hartley, Wright, Hogan, & Moore, 2000), even after accounting for the effect of procedure-related skills (Dawes & Bishop, 2008). At the speech level, it coincides with behavioral speech perception studies demonstrating that the identification of stop consonants is not yet mature by the age of 11 (Hazan & Barrett, 2000; Johnson, 2000; Krause, 1982; Simon & Fourcin, 1978; Medina, Hoonhorst, Bogliotti, & Serniclaes, 2010), whereas the identification of vowels does only slightly, though not significantly, improves towards adolescence (Pursell, Swanson, Hedrick, & Nabelek, 2002; Ohde, Haley, & McMahon, 1996; Johnson, 2000, but see Walley and Flege, 1999). Further elaboration on this topic is needed, but the indication that perception of sounds with temporal versus nontemporal cues follows different maturational trajectories in both normal and dyslexic readers, may have practical implications with regard to auditory temporal training programs. Studies on the plasticity of the auditory system have demonstrated a more pronounced effect of intervention on immature than on mature auditory pathways (Moore, 1993). Given that the auditory temporal processing abilities are not yet fully maturated in late childhood, the effects of auditory training may not be limited to childhood but could be extended to adolescence. Nevertheless, despite the positive effect of auditory temporal training on auditory, speech and language skills (e.g., Hayes, Warrier, Nicol, Zecker, & Kraus, 2003; Wright, Buonomano, Mahncke, & Merzenich, 1997), more studies are needed to verify whether these training effects also have a positive influence on literacy development (Strehlow et al., 2006), especially in adolescence and adulthood where phonological representations have already largely been built up.

To conclude, our results indicate that 11-year-old children with dyslexia are specifically impaired in labeling sounds that contain rapidly changing information, whereas they perform adequately in labeling steady-state sounds. This temporal-specific deficit is not limited to the speech level, but extends to labeling temporal nonspeech sounds as well. The same pattern of results was also found in adults with dyslexia (Vandermosten et al., 2010). When comparing results obtained in adults and children, the temporal deficit in individuals with dyslexia does not appear to enlarge or decline from childhood to adulthood. Sound labeling by temporal cues is subject to much more improvement from childhood to adulthood in terms of consistency than sound labeling by steady-state cues. Accordingly, training in auditory temporal processing may provoke more progress, even at a later age, though the transfer to literacy skills still needs verification.

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