Evidence for a General Auditory Processing Deficit in Developmental Dyslexia From a Discrimination Paradigm Using Speech Versus Nonspeech Sounds Matched in Complexity

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Purpose: It is unknown whether phonological deficits are the primary cause of developmental dyslexia or whether they represent a secondary symptom resulting from impairments in processing basic acoustic parameters of speech. This might be due, in part, to methodological difficulties. Our aim was to overcome two of these difficulties: the comparability of stimulus material and task in speech versus nonspeech conditions.

Method: In this study, the authors (a) assessed auditory processing of German vowel center stimuli, spectrally rotated versions of these stimuli, and bands of formants; (b) used the same task for linguistic and nonlinguistic conditions; and (c) varied systematically temporal and spectral parameters inherent in the German vowel system.

Forty-two adolescents and adults with and without reading disabilities participated.

Results: Group differences were found for all linguistic and nonspeech conditions for both temporal and spectral parameters. Auditory deficits were identified in most but not all participants with dyslexia. These deficits were not restricted to speech stimuli—they were also found for nonspeech stimuli with equal and lower complexity compared with the vowel stimuli. Temporal deficits were not observed in isolation.

Conclusion: These results support the existence of a general auditory processing impairment in developmental dyslexia.

The terms developmental dyslexia or specific reading disorder refer to specific difficulties in learning to read despite normal intelligence, unaffected sensory abilities, motivation, and conventional instruction (American Psychiatric Association, 1994; Démenet, Taylor, & Chaix, 2004). These difficulties are supposed to be evident during childhood and can be accompanied by poor spelling performance (Dilling & Freyberger, 2012). Longitudinal studies indicate that dyslexia is a persistent condition and does not represent a “transient developmental lag” (Shaywitz & Shaywitz, 2005; Svensson & Jacobson, 2006). This definition of dyslexia is simply descriptive because after more than 100 years of research, consensus about the etiological basis of dyslexia is still lacking to date, although there is general agreement that the disorder has a neurobiological basis (for a review, see Démenet et al., 2004; Gabrieli, 2009; Habib, 2000).

On the behavioral level, dyslexia is characterized by phonological deficits (Ramus et al., 2003; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Wagner & Torgesen, 1987). These deficits have been found for phonological recoding in (a) lexical access, as assessed by rapid picture naming (Denckla & Rudel, 1976; Swan & Goswami, 1997); (b) phonological awareness—that is, the ability to consciously access and manipulate the sound units of language (Bradley & Bryant, 1983; Bruck, 1992; Elbro & Jensen, 2005); and (c) phonological short-term memory, as assessed by immediate serial recall of unrelated verbal items such as digits or words or by nonword repetition (Jeffries & Everatt, 2004; Nelson & Warrington, 1980; Steinbrink & Klatte, 2008). Developmental dyslexia is also associated with deficits in the perception of phonemes (Adlard & Hazan, 1998; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Manis et al., 1997; Mody,)
these representations and strictly reject Laasonen, Service, & Virsu, 2001; for a review, see Vol. 58 121 Journal of Speech, Language, and Hearing Research February 2015 Support for the temporal processing theory comes accepted. The reasons are that, first, some psychophysical processing theory of dyslexia is, however, far from being widely van Ingelhem et al., 2001; for review, see Farmer & Klein, Sapir, 2007; Heiervang, Stevenson, & Hugdahl, 2002; Farmer & Klein, 1995) and children (Cohen-Mimran & 2005; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998). Second, some studies investigated different auditory processing functions and found that auditory processing problems of persons with dyslexia are not confined to temporal aspects ( Amitay, Ahissar, & Nelken, 2002). Many of these studies suggested that the processing of temporal as well as spectral (frequency) information in the auditory signal is impaired in developmental dyslexia ( Ahissar et al., 2000; Cacace, McFarland, Ouimet, Schriber, & Morro, 2000; King, Lombardino, Crandell, & Leonard, 2003; Montgomery, Morris, Sevick, & Clarkson, 2005; Walker, Givens, Cranford, Holbert, & Walker, 2006). In this context, Ahissar et al. (2000) proposed that fine representation of spectral and temporal details of acoustic features facilitates the encoding of acoustic patterns into phonological representations.

To summarize, there is a general agreement that phonological processing abilities are impaired in developmental dyslexia. The underlying cause of these phonological problems is, however, hotly debated.

**German Vowel Length Paradigm**

In experiments dealing with phonological versus auditory processing deficits in developmental dyslexia, different tasks and stimuli usually are employed to study phonological versus auditory processing, respectively. As already mentioned, tasks such as phoneme deletion, nonword repetition, and rapid automatized naming have been used for the investigation of phonological deficits, whereas temporal order judgments (see, e.g., Tallal, 1980), gap detection (see, e.g., van Ingelhem et al., 2001), same–different judgments with two (see, e.g., Groth, Lachmann, Riecker, Muthmann, & Steinbrink, 2011) or more (see, e.g., Hill, Bailey, Griffiths, & Snowling, 1999; Vandermosten et al., 2010) stimuli, and high–low discrimination (see, e.g., Banai & Ahissar, 2006) were applied to detect auditory deficits in dyslexia. Banai and Ahissar (2006) were able to show that the performance of participants with dyslexia is dependent on the type of task. Performance decreases with increasing working memory load. This could be one reason why phonological deficits have been found more frequently compared with auditory deficits. The authors proposed to use a same–different task with two stimuli in order to avoid a confounding with working memory load.

