Phonological, temporal and spectral processing in vowel length discrimination is impaired in German primary school children with developmental dyslexia

Claudia Steinbrink *, Maria Klatte, Thomas Lachmann

Department of Psychology II (Cognitive and Developmental Psychology), University of Kaiserslautern, Erwin-Schroedinger-Strasse, Building 57, 67663 Kaiserslautern, Germany

**Abstract**

It is still unclear whether phonological processing deficits are the underlying cause of developmental dyslexia, or rather a consequence of basic auditory processing impairments. To avoid methodological confounds, in the current study the same task and stimuli of comparable complexity were used to investigate both phonological and basic auditory (temporal and spectral) processing in dyslexia. German dyslexic children (Grades 3 and 4) were compared to age- and grade-matched controls in a vowel length discrimination task with three experimental conditions: In a phonological condition, natural vowels were used, differing both with respect to temporal and spectral information (in German, vowel length is phonemic, and vowel length differences are characterized by both temporal and spectral information). In a temporal condition, spectral information differentiating between the two vowels of a pair was eliminated, whereas in a spectral condition, temporal differences were removed. As performance measure, the sensitivity index d’ was computed. At the group level, dyslexic children’s performance was inferior to that of controls for phonological as well as temporal and spectral vowel length discrimination. At an individual level, nearly half of the dyslexic sample was characterized by deficits in all three conditions, but there were also some children showing no deficits at all. These results reveal on the one hand that phonological processing deficits in dyslexia may stem from impairments in processing temporal and spectral information in the speech signal. On the other hand they indicate, however, that not all dyslexic children might be characterized by phonological or auditory processing deficits.

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1. Introduction

Developmental dyslexia is a specific impairment in learning to read, which does not reflect a general cognitive impairment, and does not result from sensory deficits and/or inadequate schooling (American Psychiatric Association, 1994; Shaywitz, 1998). Longitudinal studies indicate that dyslexia is a persistent condition rather than representing a “transient developmental lag” (Shaywitz & Shaywitz, 2005; Svensson & Jacobson, 2006). Current models of literacy development
postulate that reading and spelling develop jointly; in different phases of literacy development, reading acts as a pacemaker for spelling, and vice versa (Frith, 1986). Therefore, dyslexia is often accompanied by poor spelling abilities (Shaywitz & Shaywitz, 2005).

Even though there is largely agreement that dyslexia has a neurobiological basis (see Démonet, Taylor, & Chaix, 2004; Habib, 2000, for review), consensus about its exact etiological basis is still lacking. On the behavioural level, dyslexia is mainly characterized by phonological processing deficits (Ramus et al., 2003; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Wagner & Torgesen, 1987). These deficits have been found for phonological recoding in lexical access in rapid picture naming (e.g. Denckla & Rudel, 1976), in phonological awareness, i.e. the ability to consciously access and manipulate the sound units of language (e.g. Bradley & Bryant, 1983), and in phonological short-term memory, as assessed by immediate serial recall of unrelated verbal items such as words or digits, or by nonword repetition (e.g. Steinbrink & Klatte, 2008). Dyslexia is also associated with deficits in the perception of phonemes (e.g. Godfrey, Syrdal-Lasky, Millay, & Knox, 1981). All these abilities are accomplished on the basis of phonological representations. Thus, it can be concluded that the phonological deficit in dyslexia results either from an underspecification of (Adlard & Hazan, 1998; Boada & Pennington, 2006; Elbro & Jensen, 2005; Manis et al., 1997; Mody, Studdert-Kennedy, & Brady, 1997; Swan & Goswami, 1997a, 1997b) or a suboptimal access to these representations (Ramus & Szenovits, 2008).

It is still debated, however, whether the phonological deficit constitutes the core problem of developmental dyslexia (Snowling, 2000; Stanovich, 1988) or whether it is secondary to more general auditory processing deficits (Ahissar, Protopapas, Reid, & Merzenich, 2000; Lachmann, Berti, Kujala, & Schröger, 2005; Richardson, Thomson, Scott, & Goswami, 2004). The rapid auditory processing theory of dyslexia (Tallal, 1980), for instance, argues that phonological deficits in dyslexia are secondary to low level auditory temporal processing impairments which affect the perception of acoustic elements characterized by rapid transitions or short durations (as in the speech signal). According to this view, a basic temporal processing impairment leads to an inability to integrate sensory information entering the central nervous system in rapid succession. This causes a cascade of effects, starting with disruption of the normal development of the phonological system and subsequent failure to read normally (Tallal, Miller, & Fitch, 1993).

Using non-speech stimuli, a number of psychophysical studies have revealed evidence for rapid temporal auditory processing deficits in dyslexic adults (Ben-Artzi, Fostick, & Babkoff, 2005; Laasonen, Service, & Virsu, 2001; see Farmer & Klein, 1995 for review) and children (Cohen-Mimran & Sapir, 2007; Heiervang, Stevenson, & Hugdahl, 2002; van Ingelgem et al., 2001; see Farmer & Klein, 1995, for review). There are, however, also studies in which no such evidence was found (Breier, Fletcher, Foorman, Klaas, & Gray, 2003; Bretherton & Holmes, 2003; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998).

