Universality of categorical perception deficit in developmental dyslexia: an investigation of Mandarin Chinese tones

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Background: While previous studies have shown that children affected by dyslexia exhibit a deficit in categorical perception of segmental features in alphabetic languages, it remains unclear whether the categorical perception deficit generalizes to nonalphabetic languages at the suprasegmental level. In this study, we investigated the occurrence of categorical perception deficit in Mandarin lexical tones in Chinese children with dyslexia. Methods: Both behavioral and electrophysiological measures were taken to compare Chinese dyslexic children with age-matched controls. Auditory event-related potentials were collected with a passive listening oddball paradigm. Results: Behavioral data showed that dyslexic children perceived lexical tone contrasts less categorically and less precisely than age-matched controls. Consistent with the behavioral data, the across-category tone contrast elicited larger mismatch negativity than the within-category distinction in the left hemisphere for the age-matched controls but not for the dyslexic children. Conclusion: The behavioral and electrophysiological results demonstrate impaired categorical perception of lexical tones in Chinese children with dyslexia. Our findings support the hypothesis that children affected by dyslexia have a general deficit in categorical perception of speech, which generalizes to nonalphabetic languages at the suprasegmental level. Keywords: Dyslexia, categorical perception, lexical tones, event-related potential, mismatch negativity.

Introduction

Developmental dyslexia is a specific and persistent deficit in learning to read and spell despite average or above-average intelligence and conventional instruction (Denett, Taylor, & Chaix, 2004; Shaywitz & Shaywitz, 2005; Snowling, Bishop, & Stothard, 2000). Although the etiology for dyslexia is not precisely known, converging evidence indicates that phonological disorders play a crucial role in reading impairment. Dyslexic children demonstrate severe difficulty in phonological awareness measures in which they are required to manipulate sound constituents of oral language (Ramus, 2003; Stanovich & Siegel, 1994; Wagner, Torgesen, & Rashotte, 1994). At the same time, there is also evidence that poor phonological processing in dyslexia may be attributed to more basic forms of perceptual deficit such as difficulties in auditory temporal processing (Reed, 1989; Tallal, 1980) and categorical perception of speech sounds (Brandt & Rosen, 1981; Maassen, Groenen, Crul, Assman-Hulsmans, & Gabrielis, 2001; Mody, Studdert-Kennedy, & Brady, 1997).

Originally, it was claimed that poor language skills in dyslexia might arise from a deficit in processing brief temporal information (Tallal, 1980). However, disorders of temporal processing concern only subgroups of poor readers, and this hypothesis cannot explain deficit observed in dyslexia that occurs only in linguistic contexts (Giraud et al., 2005; Serniclaes, Sprenger-Charolles, Carre, & Demonet, 2001). By contrast, some researchers proposed that phonological impairments in dyslexia are speech specific, having to do with categorical perception of speech sounds (Mody et al., 1997; Studdert-Kennedy & Mody, 1995). Categorical perception is a fundamental property of speech perception which refers to discrete perceptual warping of an analog physical continuum that includes multi-step changes from one category (i.e., /b/) to another (i.e., /p/). That is, human listeners are more likely to notice acoustic changes that signal a phonological contrast than other differences that are phonologically irrelevant. Behavioral studies have found that children with dyslexia perform more poorly than age-matched controls in categorizing speech sounds, that is, they are sensitive to acoustic rather than phonologically relevant features (Blomert, Mitterer & Paffen 2004; Cheung et al., 2009; Mody et al., 1997; Serniclaes et al., 2001; Werker & Tees, 1987).