The second methodological difference concerns the chosen stimuli: Phonological tasks involve speech stimuli, whereas nonspeech stimuli such as sinusoidal tones have been used to detect auditory deficits (see, e.g., Bredin, Martin, & Jerger, 1989; Lachmann et al., 2005). As these stimuli show a much lower physical complexity compared with speech, they may not be optimal for discovering the auditory deficits. Very few studies (but see Vandermosten et al., 2010, 2011) controlled for the complexity of the nonspeech stimuli, which might confound the results (Parviainen, Helenius, & Salmelin, 2005; Scott & Wise, 2004).
To overcome these methodological difficulties, our group developed a same–different discrimination paradigm based on the German vowel system (see Groth et al., 2011; Steinbrink, Klatte, & Lachmann, 2014). In German, 14 monophthongs can be grouped into seven pairs of vowels that differ exclusively with respect to vowel length (long vs. short; Lühr, 2000). Vowel length is phonemic. This means that it signals differences in meaning. For example, the vowels within the spoken word pairs Schiff ([ʃɪːf], [ʃip]) versus schief ([ʃiːf], [ʃkɛːf]) or kann ([kʌn], [kan]) versus Kahn ([kɑːn], [bɑrɡɛ]) differ in vowel length. Long and short vowels differ not only with respect to their durational length but also with respect to their spectral quality (for details, see Groth et al., 2011). The relative impact of durational and spectral cues for the correct identification of a German vowel is dependent on its vowel height (Weiss, 1974), which is defined by the tongue position during articulation of the vowel. For the low vowel pair /aː/ versus /a/, the durational difference is more salient than the spectral distinction (Ungeheuer, 1969), whereas the vowels of the high vowel pair /iː/ versus /l/, the durational difference is more salient than the speech stimulus. The same task and stimuli were used in a study with primary school children with and without dyslexia compared with age-matched controls (temporal condition). Contrary to this finding, discrimination was not impaired when both temporal and spectral information was available (spectrotemporal condition). This was accomplished by (a) controlling for stimulus complexity by using German vowels as tonic cues of interest from vowel stimuli (i.e., from speech stimuli). Thus, one question that remains open is whether temporal, spectral, and spectrotemporal deficits in dyslexia are also found in the processing of nonspeech stimuli. To investigate this, the German vowel length paradigm was extended with nonspeech sounds in the present experiment. In order to test the influence of stimulus complexity, two different types of nonspeech stimuli were used: one with the same complexity compared to the speech sounds and one with lower complexity. Furthermore, the differences between stimuli should be kept constant for the speech and nonspeech conditions. If one condition is easier than the other one, possible group differences for the easier condition might not be observable due to ceiling effects. This assumption is supported by a review by Bishop (2007): In the context of the preattentive discrimination (mismatch negativity) of frequency changes in nonspeech sounds, group differences between participants with and without dyslexia are hardly found when the frequency changes are greater than 10%. Smaller frequency changes result in measureable group differences. This idea is not limited to nonspeech sounds, as it has already been stated that speech perception deficits in dyslexia are only very subtle and are therefore hard to discover (Mody et al., 1997). The aims of this experiment were to study spectrotemporal, spectral, and temporal aspects of auditory processing within linguistic and nonlinguistic stimulus material in developmental dyslexia by extending the German vowel length discrimination paradigm described above with additional nonlinguistic conditions. According to the phonological hypothesis, differences between persons with and without dyslexia should be found for the vowel center stimuli but not for the nonspeech stimuli. According to the temporal processing theory, group differences should be found in the temporal conditions, independently from stimulus type (speech or nonspeech). Finally, if auditory processing is impaired in a more general way in developmental dyslexia, group differences should also be found in the spectral condition.

Care was taken to avoid methodological differences between linguistic and nonlinguistic conditions that might confound the results. This was accomplished by (a) controlling for stimulus complexity by using German vowels as
linguistic stimuli and nonspeech counterparts of these vowels with the same stimulus complexity as nonlinguistic stimuli while additionally investigating the processing of less complex nonlinguistic stimuli that maintain the most salient frequencies of the speech signal, (b) controlling for task-specific influences by using the same discrimination task in all conditions, and (c) controlling for stimulus differences by employing strictly the same physical differences between stimuli in both the linguistic and nonlinguistic conditions.

Materials and Method

Participants

Twenty-one adolescents and young adults with the diagnosis of developmental dyslexia (nine women, 12 men) and 21 control participants (10 women, 11 men)—matched with respect to intelligence, sex, and age—took part in this study. The age range was between 14 and 25 years ($M = 18.79$ years, $SD = 2.86$ years). All participants were monolingual native speakers of German. None of the participants reported a history of neurological diseases, psychiatric disorders, or hearing problems. Participants with attention problems were excluded from the study. Informed consent was obtained from every participant or from his or her parents, depending on the participant’s age.

Participants with dyslexia had been diagnosed in primary school and had a documented history of both reading and spelling difficulties across their entire school career persisting to date. All participants completed tests of nonverbal intelligence, reading, and spelling up to 4 weeks before the experiment. One inclusion criterion for participation was an average or above-average nonverbal intelligence as measured by the Culture Fair Intelligence Test (German version; Weiß, 2006). An IQ of 81 was chosen as the cutoff, as this value corresponds to 1 SD below the mean with the correction of the confidence interval (4 IQ points). Every participant completed standardized tests of reading and spelling. For the evaluation of reading abilities, we used a German reading test for adults that measured reading time and reading errors for real words and pseudowords (Schulte-Körne, 2001). Spelling was measured with a standardized German spelling test for adults (Kersting & Althoff, 2004). Table 1 shows that the two groups were comparable with respect to age and intelligence, whereas the control group significantly outperformed the group with dyslexia in all measures of reading and spelling.

Stimulus Generation

Within each of the two vowel-pair groups (/a:/–/a:/ and /i:/–/i:/), three stimulus types were used: vowel center stimuli, spectrally rotated vowel center stimuli, and bands of formants (for details, see Christmann et al., 2014). As explained in greater detail below, there were four versions of each stimulus type: long, short, lengthened, and shortened (see online supplemental materials for the vowel pair /I/–/i:/). Contrasts between the different versions of these stimulus types form the basis for the different conditions of a same–different task: (a) the original short vowel and the original long vowel for the spectrotemporal condition, (b) the original short vowel and the lengthened short vowel or rather the original long vowel and the shortened long vowel for the temporal condition, and (c) the original short vowel and the shortened long vowel or rather the original long vowel and the lengthened short vowel for the spectral condition.