There are studies in which in one and the same sample non-linguistic material was applied in order to investigate temporal processing, and linguistic material in order to investigate phonological processing. Typically, for both conditions different task demands were applied, e.g. temporal order judgement or gap detection in the auditory condition and tasks such as phoneme deletion, non-word repetition or rapid automatized naming (RAN) in order to measure phonological awareness, phonological short-term memory or phonological recoding in lexical access, respectively. These studies revealed that temporal processing deficits are not related to phonological processing impairments in dyslexia (Bretherton & Holmes, 2003; Nitttrouer, 1999) or that phonological deficits can appear in the absence of temporal processing deficits (Boets, van Wieringen, & Ghesquière, 2007; Ramus et al., 2003; White et al., 2006).

The interpretation of this pattern of results, however, is difficult, since the phonological vs. temporal processing conditions in these studies do not only differ in the linguistic nature (linguistic vs. non-linguistic), but also in task and stimulus complexity. Both are usually much higher in the phonological condition as compared to the auditory one. This alone might explain why dyslexics showed deficits only in the phonological conditions.

With the aim to overcome these potential methodological confounds, we developed an experimental paradigm in which the same task and the same stimulus material is used to investigate both phonological and basic auditory processing. This paradigm was already used in studies with dyslexic adolescents and adults (behavioural experiments: Christmann et al., submitted for publication; Groth, Lachmann, Riecker, Muthmann, & Steinbrink, 2011; fMRI experiment: Steinbrink, Groth, Lachmann, & Riecker, 2012). As the current behavioural experiment with children employed a methodology that is strictly comparable to that introduced by Groth et al. (2011), we will concentrate in the following on this first study with the vowel length discrimination paradigm, in which two CVC syllables, presented in succession (e.g. /nap/⁠→⁠/napː/; /flp/⁠→⁠/flːp/), were used in a same–different paradigm in order to test vowel length discrimination abilities in dyslexic adolescents and adults. In German, vowel length discrimination is a phonological task, as the opposition of long and short vowels is phonemic. For example, the vowels within the spoken word pairs Schiff (/ʃid/, [ship]) vs. schieß (/ʃɪʃ/, [askew]) or kann (/kan/, [kan]) vs. Kahn (/kaːn/, [bargel]) differ in vowel length.

Three stimulus conditions were applied in Groth et al. (2011): In the first condition (phonological condition) natural speech stimuli were used to form CVC–pseudoword pairs. In German, these natural speech stimuli provide spectral as well as temporal (length) cues for discrimination. In the other two stimulus conditions (temporal conditions), a pair always contained one natural and one manipulated CVC–pseudoword. The manipulation was either a lengthening or a shortening of the quasi-stable phase of the natural vowel to the length of its long or short counterpart, respectively (e.g. long /aː/ was shortened to the length of short /a/ and vice versa). In the temporal conditions, natural and manipulated CVC–pseudowords were always paired in a way that length was the only available cue for discrimination, e.g. by combining a CVC–syllable including an original long /aː/ with a syllable containing the manipulated version of the same vowel, i.e. shortened /aː/.
No group effect was found in the phonological condition (natural CVC–pseudowords) in Groth et al. (2011), with both groups showing high discrimination accuracy. In contrast, in the temporal conditions dyslexics showed worse discrimination accuracy as compared to controls. The result that German dyslexics perform well in the phonological condition where both spectral and temporal cues are available for vowel length discrimination, while they fail when only temporal cues are available was interpreted as evidence for a temporal processing deficit.

The Groth et al. (2011) study leaves open at least two questions. Firstly, since German vowels differing in vowel length do not only differ in length (quantity), but also in terms of their spectral information (quality), it cannot be decided from these results whether dyslexics are exclusively impaired in temporal auditory processing or if they additionally have deficits in spectral auditory processing and thus suffer from a more general auditory processing deficit. In fact, some studies found that auditory processing problems in dyslexics are not confined to temporal aspects (Amitay, Ahissar, & Nelken, 2002). The majority of these studies suggest that temporal as well as spectral (frequency) auditory processing is impaired in dyslexia (Ahissar et al., 2000; Caccace, McFarland, Oumet, Schriever, & Marro, 2000; King, Lombardino, Crandell, & Leonard, 2003; Montgomery, Morris, Sevcik, & Clarkson, 2005; Walker, Givens, Cranford, Holbert, & Walker, 2006). Ahissar et al. (2000) argue that fine representation of spectral and temporal details of acoustic features facilitates the encoding of acoustic patterns into phonological representations. Thus, both temporal and spectral processing deficits could lead to faulty phonological representations in dyslexia.

A second open question is why dyslexics did not differ from controls in the phonological condition in Groth et al. (2011). This result might reflect compensatory processes: In psychophysical tasks, as a result of compensatory strategies learned during biography, the effects of auditory processing deficits in dyslexics may be covered (Stoodley, Hill, Stein, & Bishop, 2006). If that was true, the group effect in the phonological condition should depend on age. Since in Groth et al. (2011) the participants were adolescents and young adults it might well be that they have overcome these difficulties due to maturational processes and experience with this kind of rather easy phonological task demands (see also Hautus, Setchell, Waldie, & Kirk, 2003; Wright & Zecker, 2004, for age-related changes in auditory perception in dyslexia). Another explanation would be that the task is simply too easy to tap into the deficit (Banai & Ahissar, 2006). The high accuracy rates in both groups of Groth et al. (2011) in the phonological condition are in favour of this interpretation.