*These authors contributed equally to this study.
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One limitation of behavioral measures is that the results inherently reflect task-related factors such as attention and motivation. Given this limitation, it remains unclear whether the observed categorical speech perception deficit in dyslexics occurs at the level of sensory processing. Electrophysiological measures, such as the mismatch negativity (MMN) component of auditory event-related potential (ERP), are better suited for examining the nature of categorical perception deficit. MMN is elicited when the auditory perceptual system detects a mismatch between the standard and deviant stimuli in an oddball paradigm in which one stimulus is presented frequently (standard), while others are presented at a lower probability (oddball/deviant). This ERP component peaks around 100–250 ms with a negative fronto-central scalp distribution. Because elicitation of MMN requires no attention to the auditory stimuli and no motor or verbal response, it is assumed to index auditory change detection at an automatic, preattentive level ( Näätänen, 1979, 1985; Näätänen, 2000; Xi, Zhang, Shu, Zhang, & Li, 2010). There is also evidence that MMNs to across-category speech sounds differ between normal controls and children with dyslexia or genetically at risk for dyslexia (Leppänen et al., 2002; Maurer, Bucher, Brem, & Brandeis, 2003; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998; Van Leeuwen et al., 2006). These studies showed absent or reduced MMN responses in dyslexic children as compared with normally developing children, supporting the hypothesis that automatic detection of phonologically relevant changes is impaired in dyslexia.

However, the universality of the categorical speech perception deficit hypothesis remains untested as most of the relevant behavioral and electrophysiological studies (a) have examined dyslexia in alphabetic languages and (b) have focused on segmental features for individual phonemes such as /b/ and /d/, rather than suprasegmental features such as lexical tones at the syllable level. Dyslexia in Chinese presents an important case to test the hypothesis. The Chinese writing system is nonalphabetic or logographic because the phonemic segments are not coded in writing and the visuospatial features of the square-shaped characters are important to reading. Furthermore, Chinese is a tone language in which lexical tone represents phonological information at a suprasegmental (or syllabic) level and its role is as critical as segmental (consonant and vowel) features in determining a word’s meaning. Tone awareness is central to successful reading in Chinese, unlike in alphabetic languages where awareness of phonemic onsets can explain a significant portion of variance over other levels of phonological awareness for reading skills (McBride-Chang, Bialystok, Chong, & Li, 2004; McBride-Chang et al., 2008; Shu, Peng, & McBride-Chang, 2008).

Despite the importance of tone awareness in the development of reading skills in Chinese, the perception of lexical tones, especially categorical perception of lexical tones in children with or without dyslexia has rarely been investigated. So far only two studies have directly examined lexical tone perception in Chinese dyslexics. In a behavioral study, Cheung et al. (2009) found that dyslexic Cantonese-speaking children perceived the tonal continuum from the high-level tone /55/ to the midlevel tone /33/ less categorically than age-matched controls, indicating that categorical perception of lexical tones can be used as a behavioral marker to distinguish Cantonese-speaking children with and without dyslexia. Different from Cantonese-speaking Chinese children in which there are three level tones, there is only one level tone in Mandarin Chinese. Therefore, unlike Cantonese that allows category shifts among its level tones, any Mandarin tonal continuum from one tone to another involves contour tones. Previous studies have shown that the nature of categorical perception of lexical tones is determined by whether contour tones are involved in the tonal continuum (Francis, Ciocca, & Ng, 2003). Because only level tones were included in Cheung et al.’s study, whether categorical perception of lexical tones is impaired in Mandarin-speaking Chinese children with dyslexia requires further investigation. Another ERP study using the Mandarin high-level tone /55/ as standard stimuli and the high rising tone /35/ as deviant stimuli found that Chinese dyslexic and normally developing children did not differ in MMNs elicited by the deviant stimuli, indicating that perception of lexical tones might not be impaired in Chinese dyslexics (Meng et al., 2005). However, categorical perception of lexical tones was not explored in Meng et al.’s study because they did not use a tonal continuum, which would allow the differentiation of acoustic and phonological processing.

To sum up, although research has shown that children affected by dyslexia in alphabetic languages exhibit a deficit in the categorical perception of speech sounds, it remains unclear whether this finding can generalize to the nonalphabetic Chinese language at the suprasegmental level. The primary goal of this study was to investigate the occurrence of categorical perception deficit in Mandarin lexical tones in Chinese children with dyslexia. Findings from our study can in turn provide a better understanding of the relationship between tone processing and reading acquisition in Chinese. Furthermore, Chinese lexical tones are characterized by slowly changing pitch information at the syllable level in contrast to rapidly changing temporal information at the individual phoneme level. The findings can also further test the temporal processing deficit.
hypothesis (Tallal, 1980). In order to systematically examine categorical perception of lexical tone in Chinese children with and without dyslexia, we collected both behavioral and ERP data in this study.