The intensity was about 80 dBA for each stimulus type and all versions of them. This was guaranteed by additional measurements with an artificial head (HSM III.0, Head Acoustics, Aachen, Germany).

Vowel Center Stimuli

Vowel center stimuli were based on two naturally spoken vowel pairs: /a:/–/a:/ and /i:/–/i:/. These isolated vowels are no lexical items in German. The vowels were pronounced in isolation by a trained female speaker whose native language is German. In order to get the static spectral information of each vowel only, everything except the steady-state part was removed. The pitch was kept constant within one vowel pair. The duration of the long and short vowels was brought into line with those reported by Groth et al. (2011): 75 ms for /a/, 145 ms for /a:/, 51 ms for /I/, and 93 ms for /i:/.

Intensity of the vowels was kept constant by setting the scale intensity in Praat (Boersma, 2001; Boersma & Weenink, 2013) to 75 dB.

The Pitch Synchronous Overlap and Add algorithm of Praat was used to change the length of the vowels without distorting their spectral properties. The short vowel center stimulus was lengthened to the duration of the long one (/a/ lengthened to 145 ms and /I/ lengthened to 93 ms), and the long vowel center stimulus was shortened to the duration of the short one (/a:/ shortened to 75 ms and /i:/ shortened to 51 ms). As a result, there were four stimuli for each vowel pair: the original short–long pair and the modified stimulus pair (see also online supplemental materials). The first and last 5 ms of each stimulus were faded with Adobe Audition (Version CS5.5; Adobe, München, Germany).

In contrast to previous studies with our German vowel length discrimination paradigm (Groth et al., 2011; Steinbrink et al., 2012; Steinbrink, Klatte, et al., 2014), vowels used in the present study were not embedded into CVC syllables but rather were presented in isolation. The reason for this is that in a pilot experiment in which we used CVC syllables and their spectrally rotated counterparts, most participants reported that the spectrally rotated CVC stimuli still sounded like speech. This observation is in line with the finding by Azadpour and Balaban (2008) that spectrally rotated speech syllables might be processed using phonological representations. This kind of information processing might be triggered by the consonants, as some spectrally rotated consonants may still be perceived as consonants (e.g., fricatives and plosives; for details, see Bless, 1972). Thus, in the current experiment, isolated vowels were used to ensure that spectrally rotated versions of these vowels would bear no resemblance to speech. As is reported
in greater detail later, the spectrally rotated vowels were indeed classified as less speechlike than the vowels.

**Spectrally Rotated Vowel Center Stimuli**

For each of the eight vowel center stimuli, one spectrally rotated counterpart was produced (Blesser, 1972). This was carried out in MATLAB (Version R2011a; MathWorks, Ismaning, Germany) using the script provided by Scott, Blank, Rosen, and Wise (2000). Comparable to prior research, 2000 Hz was chosen as the middle frequency at which all remaining frequencies were mirrored. One important shortcoming of this procedure is that the original speech signal must be low-pass filtered with 4000 Hz as the cutoff frequency. The intelligibility of the signal is not reduced in this way (Scott & Wise, 2004). Its naturalness, however, can be impaired severely (Moore & Tan, 2003). Therefore, the original speech sounds with the complete spectrum were used in the current study. To create corresponding spectrally rotated sounds, all frequencies of the vowel above 4000 Hz were added to the spectrally rotated stimulus with Adobe Audition (Version CS5.5; Adobe, München, Germany). As a result, only the lower part (below 4000 Hz) was modified by the inversion. The upper frequencies were not affected. These stimuli are supposed to be perceived as nonspeechlike.

**Bands of Formants**

The third stimulus type, bands of formants, is also assumed to be perceived as nonspeech while maintaining the most important information of the speech signal. It comprises only the first two formants of the vowel, including all bandwidth frequencies. The bandwidth of a vowel is the region of frequencies with an intensity of, at the most, 3 dB beneath the power of the formant (Fant, 1960). The relative intensity of the two formants was adapted to the formants’ intensity within the vowel center stimuli. All information that is necessary to produce the bands of formants is provided in Table 2.

The two bands were produced separately in MATLAB with a continuous Fourier synthesis. There is a Gaussian function in which the middle frequency corresponds to the formant of the vowel, and the half width corresponds to the bandwidth of the formant. This function is transformed numerically to the time domain by means of the fast Fourier transform. As a result, one gets a stimulus with a limited band of frequencies. The middle frequency shows the highest intensity, and the intensity of all frequencies decreases with increasing distance from the center. The resulting band is very short in duration. Therefore, phase noise is added to the frequency domain in order to lengthen the stimulus to the desired temporal duration. In a second step, the two bands

### Table 1. Age, nonverbal intelligence quotient (IQ), and reading and spelling test scores for a group with dyslexia and the control group.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group with dyslexia (n = 21)</th>
<th>Control group (n = 21)</th>
<th>p&lt;sup&gt;a&lt;/sup&gt;</th>
<th>d&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>19.10</td>
<td>18.48</td>
<td>.490</td>
<td>.233</td>
</tr>
<tr>
<td>Nonverbal IQ</td>
<td>102.86</td>
<td>107.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Real-word reading</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Errors (max = 48)</td>
<td>2.90</td>
<td>0.62</td>
<td>&lt; .001</td>
<td>1.28</td>
</tr>
<tr>
<td>Reading time (s)</td>
<td>55.95</td>
<td>42.29</td>
<td>.002</td>
<td>1.02</td>
</tr>
<tr>
<td>Pseudoword reading</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Errors (max = 48)</td>
<td>9.19</td>
<td>4.43</td>
<td>.008</td>
<td>0.86</td>
</tr>
<tr>
<td>Reading time (s)</td>
<td>102.52</td>
<td>70.10</td>
<td>&lt; .001</td>
<td>1.53</td>
</tr>
<tr>
<td>Spelling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Errors (max = 60)</td>
<td>36.24</td>
<td>13.38</td>
<td>&lt; .001</td>
<td>2.20</td>
</tr>
<tr>
<td>Standard score&lt;sup&gt;c&lt;/sup&gt;</td>
<td>81.52</td>
<td>103.00</td>
<td>&lt; .001</td>
<td>2.23</td>
</tr>
</tbody>
</table>