The main aim of the current study was to investigate phonological, temporal and spectral processing in dyslexic primary school children, using the vowel length discrimination task introduced in Groth et al. (2011). With this study we aimed at answering the question if auditory processing deficits in vowel length discrimination are confined to temporal processing, or if they extend to phonological and spectral processing of vowel length in dyslexics of a young age group.

2. Materials and methods

2.1. Participants

Nineteen children diagnosed with developmental dyslexia (14 males) and 19 control participants (14 males) matched with respect to intelligence, sex, age and school grade took part in this study. Participants were aged between 8;3 and 10;10 (years;months; M = 9;1). All children were monolingual native speakers of German. Each group consisted of 11 third-graders and 8 fourth-graders. For none of the children the parents reported a history of neurological diseases, psychiatric disorders or hearing problems.

During Grade 2 of primary school dyslexic children received a discrepancy-based diagnosis of developmental dyslexia based on the test battery by Weigt (1980). The examination was performed by school authorities and included reading and spelling of letters and words, phoneme segmentation, visual recognition, phonological and visual differentiation, as well as a number of test lessons. Furthermore, physical development and sensory functioning were tested. According to local state law the diagnosis justified their enrollment in a 2-year programme in which the curriculum of Grade 3 is extended to two years in order to have the opportunity to increase the amount of German lessons without neglecting other subjects. We recruited dyslexic children from the first (third-graders) or second (here considered as fourth-graders) year of this programme. The children of the control group were obtained from the third and the fourth grade of the same school in Leipzig from which the dyslexic children were recruited.

In order to validate the previously given diagnoses, all participants were tested again (dyslexics) or for the first time (controls) up to four weeks before the experiment. Inclusion in this study required at least average (IQ ≥ 85) non-verbal intelligence as measured by the Culture Fair Intelligence Test CFT 20–R (German version, Weiß, 2008). For the evaluation of reading abilities, a standardized German reading test for primary school children measuring reading speed was used (Würzburger Leise Leseprobe WLLP; Kispert & Schneider, 1998), as reading speed was found to be a better indicator of reading skills in German than reading accuracy (Wimmer, Landerl, & Frith, 1999; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003). For the evaluation of spelling abilities, standardized German spelling tests for third (Weingartener Grundwortschatz Rechtschreib–Test für zweite und dritte Klassen WRT 2+; Birkel, 2007a) and fourth graders (Weingartener Grundwortschatz Rechtschreib–Test für dritte und vierte Klassen WRT 3+; Birkel, 2007b) were used. To qualify as dyslexic, participants had to score below one standard deviation of the mean performance of the reference population in both the reading and the spelling test (T-scores <40), while the control participants had to show average or above average performance in both reading and spelling skills (T-scores >40). Table 1 provides an overview of participant characteristics and group differences.
Table 1

<table>
<thead>
<tr>
<th></th>
<th>Dyslexics (n = 19)</th>
<th>Controls (n = 19)</th>
<th>Group difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (months)</td>
<td>M = 109.21</td>
<td>SD = 7.49</td>
<td>M = 110.26</td>
</tr>
<tr>
<td>Intelligence (CFT 20-R, IQ)</td>
<td>96.11</td>
<td>8.03</td>
<td>100.84</td>
</tr>
<tr>
<td>Reading speed (WLP, T-score)</td>
<td>28.53</td>
<td>10.00</td>
<td>57.63</td>
</tr>
<tr>
<td>Spelling (WRT 2+/3+, T-score)</td>
<td>31.58</td>
<td>4.43</td>
<td>54.95</td>
</tr>
</tbody>
</table>

* t – test for independent samples.

2.2. Stimulus materials

In Groth et al. (2011) we used all existing seven German vowel pairs characterized by differences in vowel length. In order to adjust to the restrictions of experiments with children, in the present study we used only three out of seven vowel pairs. The selection was based on our earlier finding of decreased discrimination accuracy with increasing vowel height in the temporal condition in both groups (vowel height is defined by the tongue position during articulation of the vowel). This pattern of results is in accordance with former findings in vowel identification (Sendmeier, 1981; Strange & Bohn, 1998; Weiss, 1974). The authors of these former studies found that the influence of spectral and temporal cues on vowel identification depends on vowel height. To identify high vowels, listeners rely more on spectral than on temporal information. With decreasing vowel height, the pattern turns vice versa; to identify low vowels, listeners rely more on temporal than on spectral information.

In order to represent the whole spectrum of discrimination performance, in the present study one vowel pair from each vowel height was chosen (in the following, vowels are transcribed using SAMPA-notation): One with low vowel height, i.e. /a:/ - a/, one with mid vowel height, i.e. /o:/ - O/, and one with high vowel height, i.e. /i:/ - I/. These vowels are characterized by a linear decline in temporal difference from the low vowel pair /a-a:/ (67 ms) over the mid vowel pair /o: - O/ (53 ms) to the high vowel pair /i: - I/ (40 ms; see Table 2). Note that the temporal characteristics differentiating long from short German vowels are in an appropriate range for the investigation of temporal processing (see Tallal & Piercy, 1975).