Method
Participants
Thirty-six children were included in the study. Eighteen of them showed typical sequelae of developmental phonological dyslexia (10 boys and 8 girls) and 18 were normally developing children (8 boys and 10 girls). All participants were physically healthy and free of neurological disease, psychiatric disorder, or hearing deficit. The controls were selected to match the dyslexics on age and on intelligence (according to Raven’s IQ; see below). Mean scores and standard deviations of the screening variables for the dyslexic and age-matched controls were presented in Table 1. Participants gave written consent before they took part in the experiments. The study was approved by the ethics review board at Beijing Normal University’s Imaging Center for Brain Research. The ERP data of one dyslexic boy were collected both behaviorally and ERP data in this study.

Diagnosis of dyslexia
Based on previously established criteria (Lei et al., 2011; Shu, McBride-Chang, Wu, & Liu, 2006), four behavioral tests, including three literacy subtests and one phonological awareness test, were used to identify children with dyslexia. The dyslexic children scored at least one standard deviation below their respective age means in all the tests.

Literacy. Three literacy subtests were included to measure Chinese literacy. (a) The character recognition subtest consisted of 150 characters, all of which were expected to have been learned by Grade-6 school children in Beijing (Shu, Chen, Anderson, Wu, & Xuan, 2003). Children were asked to read the characters aloud and the testing was discontinued when they failed 15 consecutive items. Each character was worth one mark. (b) The word list reading subtest included 180 two-character words composed of simple and familiar characters. Children were asked to name all the items as quickly as possible. Each word was worth one mark. (c) The reading fluency subtest was a timed task, which followed the procedure of Landerl, Fussenegger, Moll, and Willburger (2009). Each child was given 3 min during which the child was asked to read as many sentences as possible and indicate with ‘·’ or ‘×’ whether each sentence was correct or not. There were 100 sentences in total, gradually increasing in length across the test. The characters in the sentences that were correctly judged were summed and each character was worth one mark.

Phonological awareness. Phonological awareness was measured using a phoneme deletion test. The test consisted of 26 orally presented syllables, and for each syllable the child was asked to say aloud what would be left when a given consonant or vowel was deleted, for example, say /ao1/ in response to the syllable /gao1/ if /g/ was deleted.

Stimuli
The stimuli were used in a previous study of categorical perception of lexical tones with behavioral and MMN measures (Xi et al., 2010). They were resynthesized from two natural Chinese monosyllables /pa/ that differed in their lexical tones (Tone 2, the high rising tone, and Tone 4, the falling tone). The original stimuli were recorded from a female native Chinese speaker and were digitally edited using Sound-Forge (SoundForge9; Sony Corporation, Tokyo, Japan), each having a duration of 200 ms. To isolate the lexical tones and keep the rest of the acoustic features identical, pitch tier transfer was performed using the Praat software (http://www.fon.hum.uva.nl/praat/). This procedure generated two stimuli, /pa2/ and /pa4/, which were identical with each other except for the pitch contour difference. The /pa2/ and /pa4/ stimuli were taken as the endpoint stimuli and a morphing technique was then performed in Matlab (Mathworks Corporation, Natick, MA, USA) using STRAIGHT (Kawahara, Masuda-Katsuse, & de Cheveigne, 1999) to create a 10-interval lexical tone continuum (Figure 1). All the 11 stimuli in the /pa2/-/pa4/ lexical tone continuum were used in a behavioral identification test. Based on the results from the behavioral test, three stimuli were chosen for the ERP oddball paradigm experiment, which formed an across-category stimulus pair (3 and 7) and a within-category stimulus pair (7 and 11). In particular, stimulus 7 in the continuum was used as the standard stimulus, and stimuli 3 (an across-category deviant) and 11 (a within-category deviant) were used as deviants.