**Note.** Max = maximum.
<sup>a</sup>Independent-samples t test. <sup>b</sup>Effect size Cohen’s d for independent samples. <sup>c</sup>M = 100; SD = 10.

### Table 2. Summary of the most important information for creating the bands of formants based on the vowel center stimuli.

<table>
<thead>
<tr>
<th>Vowel type</th>
<th>Duration (ms)</th>
<th>F1 (Hz)</th>
<th>F2 (Hz)</th>
<th>B1 (Hz)</th>
<th>B2 (Hz)</th>
<th>ΔF1–F2 intensity (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>/a/</td>
<td>75</td>
<td>792</td>
<td>1302</td>
<td>166</td>
<td>161</td>
<td>4.06</td>
</tr>
<tr>
<td>/a:/</td>
<td>145</td>
<td>922</td>
<td>1272</td>
<td>284</td>
<td>225</td>
<td>1.28</td>
</tr>
<tr>
<td>/ɪ/</td>
<td>51</td>
<td>2117</td>
<td>89</td>
<td>124</td>
<td>16.92</td>
<td>27.31</td>
</tr>
<tr>
<td>/ɪ:/</td>
<td>93</td>
<td>338</td>
<td>2439</td>
<td>262</td>
<td>197</td>
<td></td>
</tr>
</tbody>
</table>

**Note.** The length of the stimulus is comparable to that of the vowel center stimulus. The center of the two bands is given by the first two formants (F1 and F2). The relative intensity of the two bands is adapted to the formants’ intensity within the vowel center stimuli. The width of the bands corresponds to the bandwidth of the formants (B1 and B2).
were mixed together in Adobe Audition (Version CS5.5; Adobe, München, Germany). The intensity of the bands of formants was comparable to that of the original formants. This is the reason why the first band shows a higher power than the second one (see Table 2).

**Ratings of the Three Stimulus Types**

After completing the experiment, participants were asked to rate all stimuli regarding their similarity to speech (on a scale of 1 to 7; 1 = *totally nonspeech*, 7 = *clearly speech*). In both groups, the vowel center stimuli were rated (control group, \( M = 5.52, SD = 1.50 \); group with dyslexia, \( M = 4.95, SD = 1.53 \)) as more similar to speech than (a) the spectrally rotated vowels group with dyslexia, \( p < .01 \); and (b) bands of formants group with dyslexia, \( p < .01 \). No difference was found between the spectrally rotated vowel center stimuli and the bands of formants: control group, \( t(20) = 10.59, p < .01 \); spectrally rotated vowels control group, \( M = 1.48, SD = 0.75, t(20) = 9.02, p < .01 \); and (b) bands of formants control group, \( M = 1.90, SD = 1.00, t(20) = 10.03, p < .01 \); bands of formants group with dyslexia, \( M = 1.71, SD = 1.15, t(20) = 8.93, p < .01 \). No difference was found between the spectrally rotated vowel center stimuli and the bands of formants: control group, \( t(20) = -0.87, p = .40 \); group with dyslexia, \( t(20) = 0.82, p = .42 \).

**Experimental Procedure**

We conducted an auditory two-alternative, forced-choice discrimination experiment. In this same–different task, pairs of vowel center stimuli, spectrally rotated vowel center stimuli, or bands of formants were presented successively, and participants had to decide whether they were the same or different.

There were three types of different trials (see also online supplemental materials). These are explained on the basis of the vowel center stimuli, as the features of the two nonspeech stimulus types are associated directly with those of the vowel center stimuli. In the spectrotemporal condition, vowel length differences were phonological in nature. Thus, only natural vowels were used; that is, an original long vowel was always combined with its original short counterpart. The two vowels of a pair 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 the spectral information of either 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. This means that both paired vowels carried the temporal information of either a long or a short vowel and differed exclusively with respect to spectral content.

There were three blocks, one for each stimulus type (vowel center stimuli, spectrally rotated vowel center stimuli, bands of formants). These blocks were counterbalanced across participants. In total, there were six different combinations for each of the three stimulus types: three experimental conditions (spectrotemporal, temporal, and spectral) and two vowel types (/a/-/a:/ and /l/-/i:/). Each combination was repeated 16 times, amounting to a total of 96 different trials used in each block of the experiment. An equivalent number of same trials were used to avoid response bias. For these, all stimuli used for the different trials were presented at an equal rate. Altogether, the whole experiment consisted of 576 trials.

All sessions took place in an acoustically shielded room. For stimulus delivery and experimental control, the software known as Presentation (Neurobehavioral Systems Inc., San Francisco, CA) was used. The sound files were presented using an external sound card (UGM96, ESI Audiotechnik GmbH, Leonberg, Germany) controlled by a laptop computer. Stimuli were presented with an intensity of 80 dBA, as measured by an artificial head (HSM III.0, Head Acoustics, Aachen, Germany), via closed headphones (DT 770, Beyerdynamic, Heilbronn, Germany).