In the following we will describe those parts of the general methodology employed in Groth et al. (2011) for generating and manipulating the stimuli in more detail that are relevant for the present experiment. In the experiment, vowels were presented in the context of the CVC syllables /fVp/ and /nVp/. All resulting syllables are pseudo-words, which are legal phoneme strings according to German phonotactic rules. Syllables were spoken embedded in a sentence by a female trained speaker, with normal speaking rate and without stress. The best samples of syllables were double checked by a naïve sample of 10 adults in an identification task to assure that the chosen syllables fall within the aforementioned CVC category boundaries. This set of stimuli was used in its natural, inartificial way and is therefore in the following referred to as original or natural vowels/stimuli.

Additionally, a second stimulus set was generated by manipulating the durations of the original vowels (see Table 2 for durations of long and short vowels). This manipulation was based on vowel length determination of the natural vowels and was performed with a special phonetics software package (Praat; Boersma & Weenink, 2005). First, the duration of the vowel in each original CVC-syllable was measured. Here, only the steady-state phase of the vowels was used. Vowel length was identified by visual inspection of spectrograms (formant movements) and waveforms. Additionally, selected vowel parts were controlled acoustically to exclude possible co-articulations. Second, the duration of each long vowel was shortened by adjusting its vowel length to the duration of the short partner vowel, while the spectral characteristics of the long vowel were retained. Similarly, the duration of each short vowel was lengthened by adjusting its vowel length to the duration of the long partner vowel, while the spectral characteristics of the short vowel were retained. For that purpose, Praat performs linear interpolations within the selected portion and compresses or extends, respectively, it to the defined duration. This procedure resulted on the one hand in shortened long vowels with the length of a short vowel but the spectral information of a long vowel, and on the other hand in lengthened short vowels with the length of a long vowel but the spectral information of a short vowel.

Table 2

<table>
<thead>
<tr>
<th>Vowel pair</th>
<th>Vowel duration (in ms)</th>
<th>Difference (in ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long</td>
<td>Short</td>
</tr>
<tr>
<td>/i:-I/</td>
<td>91</td>
<td>51</td>
</tr>
<tr>
<td>/o:-O/</td>
<td>128</td>
<td>75</td>
</tr>
<tr>
<td>/a:-a/</td>
<td>142</td>
<td>75</td>
</tr>
</tbody>
</table>

Average durations (ms) of long and short vowels produced in continuous speech syllables (/fVp/ & /nVp/).
2.3. Experimental procedure

We conducted an auditory two-alternative forced-choice discrimination experiment. In this same-different task, pairs of syllables were presented successively, and participants had to decide whether they are the same or different. In the category different, the CVC-pairs did only differ with respect to their vowel component. In particular, the two vowels did exclusively differ in vowel length, not in any other distinctive feature. This results in the following possible vowel combinations embedded in the two syllables to be judged as different: /iː - ɪ/, /oː - ɐ/ and /aː - æ/. Examples of CVC-different pairs are /faː-p/ or /niː-p - niːp/.

There were three types of different trials: In the phonological condition, an original long vowel was combined with its original short counterpart. In these trials the vowel length difference was phonological in nature, i.e. vowels differed in spectral as well as temporal content. In the temporal condition, an original long vowel was paired with a shortened long vowel, or an original short vowel was paired with a lengthened short vowel. That means that both paired vowels carried either the spectral information of a long or a short vowel and differed exclusively with respect to duration. In the spectral condition, an original long vowel was paired with a lengthened short vowel, or an original short vowel was paired with a shortened long vowel. That means that both paired vowels carried either the temporal information of a long or a short vowel and differed exclusively with respect to spectral content.

In total, there were 18 different combinations: three experimental conditions (phonological vs. temporal vs. spectral), three vowel types (/iː-ɪl/, /oː-ɔl/ and /aː-æl/), and two pseudo-word contexts (/fVp/ vs. /nVp/). Each combination was repeated four times, amounting to a total of 72 different trials used in the experiment. An equivalent number of same trials was used to avoid response bias. For these, original and manipulated syllables with long and short vowels were used at an equal rate. Altogether, the whole experiment consisted of 144 trials, which were presented in pseudo-randomized order within four blocks of 36 trials. Each block contained the same trial categories, allowing to test performance changes over the course of the experiment.

The experiment was performed individually in a quiet room at children’s school. For stimulus delivery and experimental control, the software “Presentation” (Neurobehavioural Systems Inc., San Francisco, CA, USA) was used. The sound files were presented using a sound box (RME Hammerfall DSP System Multiface) controlled by a laptop computer with a PCMCIA-card. Stimuli were presented via closed headphones (Beyerdynamic DT 770).

Participants were asked to decide whether two pseudo-word syllables presented in succession were the same or different. They were instructed to respond as quickly as accurately as possible. Responses were given via button press using a separate response unit. The ISI between the two syllables of a pair was 250 ms. The inter-trial-interval was 2000 ms, starting with button press.

To familiarize participants with the task and the material, a practice phase was conducted prior to the experiment. The concept of vowel length was explained to the participants and clarified by means of real German words like Stahl (/ʃtaːl/) vs. Stall (/ʃtal/). Then, a first set of practice trials using real words with different vowel lengths was presented. A second set of practice trials introduced the kind of pseudo-words used in the discrimination experiment. For this, the CVC-syllable /pVm/ was used, which was not part of the stimulus set of the experiment. In all practice trials, participants received auditory feedback (tone) if their response was wrong. No feedback was given during the experiment. The whole experiment lasted about 30 min, including instruction and practice.