Experimental procedures
Behavioral experiment. The behavioral experiment started with a short practice phase immediately followed by a test phase. On the eight practice trials, the participants were instructed to identify only the endpoint tokens. Each stimulus was randomly presented through headphones and feedback was given. The

Table 1 Group comparisons on reading and cognitive measures

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<tr>
<th></th>
<th>CA group</th>
<th>PD group</th>
<th>P-value</th>
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<tbody>
<tr>
<td>Age (year)</td>
<td>10.3 (0.47)</td>
<td>10.32 (0.48)</td>
<td>0.011</td>
</tr>
<tr>
<td>Nonverbal IQ</td>
<td>45.15 (6.64)</td>
<td>44.05 (3.46)</td>
<td>0.41</td>
</tr>
<tr>
<td>Literacy</td>
<td></td>
<td></td>
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<tr>
<td>Character recognition</td>
<td>122 (7.04)</td>
<td>92.53 (12.64)</td>
<td>82.01***</td>
</tr>
<tr>
<td>Reading fluency</td>
<td>967.1 (297.86)</td>
<td>446.95 (134.50)</td>
<td>48.50***</td>
</tr>
<tr>
<td>Wording list reading</td>
<td>178.96 (26.04)</td>
<td>121.29 (26.04)</td>
<td>51.39***</td>
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<tr>
<td>Phonological awareness</td>
<td></td>
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<tr>
<td>Phoneme deletion</td>
<td>22.9 (2.85)</td>
<td>10.42 (3.47)</td>
<td>151.55***</td>
</tr>
</tbody>
</table>

***p < 0.001.
testing session presented six trials for each of the 11 stimuli in random order and no feedback was given. The rate of presentation was self-paced. Once a response was collected, the next stimulus was presented following an 800 ms pause. Stimulus presentation and response recording were controlled by E-prime (Psychology Software Tools Inc., Sharpsburg, PA, USA).

**ERP experiment.** The ERP experiment was carried out after the behavioral test. The stimuli were presented in an oddball paradigm. The within-category deviants and across-category deviants occurred pseudo-randomly, each with a 10% probability of occurrence, intermingled with the standards. Any two adjacent deviants were separated by at least three standards for a total presentation of 1,200 stimuli. The stimulus-onset-asynchrony was 1,000 ms. Participants were instructed to ignore the presented sounds while watching a self-selected movie, which was presented in mute mode with subtitles.

**Electroencephalogram recording**
Continuous EEG was recorded using a HydroCel Geodesic Sensor Net consisting of 128 electrodes evenly distributed across the scalp and referenced against the vertex electrode (Tucker, 1993). The GSN also included electrodes next to, and below, the eyes for recording horizontal and vertical eye movements. The impedance of each electrode was kept below 50 kΩ.

**ERP data analysis**
Off-line signal processing was carried out using Net-station software (Version 4.2). The raw data were first digitally filtered with a 0.3–20 Hz bandpass filter and segmented for 700 ms starting 100 ms prior to the onset of stimuli. Data were then re-referenced to the average of all the electrodes, and baseline corrected. Recorded trials with eye blinks or other activities beyond the range of -50 to 50 μV were rejected.

Based on previous studies (Chandrasekaran, Krishnan, & Gandour, 2007; Xi et al., 2010) and visual inspection of the grand average waveforms, the left frontal (F3) and right frontal (F4) sites were selected for statistical analyses because the MMN response is known to be most robust at the frontal electrode sites. Only the standard before the deviant was used for averaging and subtraction. Difference waves for MMN were obtained by subtracting the averaged standard from the averaged deviant. The minimum voltage was calculated as the amplitude value. Statistical analysis only included those participants with at least 80 accepted deviant trials in each condition.

**Results**

**Behavioral experiment**
The identification functions of the /pa2/-/pa4/ tonal continuum for the dyslexic and control groups are shown in Figure 2. These functions were obtained by calculating the average percentage of /pa4/ responses for each of the 11 tokens. The identification data were then submitted to probit analysis (Finney, 1971), from which the values of slope were obtained. Probit analysis fits a cumulative normal curve to probability estimates as a function of stimulus level, and the slope serves as an index of identification consistency. One-way analysis of variance (ANOVA) on the slope values showed a significant group effect, $F(1, 34) = 24.23, p < .001$, the dyslexic group had a significantly shallower slope than the age-matched control group. The two groups were also compared on their accuracies in identifying the endpoint tokens. Group differences were found with identification of both /pa2/, $F(1, 34) = 18.45, p < .001$, and /pa4/, $F(1, 34) = 10.61, p < .001$.