Participants were asked to decide whether two vowel center stimuli, spectrally rotated vowel center stimuli, or bands of formants presented in succession were the same or different. They were instructed to respond as quickly and as accurately as possible. Responses were given via button press using a separate response unit. The interstimulus interval between the two syllables of a pair was 600 ms. The intertrial interval was 2,000 ms, starting with button press. Response latencies and accuracy were measured.

To familiarize participants with the task and the material, a practice phase comprising eight trials was conducted prior to the experiment. For this, sine waves that differed in temporal duration and/or spectral quality were presented. These stimuli did not form 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 45 min, including instruction and practice.

**Statistical Analysis**

To control for potential response biases, data were analyzed 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). As relative frequencies of 0 and 1 cannot be transformed into \( z \) values, a value of 0 was replaced by 0.01 and 1 was replaced by 0.99 (\( d'_{\text{minimum}} = 0, d'_{\text{maximum}} = 5.1 \); Macmillan & Creelman, 1991, p. 10).

A \( 3 \times 2 \times 3 \times 2 \) analysis of variance (ANOVA) with repeated measurement was conducted, including the within factors stimulus type (vowel center stimuli vs. spectrally rotated vowel center stimuli vs. bands of formants based on the vowel center stimuli), vowel type (/a/-/a:/ vs. /l/-/i:/).
and auditory contrast (temporal vs. spectral vs. spectrotemporal) and the group factor (group with dyslexia vs. control group). Greenhouse–Geisser correction was applied whenever the numerator degrees of freedom were 2 or more; uncorrected degrees of freedom and corrected p values are reported. Post hoc analyses were performed with follow-up ANOVA, independent-samples t tests, and/or paired t tests. For all group differences and mean differences within one sample, effect sizes according to Cohen (Cohen’s d in the context of t tests, Cohen’s f in the context of ANOVA) were calculated. Effects can be considered large with $d > 0.8$ and $f > 0.4$, medium with $d > 0.5$ and $f > 0.25$, and small with $d > 0.2$ and $f > 0.1$ (see Cohen, 1988).

Results

Speed–Accuracy Correlation

To rule out a speed–accuracy trade-off, the correlation between error rate and reaction time was calculated for each group. The biserial correlation coefficient was $r = -0.12$ ($p < .01$) for the control group and $r = -0.15$ ($p < .01$) for the group with dyslexia, indicating that correct responses were faster compared with incorrect responses in both groups.

Discrimination Accuracy

The ANOVA revealed four main effects. First, it revealed a main effect of group, $F(1, 40) = 11.98$, $p < .01$, effect size $f = 0.54$, with participants with dyslexia ($M = 2.96$, $SD = 0.59$) showing lower performance than the control group ($M = 3.60$, $SD = 0.60$; see also Figure 1). Second, it revealed a main effect of stimulus type, $F(2, 80) = 8.18$, $p < .01$. The spectrally rotated vowel center stimuli were easier to discriminate compared with the vowel center stimuli, $t(41) = 4.62$, $p < .01$, $d = 0.72$, and the bands of formants, $t(41) = 3.03$, $p = .01$, $d = 0.48$. The difference between the vowel center stimuli and bands of formants did not reach significance, $t(41) = -0.98$, $p = .33$. The main effect of auditory contrast was also found to be significant, $F(2, 80) = 87.49$, $p < .01$. The spectrotemporal condition was discriminated more accurately compared with the spectral condition, $t(41) = 7.68$, $p < .01$, $d = 1.19$, and the temporal condition, $t(41) = 11.40$, $p < .01$, $d = 1.76$. The temporal condition was discriminated less accurately compared with the spectral condition, $t(41) = -7.51$, $p < .01$, $d = 1.16$. There was a significant main effect of vowel type, $F(1, 40) = 7.58$, $p < .01$. The vowel pair /h/-/fi:/ was easier to discriminate compared with the vowel pair /al/-/aI:/, $t(41) = 2.70$, $p = .01$, $d = 0.42$. However, there was also a significant Stimulus Type × Vowel Type interaction, $F(2, 80) = 14.63$, $p < .01$. The difference of performance between the two vowel pairs /al/-/aI:/ and /h/-/fi:/ was significant only for the vowel center stimuli, $t(41) = -4.79$, $p < .01$, $d = 0.74$, and not for the two nonspeech stimulus types: rotated vowels, $t(41) = -0.90$, $p = .37$; bands of formants, $t(41) = 1.51$, $p = .138$.

Moreover, the ANOVA revealed a significant Stimulus Type × Auditory Contrast interaction, $F(4, 160) = 2.13$, $p < .01$. For the temporal condition, no significant differences between the different stimulus types were found, $F(2, 80) = -1.17$, $p = .31$, whereas discrimination performance varied systematically for the spectral condition, $F(2, 80) = 18.94$, $p < .01$, and for the spectrotemporal condition, $F(2, 80) = 7.11$, $p < .01$, for different types of stimulus as revealed by three additional ANOVAs. For the spectral condition, vowels were harder to discriminate compared with spectrally rotated vowels, $t(41) = -7.19$, $p < .01$, $d = 1.10$, and the bands of formants, $t(41) = -2.75$, $p < .01$, $d = 0.42$. Moreover, the bands of formats were harder to discriminate compared with the spectrally rotated vowels, $t(41) = -3.16$, $p < .01$, $d = 0.48$. For the spectrotemporal condition, there was no difference between the vowels and the bands of formants, $t(41) = 1.36$, $p = .18$. Both were harder to discriminate compared with the spectrally rotated vowels: for the vowels, $t(41) = -2.30$, $p = .03$, $d = 0.35$; for the bands of formants, $t(41) = 4.08$, $p < .01$, $d = 0.66$.