2.4. Statistical analysis

To control for potential response biases, data were analysed within the framework of signal detection theory as extended to same–different paradigms (Macmillan & Creelman, 1991). The sensitivity index d’ was computed from the relative frequencies of hits (different responses when stimuli were different) and false alarms (different responses when stimuli were the same) for the response categories of interest, which were the three vowel types used (/iː-ɪl/ vs. /oː-ɔl/ vs. /aː-æl/), and the three types of differences between long and short vowels (phonological vs. temporal vs. spectral). To avoid infinite values, rates of 100% were converted to 99% and rates of 0% were converted to 1% (see Macmillan & Creelman, 1991).

The computed d’ (max. = 5.1) were then used as a data basis for a three-factorial omnibus ANOVA with the between-subject factor Group (dyslexics vs. controls) and the within-subject factors Type of difference (phonological vs. temporal vs. spectral) and Vowel type (/iː-ɪl/ vs. /oː-ɔl/ vs. /aː-æl/). Post hoc analyses were performed with follow-up ANOVAs, t-tests for independent samples and/or paired t-tests. For ANOVAs, the effect size partial η² was computed using SPSS. For t-tests, the effect size Cohen’s d was computed using G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007).

3. Results

The omnibus ANOVA revealed three main effects: First, a main effect of Group, F(1, 36) = 22.99, p < .001, partial η² = .39, with dyslexics performing worse than controls (dyslexics: M = 2.68, SD = .84; controls: M = 3.69, SD = .35). Second, a main effect of Type of difference, F(2, 72) = 127.09, p < .001, partial η² = .78, with pairwise comparisons revealing that performance in the phonological condition (M = 4.09, SD = 1.11) was better than in the temporal condition (M = 2.26, SD = .85, p < .001,
Cohen’s $d = 2.14$) as well as in the spectral condition ($M = 3.19$, $SD = .75$, $p < .001$, Cohen’s $d = 1.53$) and that performance was also better in the spectral condition than in the temporal condition ($p < .001$, Cohen’s $d = 1.36$). Third, a main effect of Vowel type, $F(2, 72) = 26.28$, $p < .001$, partial $\eta^2 = .42$, with pairwise comparisons showing that performance for vowel pair /a:-O/ ($M = 3.58$, $SD = .90$) was better than for vowel pair /i:-I/ ($M = 3.16$, $SD = .86$, $p < .01$, Cohen’s $d = .59$) and for vowel pair /a:-a/ ($M = 2.81$, $SD = .94$, $p < .001$, Cohen’s $d = 1.32$). Moreover, performance for the vowel pair /i:-I/ was better than that for vowel pair /a:-a/ ($p < .01$, Cohen’s $d = .53$).

The interaction between Type of difference $\times$ Vowel type was found to be significant, $F(4, 144) = 161.55$, $p < .001$, partial $\eta^2 = .82$. The post hoc examination of this interaction showed that the sensitivity indices found in the three experimental conditions were highly dependent on the vowel type under consideration (see Fig. 1a–c). Pairwise comparisons within the type of difference categories revealed that in the phonological condition, performance for vowel type /a:-a/ ($M = 3.88$, $SD = 1.39$) was worse than for vowel type /i:-I/ ($M = 4.12$, $SD = 1.10$, $p < .05$, Cohen’s $d = .36$) and vowel type /o:-O/ ($M = 4.28$, $SD = 1.08$, $p < .01$, Cohen’s $d = .44$). In the temporal condition, performance for vowel type /i:-I/ ($M = 1.23$, $SD = 1.09$) was worse than for vowel type /o:-O/ ($M = 2.15$, $SD = 1.12$, $p < .001$, Cohen’s $d = .75$) and /a:-a/ ($M = 3.41$, $SD = 1.11$, $p < .001$, Cohen’s $d = 1.56$). Additionally, performance for vowel type /o:-O/ was worse than for vowel type /a:-a/ ($p < .001$, Cohen’s $d = 1.26$) in the spectral condition, the same pattern as in the phonological condition was found: Performance for vowel type /a:-a/ ($M = 1.14$, $SD = 1.01$) was worse than for vowel type /i:-I/ ($M = 4.12$, $SD = .96$, $p < .001$, Cohen’s $d = 2.47$) and vowel type /o:-O/ ($M = 4.31$, $SD = .97$, $p < .001$, Cohen’s $d = 2.71$). Likewise, pairwise comparisons within vowel types showed that performance for vowel type /i:-I/ was worse in the temporal ($M = 1.23$, $SD = 1.09$) than in the phonological ($M = 4.12$, $SD = 1.10$, $p < .001$, Cohen’s $d = 2.51$) and spectral condition ($M = 4.12$, $SD = .96$, $p < .001$, Cohen’s $d = 2.93$). Similarly, the performance for vowel type /o:-O/ was worse in the temporal ($M = 2.16$, $SD = 1.12$) than in the phonological ($M = 4.28$, $SD = 1.08$, $p < .001$, Cohen’s $d = 1.79$) and spectral condition ($M = 4.31$, $SD = .97$, $p < .001$, Cohen’s $d = 2.02$). The performance for vowel type /a:-a/, on the contrary, declined from the phonological to the temporal and to the spectral condition: The performance for this vowel type was worse for the spectral ($M = 1.14$, $SD = 1.01$) than the phonological ($M = 3.88$, $SD = 1.39$, $p < .001$, Cohen’s $d = 1.90$) and temporal condition ($M = 3.41$, $SD = 1.11$, $p < .001$, Cohen’s $d = 1.87$), and performance for the temporal condition was worse than for the phonological condition ($p < .01$, Cohen’s $d = .47$). This rather complex pattern of interactions between vowel type and type of difference was largely expected, as the saliency of temporal and spectral cues in vowel length perception depends on vowel type: For the high vowel pair /i:-I/, spectral differences are more pronounced and this vowel pair thus receives better results in the spectral condition. On the contrary, the low vowel pair /a:-a/ has the largest temporal differences between long and short vowels (see also Table 2) and thus receives the best results in the temporal condition.

