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Speech perception deficits by Chinese children with phonological dyslexia

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ABSTRACT

Findings concerning the relation between dyslexia and speech perception deficits are inconsistent in the literature. This study examined the relation in Chinese children using a more homogeneous sample—children with phonological dyslexia. Two experimental tasks were administered to a group of Chinese children with phonological dyslexia, a group of age-matched control children, and a group of adults. In addition to a categorical perception task, a selective adaptation task was carried out. The results indicated that Chinese children with phonological dyslexia were less consistent than both the child and adult control groups in identifying stimuli within a given phonetic category. Furthermore, they did not show any significant adaptation effects in the selective adaptation task even when the adapting stimulus was identical to an endpoint stimulus in the test continuum. It seems that children with phonological dyslexia have a general deficiency in representing and processing speech stimuli.

Introduction

It is well established that developmental dyslexia is associated with deficits in phonological processing skills, especially phonological awareness (e.g., Bradley & Bryant, 1978; Morris et al., 1998; Stanovich & Siegel, 1994). Children or adults with developmental dyslexia show severe difficulty in tasks that ask them to consciously segment and manipulate phonological units (mainly phoneme) in syllables or words, for example, saying what *cat* would sound like without the *c*. Concerning the

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nature of phonological deficits in dyslexia, it has been suggested that the phonological representation in dyslexics is coarse and the representation of the phonemic level is deficient, and this may interfere with the establishment of mapping between graphemes and phonemes (Goswami, 2002; Share, 1995; Swan & Goswami, 1997). However, the concept of coarse phonological representation is still obscure and lacks empirical evidence. Exploring the speech perception process, which has focused on exploring how humans perceive phonological segments from running and variable acoustic signals, may provide a more direct approach to disclose the essence of phonological representation in children or adults with dyslexia. Among the tasks developed by speech perception researchers, the categorical perception paradigm has been used intensively to examine speech perception abilities in dyslexics. In categorical perception tasks, researchers develop stimulus continua that vary along one or more acoustic dimensions and range across two or more phonemic categories such as the voice onset time (VOT, i.e., the interval between the release of articulatory occlusion and the onset of voicing) continuum relevant to voicing contrast (e.g., /b/ vs. /p/). When these stimulus continua are presented to participants, their perception is not continuous but rather categorical; that is, their identification performances exhibit sharp changes at categorical boundaries, and their discrimination accuracy is nearly perfect for stimulus pairs that straddle a category boundary and is poor for stimulus pairs within a category (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Liberman, Harris, Hoffman, & Griffith, 1957).

Significant categorical perception deficits in children with developmental dyslexia have been revealed by some studies. In identification tasks, dyslexics have shallower identification functions and larger identification inconsistency with stimuli from the same category than do control groups. In discrimination tasks, they show lower discrimination peaks on stimulus pairs that straddle a category boundary but have higher discrimination scores on stimulus pairs within a phonetic category (e.g., Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Reed, 1989; Serniclaes, Sprenger-Charolles, Carré, & Démonet, 2001; Werker & Tees, 1987). Researchers suggest that speech perception is less categorical in dyslexics than in normal readers and that phonemic-level representations in dyslexics' long-term memory are less robust and more inconsistent than those in normal readers' long-term memory; this in turn results in failure of mapping between graphemes and phonemes (Breier, Fletcher, Denton, & Gray, 2004; Godfrey et al., 1981; Werker & Tees, 1987).

Serniclaes and his colleagues provided further evidence for categorical perception deficits in children with dyslexia and concluded that dyslexic children perceived speech in an *allophonic mode;* that is, they were more sensitive to acoustic differences within a native phonetic category and less sensitive to acoustic changes across native phonetic categories. Furthermore, the allophonic perception disrupted the invariance of phonemic-level representation and the mapping between graphemes and phonemes (Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; Serniclaes, van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004).

However, some studies find that children or adults with dyslexia do not show categorical perception deficits or exhibit individual variability in speech perception abilities. Lieberman, Meskill, Chatillon, and Schupack (1985) compared the abilities of dyslexic adults and control groups to identify synthesized vowels and stop consonants. The results indicated that a subgroup of dyslexics did not show any deficits in identifying synthesized vowels or consonants. The finding that only a subgroup of dyslexics showed speech perception deficits was replicated in later studies (Adlard & Hazan, 1998; Joanisse, Manis, Keating, & Seidenberg, 2000; Manis et al., 1997; Ramus et al., 2003). For example, Manis and colleagues (1997) found that only dyslexic children with low phonemic awareness showed less sharply defined categorical perception than control groups. Joanisse and colleagues (2000) indicated that only dyslexics with additional language impairments showed categorical perception deficits. Furthermore, some other studies found that dyslexics had normal categorical perception when the experimental stimuli were more natural speech sounds (Blomert & Mitterer, 2004; Blomert, Mitterer, & Paffen, 2004).