Furthermore, there was a significant Vowel Type × Auditory Contrast interaction, $F(2, 80) = 133.41$, $p < .01$. The vowel pair /h/-/fi:/ was harder to discriminate compared with the vowel pair /al/-/aI:/, but only in the temporal condition, $t(41) = -8.25$, $p < .01$, $d = 1.26$; the opposite pattern of results was found for the spectral condition, $t(41) = 10.08$, $p < .01$, $d = 1.55$, and for the spectrotemporal condition, $t(41) = 4.54$, $p < .01$, $d = 0.77$. The Stimulus Type × Vowel Type × Auditory Contrast interaction did not reach significance, $F(4, 160) = 34.53$, $p = .44$, nor did all interactions with the group factor.

There were no correlations between age and performance for any condition. Performance of both groups did not deteriorate over the course of the experiment, ruling out severe attention problems.

In order to determine how well participants can be classified as a person with dyslexia or a typical reader on the basis of their speech and nonspeech auditory perception performance, three different discriminant analyses—one for each stimulus type (vowels, spectrally rotated vowels, and bands of formants)—were conducted. The predictors were the discrimination performance for each auditory contrast (temporal, spectral, and spectrotemporal) and vowel type (/al/-/aI:/, /h/-/fi:/). A significant discrimination power was observed only for the two nonspeech conditions, spectrally rotated vowels, $\Lambda = .57$, $\chi^2(6) = 20.54$, $p < .01$, and bands of formants, $\Lambda = .63$, $\chi^2(6) = 17.26$, $p < .01$, and for the vowel center stimuli, $\Lambda = .77$, $\chi^2(6) = 9.70$, $p = .14$ ($\alpha_{\text{corrected}} = .016$). The classification results are depicted in Table 3. The percentage of correct classifications was 73.8% for the vowel center stimuli, 73.8% for the bands of formants, and 83.3% for the spectrally rotated vowels.

Three further discriminant analyses based on the different auditory contrasts (temporal, spectral, and spectrotemporal) revealed that only the spectral contrast was able to discriminate between the two groups: temporal condition, $\Lambda = .81$, $\chi^2(6) = 8.01$, $p < .24$; spectral condition, $\Lambda = .58$, $\chi^2(6) = 20.48$, $p < .01$; and spectrotemporal condition, $\Lambda = .74$, $\chi^2(6) = 11.42$, $p = .08$ ($\alpha_{\text{corrected}} = .016$). The percentage of correct classifications was 78.6% for the
Figure 1. Mean discrimination performance ($d'$ maximum = 5.1) for the group with dyslexia (gray) and the control group (black) in the spectrotemporal (top panel), temporal (middle panel), and spectral (bottom panel) conditions for each vowel pair (/a/–/a:/ vs. /ɪ/–/i:/) and each stimulus type. The error bars represent the standard error.
temporal condition, 76.2% for the spectral condition, and 71.4% for the spectrotemporal condition.

**Identification of Subgroups**

Comparable to Ramus et al. (2003) and White et al. (2006), each person with dyslexia was classified in accordance with his or her individual pattern of deficits. A deficit was defined as 1 SD or more under the control group’s performance (see also Steinbrink, Klatte, et al., 2014). This classification procedure was performed twice: one time for the three stimulus types (see Figure 2, upper panel) and one time for the three auditory contrasts (see Figure 2, lower panel). This procedure was useful for identifying profiles of auditory performance deficits in the group with dyslexia. Note, however, that the performance of the group with dyslexia is compared only to that of the control group and not to that of a control population.

The analysis with respect to stimulus types revealed that four individuals did not show any deficit at all. Only one participant with dyslexia showed impairment specifically for the vowel center stimuli. Eight of the remaining 16 participants with dyslexia showed deficits for both the vowel center stimuli and at least one nonspeech type of stimulus. The remaining eight participants showed impairment for nonspeech stimuli only.

Regarding the three auditory contrasts, there was not a single participant with dyslexia who had a specific temporal deficit. Nine participants with dyslexia showed deficits for all three auditory contrasts. Only two participants specifically showed impairment in spectral and spectrotemporal processing, respectively.

**Discussion**

The aim of the present study was to investigate temporal, spectral, and spectrotemporal auditory processing of vowels and nonspeech sounds with the same and lower complexity compared to vowels in a group of adults with dyslexia and in a group of age-matched controls. All stimuli were presented within a same–different task, as this task

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**Table 3. Classification results of the six discriminant analyses.**

Note. D = group with dyslexia; C = control group.

**Figure 2.** A: Classification of each participant with dyslexia depending on processing deficits for the three types of stimulus. B: Classification of each participant with dyslexia depending on processing deficits for the three auditory contrasts. Each dot represents one person.
Auditory Processing of Speech and Nonspeech in Developmental Dyslexia

The vowel length discrimination paradigm as introduced in Groth et al. (2011) and Steinbrink, Klatte, et al. (2014) was used in the present study. Therefore, we expected comparable results. In accordance with Groth et al. (2011) and Steinbrink, Klatte, et al. (2014), participants with dyslexia showed impairments in spectral and temporal vowel length discrimination. In addition, the control group outperformed the group with dyslexia in the spectrotemporal (i.e., phonological) condition. Deficits in phonological vowel length perception are frequently found in German children with dyslexia (Klatte, Steinbrink, Bergström, & Lachmann, 2013; Landerl, 2003; Steinbrink, Klatte, et al., 2014); therefore, this result as such is not surprising. However, the adults with dyslexia in the study by Groth et al. (2011) did not have any problems with this kind of task: The group with dyslexia as well as the control group showed near-perfect performance. Considering that the same task and paradigm were used in Groth et al. (2011) and that the present study deals with groups of a comparable age, some other methodological difference must explain the divergent pattern of results concerning the spectrotemporal discrimination performance in adults with dyslexia. In contrast to the present study, in which isolated vowel center stimuli were used, in the Groth et al. (2011) study, vowels were embedded into CVC syllables. It might be that the isolated vowels presented in the current study are more difficult to discriminate than vowels embedded into CVC syllables. This assumption is supported both by the somewhat lower performance of the control group in the current study and by the deficit in phonological (spectrotemporal) vowel length perception for the group with dyslexia. Thus, under certain task demands, deficits in phonological vowel length perception can be found even in adults with dyslexia.