There was no interaction between Type of difference $\times$ Group, $F(2, 72) = 2.54$, $p = .10$. That means that differences between groups concerning $d'$ were not dependent on the type of difference between long and short vowels (phonological vs. temporal vs. spectral). Similarly, the interaction Vowel type $\times$ Group did not turn out to be significant, $F(2, 72) = 1.45$, $p = .24$. Thus, group differences concerning $d'$ were not dependent on vowel type ( /i:-I/ vs. /o:-O/ vs. /a:-a/).

Finally, the three-way interaction Group $\times$ Type of difference $\times$ Vowel type turned out to be significant, $F(4, 144) = 3.40$, $p < .05$, partial $\eta^2 = .09$. Post hoc tests were based on the results of two-factorial follow-up ANOVAs.

In the phonological condition (see Fig. 1a), the main effects of Group, $F(1, 36) = 16.01$, $p < .001$, partial $\eta^2 = .31$, and Vowel type, $F(2, 72) = 5.70$, $p < .01$, partial $\eta^2 = .14$, as well as the interaction of Group and Vowel type, $F(2, 72) = 4.58$, $p < .05$, partial $\eta^2 = .11$, were significant. Dyslexics’ performance was worse than that of controls for all three vowel types ($p < .001$, Cohen’s $d = 1.39$, for /a:-a/; $p < .05$, Cohen’s $d = .87$, for /o:-O/; $p < .01$, Cohen’s $d = 1.26$, for /i:-I/). Performance did not change with vowel type in controls ($p > .68$). In dyslexics, however, performance was worse for /a:-a/ than for /o:-O/ ($p < .01$, Cohen’s $d = .77$) and /i:-I/ ($p < .05$, Cohen’s $d = .55$).

In the temporal condition (see Fig. 1b), the main effects of Group, $F(1, 36) = 25.82$, $p < .001$, partial $\eta^2 = .42$, and Vowel type, $F(2, 72) = 65.03$, $p < .001$, partial $\eta^2 = .64$, as well as the interaction of Vowel type and Group, $F(2, 72) = 3.31$, $p < .05$, partial $\eta^2 = .08$, were again significant. Controls showed a higher performance than dyslexics for vowel type /a:-a/ ($p < .001$, Cohen’s $d = 1.99$) and vowel type /o:-O/ ($p < .01$, Cohen’s $d = 1.17$), but not for vowel type /i:-I/ ($p = .11$). For a proper interpretation of the latter result one has to consider that both groups showed rather low performance when the discrimination of /i/ and /I/ was based on the non-salient temporal cue. In both groups, performance linearly decreased from /a:-a/ over /o:-O/ to /i:-I/ in the temporal condition ($p < .05$, Cohen’s $d = .51$, for /o:-O/ vs. /i:-I/ in the dyslexic group; all other differences $p < .001$, Cohen’s $d > 1.05$).

In the spectral condition (see Fig. 1c), there was a main effect of Group, $F(1, 36) = 11.00$, $p < .01$, partial $\eta^2 = .23$, and Vowel type, $F(2, 72) = 200.19$, $p < .001$, partial $\eta^2 = .85$, but no interaction of these two factors, $F(2, 72) = .87$, $p = .42$, i.e. dyslexics’ performance was inferior to that of controls for all three vowel types. Both groups showed lower performance for the vowel type /a:-a/ than for the vowel types /o:-O/ and /i:-I/ (all $p < .001$, all Cohen’s $d > 2.32$) in the spectral condition.

In addition to comparisons between the dyslexic vs. control group, we classified each individual child of the dyslexic group ($n = 19$) with respect to his or her individual processing deficits (see Ramus et al., 2003; White et al., 2006, for a similar approach). Children were rated as having a processing deficit in a specific auditory processing domain (phonological vs. temporal vs. spectral) if their performance was at least 1 SD below the mean of the control group for at least two of the three vowel categories. The results are illustrated in Fig. 2.
Fig. 1. Performance (sensitivity index $d'$; max. = 5.1) of dyslexics vs. controls in (a) phonological vs. (b) temporal vs. (c) spectral vowel length discrimination for the three vowel categories tested. The graph depicts standard errors.
4. Discussion

The aim of the present study was to investigate phonological vs. temporal vs. spectral aspects of vowel length processing in a sample of German primary school children with developmental dyslexia. In a behavioural same-different experiment, pairs of German vowels, each embedded into monosyllabic pseudo-words, had to be compared. The sensitivity ($d'$) of vowel length discrimination was analysed. The discrimination of vowel lengths is a phonological task, as vowel length is phonemic in German. Long and short German vowels differ with respect to both their temporal (quantity) and spectral (quality) content. There were three types of difference. In the phonological condition, both temporal and spectral information was available for discrimination. In the temporal condition, spectral information was kept constant between the two vowels, thus the two vowels within the syllables differed only with respect to their temporal content. In the spectral condition, temporal information was kept constant between the two vowels, thus the two vowels within the syllables differed only with respect to their spectral content.