It is obvious that the findings about the relation between dyslexia and speech perception deficits are far from consistent. The heterogeneity of dyslexia might be one of the reasons for the inconsistency of findings. Considerable studies have indicated that developmental dyslexia has different subtypes such as phonological dyslexia and delay-type dyslexia (Castles & Coltheart, 1993; Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Stanovich, Siegel, & Gottardo, 1997). Children with phonological dyslexia show phonological awareness deficits, but children with delay-type dyslexia have reading and phonological achievements similar to reading level-matched young readers (Manis et al., 1996; Stanovich et al., 1997). Considering the general hypothesis that speech perception deficits may be the cause of phonological awareness deficits and reading difficulties (Breier et al., 2004; McBride-Chang, 1995; Serniclaes et al., 2004), we can expect that speech perception deficits are associated with the subtype of phonological dyslexia rather than other dyslexic subtypes. So, it is reasonable to examine whether children with phonological dyslexia show speech perception deficits. Furthermore, children with phonological dyslexia represent a more homogeneous sample to examine the relation between dyslexia and speech perception deficits. Manis and colleagues (1997) and Joanisse and colleagues (2000) examined whether dyslexic children with phonological awareness deficits showed abnormal categorical perception. Manis and colleagues (1997) found that phonological dyslexics as a group showed categorical perception deficits; further examination of individual profiles revealed that more than half of phonological dyslexics had normal categorical perception. Joanisse and colleagues (2000) found that phonological dyslexics exhibited normal categorical perception; only dyslexics with additional language impairments showed categorical perception deficits. Therefore, even in the case of phonological dyslexia, the results are still inconsistent. To clarify the inconsistency, it is necessary to further examine the relation between phonological dyslexia and speech perception deficits.

The present study investigated the relation between phonological dyslexia and speech perception deficits in Chinese children. The Chinese language and script have some characteristics different from the European languages that have most often been investigated. Chinese language is a tonal language that uses tone to distinguish words. In Mandarin phonology, syllables consist of onsets, rimes, and tones; these onsets, rimes, and tones combine into more than 1200 legal syllables, and other combinations are illegal. So, compared with English syllables, Mandarin syllables are relatively simple and constrained. Chinese characters are called a kind of logographic script that lacks the grapheme–phoneme correspondence rules. Each Chinese character represents a syllable and usually is a morpheme. The visual–orthographic components of Chinese characters are more complicated than those of alphabetic scripts. Thousands of characters are composed of combinations of approximately 650 basic components that are assembled by strokes—the smallest writing units of Chinese characters. More than 80% of characters are semantic–phonetic compounds that consist of a semantic component (which gives cues to the meaning of the character) and a phonetic component (which provides information about the pronunciation of the character). For example, the character 爸 /ba^{51}/ (dad) consists of a semantic component 父 (father) and a phonetic component 巴 /ba^{55}/. Although Chinese children can use the logic of characters to learn to read, they need more time to practice before becoming skilled readers than do Western children (Shu, Chen, Anderson, Wu, & Xuan, 2003). In addition, learning to read Chinese characters depends more on morphological awareness and writing practices (McBride-Chang, Shu, Zhou, Wat, & Wagner, 2003; Tan, Spinks, Eden, Perfetti, & Siok, 2005). However, concerning the role of phonological awareness in Chinese reading development and Chinese developmental dyslexia, we may assume that the findings are mostly consistent with those obtained from alphabetic scripts. Phonological awareness skills (especially onset–rime awareness) predict reading development of Chinese children (Ho & Bryant, 1997b; McBride-Chang & Ho, 2000; McBride-Chang & Kail, 2002; Siok & Fletcher, 2001), and those learning to read Chinese also experience an orthographic–phonological phase before becoming skilled readers (Ho & Bryant, 1997a; Siok & Fletcher, 2001). Dyslexia in Chinese children is heterogeneous and has different subtypes; some dyslexic children show rapid-naming deficits or orthographic-related deficits (Ho, Chan, Lee, Tsang, & Luan, 2004), some dyslexic children show morphological awareness deficits (Shu, McBride-Chang, Wu, & Liu, 2006), and (most important) phonological dyslexia is also a phenotype in Chinese, with some dyslexic children showing severe phonological awareness deficits (Ho, Law, & Ng, 2000; Liu, Liu, & Zhang, 2006; Shu, Meng, Chen, Luan, & Cao, 2005).