The temporal deficit was also found for both nonspeech stimulus types. This result is in line with prior studies that dealt with the ability to discriminate durational differences between nonspeech stimuli in dyslexia. These studies revealed higher thresholds of durational differences for persons with dyslexia (see, e.g., Banai & Ahissar, 2004; Thomson, Fryer, Maltby, & Goswami, 2006; for an overview, see Hämäläinen, Salminen, & Leppänen, 2013). Deficits in spectral processing were observed for both nonspeech stimulus types, which supports prior studies on frequency discrimination in dyslexia (see, e.g., Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999; Banai & Ahissar, 2004; McNally & Stein, 1996; for an overview, see Hämäläinen et al., 2013). It is interesting to note that the deficit was also detectable in the spectrotemporal condition of both nonspeech stimulus types. Although discrimination was improved compared with the spectral or temporal conditions, providing both cues (temporal and spectral) was not sufficient to compensate the auditory processing deficit in the group with dyslexia.

As the group with dyslexia showed a lower performance for all auditory contrasts and stimulus types, one might wonder if differences in attention might contribute to the group differences found. Although subtle differences in attention between groups cannot be ruled out, care was taken to avoid them. On the one hand, persons with dyslexia with comorbid attention problems were excluded from the study. On the other hand, the performance of the group with dyslexia did not deteriorate over the course of the experiment.

To summarize, the group with dyslexia showed lower discrimination performance in temporal, spectral, and spectrotemporal processing for vowels and both nonspeech stimulus types. Moreover, the results of the discriminant analyses suggest that differences in the processing of the nonspeech stimuli are at least equally predictive for group classification compared to the vowel center stimuli and that spectral processing is the most important predictor. This finding supports the assumption of a general auditory processing deficit as one cause of developmental dyslexia (Ahissar et al., 2000; Amitay et al., 2002).

Subgroups of Developmental Dyslexia

The results presented in Figure 1 might evoke the impression that all members of the group with dyslexia performed worse compared with the control group. However, differences on the group level cannot be taken as evidence that every participant with dyslexia showed impairment for all stimulus types (vowels, spectrally rotated vowels, and bands of formants) and all auditory contrasts (temporal, spectral, and spectrotemporal).

Only one person within the group with dyslexia showed a specific deficit in the processing of speech stimuli. Contrary to this, eight participants with dyslexia had problems concerning the discrimination of nonspeech stimuli only. Eight others showed impairment for both stimulus types. These findings favor the idea of a general auditory processing deficit in dyslexia. If the deficit was speech specific (see, e.g., Liberman, 1989; Ramus, 2003; Vellutino, 1987), most members of the group with dyslexia should show reduced discrimination indexes for the vowel center stimuli only.

However, one could argue that auditory impairments might co-occur with speech perception problems without being the origin of the phonological problems (see, e.g., Breier et al., 2003; Mody et al., 1997; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998) or that they might aggravate the phonological deficit without being the core of dyslexia (Ramus, 2003). The predictive nature of temporal auditory processing for phonological awareness (Corriveau, Goswami, & Thomson, 2010) and reading and spelling (Hood & Conlon, 2004; Steinbrink, Zimmer, Lachmann, Dirichs, & Kamme, 2014) was, however, shown in longitudinal studies with unselected samples. As these deficits are found prior to school entry, they can be regarded as predictors of the following reading-related skills (Goswami,
2003). Studies with samples at risk for dyslexia also revealed impaired temporal (Plakas, van Zuijen, van Leeuwen, Thomson, & van der Leij, 2013) and spectral (Maurer, Bucher, Brem, & Brandeis, 2003; Plakas et al., 2013) processing as risk factors of dyslexia.

Concerning the different auditory contrasts, participants showed a broad range of different patterns on the individual level: Nine of them showed impairment in all three auditory contrasts (temporal, spectral, and spectro-temporal). None of the participants with dyslexia were specifically impaired for the temporal condition, whereas eight members of the group with dyslexia had problems discriminating spectral contrasts and/or spectrotemporal.

Finally, about one-fifth of the group with dyslexia did not show any auditory processing deficit at all. As this study concentrated on auditory processing and did not measure additional abilities that might be associated with developmental dyslexia (e.g., phonological, visual, or motor abilities; see Ramus et al., 2003), it is not possible to make further statements about the cognitive deficits possibly underlying the reading impairment of this subsample. However, this finding is in line with prior research of our group (Groth et al., 2011; Steinbrink, Klatte, et al., 2014), indicating that auditory processing deficits reflect a major impairment in developmental dyslexia but cannot be found for all persons with dyslexia.

In summary, our pattern of results suggests that developmental dyslexia is not related to one specific aspect of auditory processing (e.g., temporal auditory processing). However, one should keep in mind that all stimuli that were used in the present study were short in duration. Therefore, it is still possible that temporal processing deficits might weaken participants’ performance in this kind of task. Developmental dyslexia might rather be characterized by various and more general auditory processing impairments, or even by deficits outside the auditory domain. It is probable that developmental dyslexia cannot be explained by a single cause (Naidoo, 1972), and multicausal subgroups have been reported regularly in prior research (see, e.g., Bakker, 1992; Boder, 1973; Castles & Coltheart, 1993; Heim et al., 2008; Ingram, 1963; Johnson & Myklebust, 1967; Lachmann & van Leeuwen, 2008; Lachmann et al., 2005; for an overview, see C. Watson & Willows, 1993). Besides, a child might have multiple deficits rather than only one (Bishop, 2006; Snowling, 2008). Therefore, it is not surprising to find a broad range of auditory processing deficits, even in adults with dyslexia.