4.1. Phonological, temporal and spectral processing of vowel length in German primary school children

Both groups performed better in the phonological condition than in the temporal and spectral condition. This was expected because in the phonological condition spectral and temporal information call jointly for the response category required. In the phonological condition, performance for all three vowel types was equally good in controls. In dyslexics, in contrast, performance was worse for the vowel pair /a:-a/ than for the other two vowel pairs. This is a first hint that dyslexics might be especially impaired in the processing of temporal information: Duration is the salient cue for the distinction between /a:/ and /a/ (see also Table 2), whereas spectral cues are besides temporal information relevant for the perception of the /o:-O/ distinction, and are even the most important cue for the /i:-I/ distinction (Sendlmeier, 1981; Weiss, 1974).

In the temporal condition, a dependency of performance on vowel category was expected: From the seven German vowel pairs with differences in vowel length, we chose for the current study those pairs which are characterized by a linear decline in temporal difference from the low vowel pair /a:-a/ to the high vowel pair /i:-I/. We expected that the performance of all children would depend on the temporal difference between long and short vowel of a pair, a result that would replicate the results of our adult study (Groth et al., 2011). Indeed, in the temporal condition, children’s performance linearly deteriorated in both groups from /a:-a/ to /i:-I/.

In the spectral condition, performance of both groups was better than in the temporal condition. As was explained in the last paragraph, the choice of the three vowel categories included in the study depended on the temporal differences between long and short vowels, not on the spectral differences between them. For both the vowel type /o:-O/ and /i:-I/, the spectral difference between long and short vowel is a rather salient cue for vowel length perception (Sendlmeier, 1981; Weiss, 1974). Thus, in the spectral condition, the discrimination task was rather easy for two out of three vowel types. On the contrary, in the temporal condition, the discrimination task was of low difficulty for /a:-a/, of medium difficulty for /o:-O/ and of high difficulty for /i:-I/. This explains why both groups performed better in the spectral than in the temporal condition.

4.2. Group differences in phonological, temporal and spectral vowel length processing

In the phonological condition, group effects were found for all three vowel types, with dyslexics’ performance being inferior to that of controls. It is not likely that these group effects are due to differences in attentional abilities, as the experiment was divided into four parts with the same difficulty and performance of both groups did not change over time. Thus, it can be concluded that primary school children with dyslexia are impaired in phonological vowel length processing. This result is in accordance with other studies finding deficits in vowel length perception in German reading or spelling disabled children (Klatte, Steinbrink, Bergström, & Lachmann, 2013; Landerl, 2003) and shows that dyslexic children can...
even be impaired in very simple phonological processing tasks like vowel length discrimination. In general, however, the results concerning speech perception deficits in dyslexic children and adults are quite mixed: Some studies with children report evidence for speech perception deficits in dyslexia (Godfrey et al., 1981; Mody et al., 1997; Werker & Tries, 1987), while others find speech perception deficits only for subgroups of dyslexics (Adlard & Hazan, 1998; Joanisse, Manis, Keating, & Seidenberg, 2000; Manis et al., 1997) or only when speech is presented in noise (Ziegler, Pech-Georgel, George, & Lorenzo, 2009). Likewise, some studies with adults find deficits in speech perception abilities in dyslexia (Lieberman, Meskill, Chatillon, & Schupack, 1985; Steffens, Eilers, Gross-Glenn, & Jallad, 1992), while others do not (Groth et al., 2011; Pennington, van Orden, Smith, Green, & Halit, 1990).

Methodological differences such as differences in task and stimuli might explain these discrepant findings (Banai & Ahissar, 2006; Blomert & Mitterer, 2004; see McBride-Chang, 1995, for a review of speech perception studies in dyslexia). Interestingly, while in the present study we observed deficits in phonological vowel length discrimination in dyslexic children, we did not find such deficits in a former study with dyslexic adults (Groth et al., 2011) in which the same task and stimuli were used. This pattern of results is in favour of developmental changes of speech perception deficits in dyslexia, i.e. maturational factors and/or experience with the tasks tested might modulate the cognitive deficits associated with dyslexia: Deficits in speech perception present in childhood might hamper the development of reading and spelling, but might then be overcome in the course of development. This hypothesis is, however, in contrast with the results from two studies with English samples that used the same battery of speech tasks with dyslexic adults (Hazen, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009) vs. children (Messaoud-Galusi, Hazan, & Rosen, 2011). Although these studies gave only little support for a general speech perception deficit in dyslexia, both age groups were impaired in across-category discrimination using a fixed-level procedure in quiet – a task and procedure comparable to the one used in our studies with German samples. Thus, for dyslexic children, both, the English (Messaoud-Galusi et al., 2011) and the current German study found deficits in across-category discrimination. For dyslexic adults, however, only the English study (Hazen et al., 2009), but not the German study (Groth et al., 2011) revealed impairments in across-category discrimination. This difference might well be explained by the fact that the stimuli used in our German studies (vowels) are easier to discriminate than the stimuli used in the two English studies (plosive consonants). Thus, speech perception deficits in dyslexia might only recover with age under certain circumstances, e.g. when phoneme discrimination difficulty is rather low.