**ERP experiment**
The grand average waveforms for the standards, within-category deviants, and across-category deviants
are shown in Figure 3. Negative peaks were observed in the deviant-minus-standard difference waves for both groups (Figure 4A). Repeated measures ANOVA tests were conducted on MMN peak amplitude and peak latency data with the following main factors, deviant type (within-category/across-category) and hemisphere (left/right) for the dyslexic group and age-matched control group separately. For all analyses, degrees of freedom were adjusted according to the method of Greenhouse–Geisser when appropriate.

**MMN peak amplitude.** Figure 4 presents the MMN peak amplitude for each group and deviant type at the electrode locations, F3 and F4, along with the topographic distribution. For the age-matched control group, the main effect of deviant type was marginally significant, $F(1, 17) = 3.822$, $p = .063$, across-category > within-category, and the main effect of hemisphere was not significant, $F(1, 17) = 0.865$, $p = .362$. There was also a significant interaction between hemisphere and deviant type, $F(1, 17) = 5.85$, $p < .05$, indicating that the amplitude of the responses to across-category deviants was greater than responses to within-category deviants in the left hemisphere, $F(1, 17) = 6.27$, $p < .05$, but not in the right hemisphere, $F(1, 17) = 0.15$, $p = .701$. For the dyslexic children, neither the main effect of deviant type, $F(1, 16) = 2.118$, $p = .165$, nor the main effect of hemisphere, $F(1, 16) = 0.235$, $p = .634$, reached significance. There was also no interaction effect, $F(1, 16) = 0.127$, $p = .727$.

**MMN peak latency.** For both age-matched controls and dyslexics, the main effects of deviant type and hemisphere failed to reach statistical significance, ($p > .10$ in all cases). For both groups, the interaction effects were not significant either ($p > .10$ in all cases).

**Discussion**

Although there is a strong consensus in the literature that phonological processing disorders play a crucial role in reading impairment, there is some debate on whether difficulties in phonological processing are attributable to low-level perceptual deficits, especially deficits in categorical perception of speech sounds. Unlike alphabetic languages such as English, the processing of lexical tone, a suprasegmental feature of high phonological relevance, is central to the comprehension of Chinese. The present study examined categorical perception of lexical tones in Mandarin-speaking Chinese children with dyslexia, a topic that has not been investigated with a carefully controlled continuum of lexical tones in
previous studies. Both behavioral and electrophysiological data were collected in this study. The findings showed that children with dyslexia identified the tonal continuum less categorically and less precisely than the age-matched controls. Furthermore, no difference was observed in the dyslexic children with respect to MMN peak amplitudes between across- and within-category deviants observed in the age-matched control group. These results indicate that categorical perception of lexical tones is substantially impaired in Chinese children with dyslexia.

In the behavioral experiment, when using a classical index of categorical labeling, that is, the slope of identification function, we found that the dyslexic children had a significantly shallower slope than the age-matched controls. This result is similar to what was observed in an earlier study by Cheung et al.

Figure 4 Mismatch negativity (MMN) responses. (A) Grand average traces of MMN evoked by within- and across-category changes from the F3, Fz, and F4 electrode locations; (B) Maps display the topographic distribution of the mean amplitudes in the MMN analysis window; (C) MMN peak amplitude values from F3 and F4 electrodes (vertical bars represent one standard error).
(2009). On the other hand, Cheung et al. showed an asymmetric pattern for dyslexic children in identifying endpoint tokens, whereas our study did not show this pattern. The dyslexic children in their study differed from age-matched controls on the identification of midlevel /33/ Cantonese tone, but the two groups did not differ on the identification of high-level /55/ tone. The authors attributed the asymmetry to the relative ease of perceiving the high-level tone. In this study, the dyslexic children had poorer accuracy in identifying both endpoint tokens than the normally developing children and no asymmetric pattern was observed. It is important to note that Cheng et al. tested level tones (/33/ and /55/) on Cantonese-speaking subjects while we tested contour tones on Mandarin-speaking children. Such differences could have significant implications for the patterns observed: previous studies of categorical perception of lexical tones have showed that contrasts between level tones behave more like vowel-related contrasts, while contrasts between contour tones are more similar to consonantal feature contrasts (Francis et al., 2003).