Taken together, these results support the idea of a general auditory impairment that might be the cause of the phonological problems at least in a large subset of persons with dyslexia. This assumption might be explained by the fact that an imprecise representation of spectral and temporal features might impair the conversion of acoustical sounds into phonological representations (see Ahissar et al., 2000).

Influence of Stimulus Complexity on Auditory Processing Deficits in Dyslexia

We argued that one reason why many former studies found auditory processing deficits for speech stimuli but not for nonspeech stimuli in dyslexia might be that basic auditory processing skills were usually investigated using stimuli of lower complexity as well as less complex tasks. Indeed, we showed that when using speech and nonspeech stimuli with the same complexity in a simple discrimination task, adults with dyslexia are equally impaired in the auditory processing of speech and nonspeech. With respect to the two nonspeech conditions, we found that less complex nonspeech stimuli (bands of formants) were not processed differently from more complex nonspeech stimuli (spectrally rotated vowels): Both types of stimuli revealed similar auditory processing deficits in participants with dyslexia (see also Banai & Ahissar, 2006). At first glance, this seems to contradict our argument that comparing experimental conditions that employ stimuli of varying complexity poses the danger of unjustified rejection or acceptance of hypotheses on auditory processing deficits in dyslexia. It has to be kept in mind, however, that the less complex stimuli that were used in this experiment (i.e., bands of formants) were already much more complex than the kinds of stimuli that are usually used in studies on auditory processing in dyslexia (e.g., sinusoidal tones). Indeed, there are a number of psychophysical studies that did not find temporal and spectral auditory processing impairments in adults with dyslexia using these kinds of simple stimuli (e.g., temporal [Baldeweg et al., 1999]; spectral [Amitay et al., 2002; B. U. Watson & Miller, 1993]). Thus, to come to firmer conclusions about the influence of stimulus complexity on auditory processing deficits in dyslexia, a parametric approach that systematically varies stimulus complexity on a continuum from very simple to very complex would be fruitful.

Spectrally Rotated Speech

In the current study, a new method of producing spectrally rotated speech was introduced. This method allows the inclusion of the complete spectrum of the speech stimulus without the limitation by a low-pass filter, which might affect the perceived naturalness of the corresponding speech stimulus (Moore & Tan, 2003). To create a spectrally rotated stimulus with complete spectrum, all frequencies of the speech sound above 4000 Hz were added to the spectrally rotated stimulus. As a result, there was a spectrally rotated stimulus with complete spectrum and the same complexity compared to the original speech sound. The stimulus ratings of the participants in the current study indicated that both the spectrally rotated vowel center stimuli and the bands of formants were perceived as nonspeech. Azadpour and Balaban (2008) claimed that phonological representations are used for the processing of spectrally rotated speech syllables. In their study, stimuli incorporating consonants were used. However, it has been reported before that spectrally rotated consonants can be interpreted as phonemes (for details, see Blesser, 1972). Thus, speech stimuli that include consonants might not always turn into nonspeech signals when they are spectrally rotated. Instead, they sometimes might still resemble speech and might thus access phonological representations when they are processed. In the current
study, however, isolated vowels were used, which guaranteed a nonspeech impression of the stimuli.

**Limitations of the Study**

The aim of the present study was to investigate spectrotemporal, spectral, and temporal aspects of auditory processing within linguistic and nonlinguistic stimulus material in developmental dyslexia. Although the results of the present study contribute to the understanding of auditory processing in dyslexia, there still remain some limitations. First, no hearing screening was conducted, which means that the possibility of influences of subtle hearing problems on the results cannot be ruled out, although none of the participants reported a history of hearing problems and stimuli were presented at a comfortable loudness level. The second limitation concerns the lack of phonological processing data. As phonological processing abilities were not investigated, our suggestion that phonological processing problems may arise from auditory processing impairments remains speculative. Thus, future studies should measure participants’ peripheral hearing abilities as well as their phonological processing abilities. Third, participants showed a wide age range, ranging from adolescence to young adulthood. Although no correlations between performance and age were found, a narrower age range seems advisable for future studies to exclude developmental influences on the results. Fourth, experiments with adults with dyslexia do not allow drawing direct causal links. The latter would be possible only in studies with children in a longitudinal design, especially when the start of the study precedes school entry. Finally, the stimulus set was restricted to vowels. Thus, it seems recommendable to replicate our results with a broader stimulus set including syllables or words.

**Clinical Implications**

The finding that auditory processing skills are impaired in persons with dyslexia might evoke the impression that the training of such basic skills should result in improvements in reading and writing ability. According to our view, however, an isolated training of basic component functions is not likely to improve reading and writing performance given that this performance is the result of a complex functional coordination process that becomes automatized over years of practice. As a result, when automatization is advanced, a direct transfer would not be expected (Lachmann, 2002; Lachmann & van Leeuwen, 2014). In this case, functional coordination must be reorganized and integrated into the automatized skill. Therefore, a training of basic functions (nonlinguistic) should be combined with a training of grapheme–phoneme conversion and orthographic and other higher-order subskills of reading and writing in order to implement the improved processing skill into a functional coordination that forms the basis of reading and writing (Klatte et al., 2013).

**Conclusions**

The performance of participants with dyslexia was inferior to that of the control group in all linguistic and nonlinguistic stimulus conditions for both temporal and spectral parameters. This pattern of results was, however, not evident in every individual. In fact, four participants with dyslexia did not show any auditory processing deficits at all. Our results support the idea that the phonological deficit in at least a subset of persons with dyslexia might be caused by a general auditory processing deficit, as auditory processing impairments were also evident for nonspeech stimuli of the same and lower complexity compared to the vowel stimuli used in this study.

**Acknowledgments**

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stimuli differing spectrally and from dichotic stimuli differing only by perceived location. *Neuropsychologia, 43,* 714–723.


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