In the temporal condition, when only temporal information was available for vowel length discrimination, dyslexics’ performance was inferior to that of controls in two out of three vowel types (i.e. /a:-a/ and /o:-O/). Concerning the vowel pair /i:-I/, no group differences were observed. In the temporal vowel length discrimination task, the vowel type /i:-I/ is the most difficult vowel category, as the differences between the long and short vowel are shorter than in the two other vowel categories (see Table 2). Both dyslexic and typically developing children show rather low performance in this task. From a developmental perspective, it is interesting to compare the results on temporal processing from the former adult study (Groth et al., 2011) with those of the current study with primary school children. For all three vowel categories tested in both groups, typically developing adults tend to perform better than typically developing children as is revealed by hit rates (/a:-a/: children: 86.1%; adults: 96.5%; /o:-O/: children: 50.6%; adults: 85.3%; /i:-I/: children: 22.4%; adults: 65.3%; see Groth et al., 2011, Fig. 1b and c). The difference between typically developing adults vs. children in this temporal vowel length discrimination task indicates that auditory temporal processing abilities improve from childhood to adulthood (see also Steinbrink, Zimmer, Lachmann, Dirichs, & Kammer, 2014). The comparison between dyslexic children and adults shows that temporal processing abilities in dyslexics also tend to improve over time, as revealed by hit rates (/a:-a/: children: 64.5%; adults: 89.1%; /o:-O/: children: 38.8%; adults: 68.1%; /i:-I/: children: 23.0%; adults: 47.8%; see Groth et al., 2011, Fig. 1b and c). Still, in the child as well as in the adult sample, dyslexics are inferior to controls in temporal auditory processing of vowel length, which can be interpreted as a stable temporal processing deficit in dyslexia which does not disappear with age. This pattern of results is in accordance with that of Vandermosten et al. (2010, 2011), who, using the same experimental design with both adults and children, found that there is a developmental progress in temporal processing in both dyslexics and controls, but that dyslexics lag behind in temporal auditory processing abilities in both childhood and adulthood.

In the spectral condition, when only spectral information was available for vowel length discrimination, dyslexics’ performance was worse than that of controls for all three vowel types. This result can be interpreted as evidence for a spectral processing deficit in dyslexia and is in line with other reports of frequency discrimination deficits in dyslexics (e.g. Ahissar et al., 2000; France et al., 2002; Halliday & Bishop, 2006).

Taken together, the results suggest that German dyslexic children are impaired in phonological as well as temporal as well as spectral processing of vowel length. Thus, deficits in phoneme perception may arise from deficits in processing temporal and spectral information in the speech signal. Phoneme perception deficits, in turn, may result in less robust phonological representations in long-term memory that impair the development of other aspects of phonological processing, such as phonological awareness (Manis et al., 1997). As vowel length perception was the only phonological task investigated in this study, the role of temporal and spectral processing skills for other aspects of phonological processing remains, however, unclear.

4.3. Individual profiles of vowel length perception deficits in dyslexic children

The analysis of individual phonological and auditory processing deficits in dyslexics revealed that nearly half of the participants of our study showed deficits in all three aspects (i.e. phonological, temporal and spectral) of vowel length
processing (see Fig. 2). For single children, isolated deficits in phonological, temporal or spectral processing of vowel length were found. Interestingly, about one fifth of the dyslexic children showed no deficits at all. This latter result is in favour of the notion of diagnostic subgroups of dyslexia that are characterized by different core deficits (see also Heim et al., 2008; Joaissé et al., 2000; Lachmann et al., 2005). Additionally, it is worth mentioning that eight out of 19 dyslexic children did not show a deficit in phonological processing of vowel length, although phonological processing deficits are generally viewed as core symptoms of dyslexia (Ramus et al., 2003; White et al., 2006). It has to be kept in mind, however, that vowel length discrimination is a rather simple phonological task. More complex and more difficult phonological processing tasks might have revealed phonological processing problems in a larger sub-sample of dyslexic children.

5. Conclusions

In the current study we found evidence that dyslexic primary school children as a group are impaired in phonological as well as temporal as well as spectral processing of vowel length. This pattern of results suggests a general auditory processing deficit in dyslexia, which encompasses both temporal and spectral auditory processing. Deficits in phonological processing, and specifically in phoneme perception, might emerge as a consequence of these general auditory processing deficits.

The comparison of the results of the current child study with our former vowel length discrimination study with adolescents and adults (Groth et al., 2011) reveals on the one hand that deficits in simple phonological tasks such as vowel discrimination may exist at an earlier age, but may then recover over the course of development. Such developmental processes might be one factor explaining discrepant findings concerning phoneme perception deficits in dyslexia. On the other hand, the comparison of the adult and the child study suggests that temporal processing abilities improve over time both in unimpaired and dyslexic readers, but that the temporal processing deficit in dyslexia still persists over time.

Analyses at an individual level revealed that many, but not all dyslexic children were characterized by phonological and/or auditory processing deficits. This indicates that there might be subgroups of dyslexics that are characterized by different core deficits. The use of a rather simple phonological task might be one factor explaining why nearly half of the dyslexic sample did not show phonological processing deficits.

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