The use of electrophysiological measures is ideally suited for investigating impaired categorical perception of lexical tones in Chinese children with dyslexia, as discussed earlier. Our study fills an important gap in this regard. Both the across- and within-category deviants elicited MMN for the normally developing children and the dyslexics, indicating that the pitch changes have been preattentively discriminated by both groups. More importantly, the age-matched control group showed a significantly enhanced MMN to the across-category deviants compared to the within-category deviants, especially in the left recording sites, whereas children with dyslexia did not show such effects. The enhanced MMN elicited by across-category tonal contrast has been reported in adults and is thought to reflect phonological processing of lexical tones (Xi et al., 2010). Thus, the present results indicate that 10-year-old normally developing Chinese children have formed phonemic representations of lexical tones that are similar to healthy adults, but dyslexic children have not acquired the same phonological knowledge of different lexical tone categories. The results seem inconsistent with the findings of Meng et al.‘s study, however, the two studies differs from each other in experimental stimuli and data analysis. Only one type of deviant stimulus was used and data analysis was confined to a single fronto-central electrode (Fz) in Meng et al.‘s study (2005). One could rule out the possibility that the acoustic difference between the chosen standard and deviant stimuli was too large, resulting saturation of MMN responses regardless of the subject group in their study. The lack of within-category versus across-category MMN comparison did not allow a detailed examination of categorical speech perception deficit in dyslexia to differentiate acoustic and phonological processing of lexical tones (Luo et al., 2006; Nääätänen et al., 2007; Xi et al., 2010). On the other hand, our results are consistent with previous ERP studies that focused on dyslexic children’s categorical perception of consonantal features (Leppänen et al., 2002; Maurer et al., 2003; Schulte-Körne et al., 1998; Van Leeuwen et al., 2006). Taken together, these results suggest that children with dyslexia do not recruit extra neural resources in the processing of phonologically relevant features, which further suggests that phonemic information might have weaker representation in their long-term memory.

Overall, our behavioral and electrophysiological results demonstrate deficit in categorical perception of lexical tones in Chinese children with dyslexia. As lexical tones are suprasegmental features which operates at the syllable level rather than the individual phoneme (i.e., segmental) level, our findings extend results of previous investigations and lend further support to the hypothesis that children affected by dyslexia have a deficit in categorical speech perception in general. Lexical tones are mainly manifested by slowly changing fundamental frequency, not rapidly changing temporal information, the results therefore contradict the temporal processing hypothesis (Tallal, 1980). Categorical perception anomalies of speech sounds are supposed to underlie dyslexia in alphabetic language by hampering the set up of grapheme–phoneme correspondences (Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008). For Chinese, categorical perception deficit in lexical tones may impair reading by hampering the child’s ability to match a phonologically unambiguous spoken morpheme to its written equivalent. For example, a child who perceives the high rising /35/ tonal continua as the falling /51/ tonal phonemes or vice versa will have difficulty in assigning the correct tones to syllables. If the tone is misrepresented, the syllable may be misidentified as a different morpheme and thus the correct character cannot be identified.

In conclusion, our study represents the first ERP study of categorical perception deficit in lexical tones and its relations to dyslexia in Chinese children. Our approach is consistent with that adopted by clinical psychologists interested in the etiology of reading disability. A number of studies have demonstrated that MMN-like responses to phonemes were attenuated in infants at risk for dyslexia even at birth (Guttorm et al., 2005; Molfese, Molfese, & Modgline, 2001). While the existing behavioral methods can only identify much older dyslexics until they have clearly fallen behind their peers in reading (Cheung et al., 2009; Lei et al., 2011), ERP studies of categorical perception of lexical tones like the current study could have significant implications for early diagnosis of Chinese infants and children at risk for dyslexia. The development and refinement of diagnostic tools such as MMN for the children at risk for dyslexia would allow intervention programs at an

early developmental stage, which are more cost-effective than later intervention.

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Key points
• Categorical perception of lexical tones is impaired in Chinese children with dyslexia, which is manifested at both behavioral and electrophysiological levels.
• Children with dyslexia show deficits in categorical perception deficit of speech sound in general regardless of the writing system.
• ERP studies of infants’ categorical perception of lexical tones might help to diagnose dyslexia in Chinese children at a very early age.
• Prevention and intervention programs aimed at improving categorical perception of lexical tones may benefit Chinese children with dyslexia.

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