Although many studies have examined the role of phonological awareness in Chinese reading acquisition and Chinese developmental dyslexia, to date there are few studies examining the relation between dyslexia and speech perception deficits in Chinese. In a recent study, Cheung et al. (in press) examined the perception of tone and aspiration contrasts in Chinese children with dyslexia, and the results showed that dyslexic children perceived both contrasts less categorically than age-matched controls. This provides preliminary evidence for speech perception deficits in Chinese children with dyslexia.

The present study further examined whether Chinese children with phonological dyslexia would have speech perception deficits and show an allophonic perception mode. Two experimental tasks were administered to Chinese children with phonological dyslexia and control groups (including both child and adult control groups). The first one was a classic categorical perception task. The identification of stimuli from a Mandarin contrast (/pa/–/p^{h}a/, which was constructed by splicing natural stimuli, with the lexical tone being confined to the high level) was carried out. The /pa/–/p^{h}a/ contrast is a kind of unaspirated–aspirated contrast. In Chinese Mandarin, there is no voiced–unvoiced contrast for stop consonants; that is, all stops are unvoiced. One important acoustic cue for distinguishing the unaspirated–aspirated contrast is voice onset time, just like the voiced–unvoiced contrast. The voicing contrast has been widely used to examine dyslexic children's categorical perception abilities in alphabetic languages. For the comparison of findings among different languages, we selected a similar contrast in Chinese phonology to examine Chinese dyslexics' speech perception abilities. We expected that Chinese children with phonological dyslexia would show categorization deficits.

In addition to the categorical perception task, we adopted another speech perception task, the selective adaptation paradigm, to further explore the speech perception process in children with phonological dyslexia. The selective adaptation task was developed by Eimas and Corbit (1973), who presented the synthetic syllable /da/ repeatedly to participants and then asked them to identify a synthetic continuum ranging from /da/ to /ta/. The results showed that an adaptation to /da/ shifted the phoneme boundary of identification function toward the *d* endpoint; that is, participants responded /ta/ more often. Repeated presentation of /ba/ (both /ba/ and /da/ are voiced stops) produced the same adaptation effect. Eimas and Corbit suggested that the adaptation effect reflected fatigue of centrally located linguistic feature detectors.

The selective adaptation paradigm has several advantages. First, the task is a very sensitive paradigm for exploring the speech perception process (Landahl & Blumstein, 1982). The subtle acoustic changes among adapting stimuli can lead to different adaptation effects; in general, the greater the acoustic similarity between an adapting stimulus and the corresponding member in a test continuum, the greater the adaptation effect (Ades, 1974; Landahl & Blumstein, 1982). For example, Ades (1974) presented several synthetic /de/ sounds repeatedly to participants (the second and third formant transitions of each /de/ had subtle differences) and then asked them to identify a synthetic /bæ/–/dæ/ continuum. Although each /de/ adaptor produced an adaptation effect (the identification boundary was shifted to the /dæ/ end), the /de/ with the most similar formant transitions to the /dæ/ endpoint produced the greatest adaptation effect. Second, adaptation effects can occur under distracted conditions. Sussman (1993a, 1993b) found that focused attention to the adapting stimuli did not augment adaptation effects and that distraction from other stimuli presented to the contralateral ear did not diminish adaptation effects. Even 5- and 6-year-olds exhibited adaptation effects under the distraction condition with the synthetic /ba/–/da/ continuum as the test stimuli and the endpoint /da/ as the adaptor. This point seems especially appropriate for exploring the speech perception process in children with dyslexia because they may be more distractible than control children when performing speech perception tasks. Finally, to our knowledge, this is the first time that the paradigm has been used to examine adaptation effects in children with dyslexia. We expected that, with a sensitive speech perception task, we could identify the underlying speech perception deficits more clearly in Chinese children with phonological dyslexia.

The selective adaptation task was administered to Chinese children with phonological dyslexia and control groups. The test consisted of stimuli from a synthetic consonant–vowel (CV) continuum ranging from the labial /pa/ to the alveolar /ta/ (both are unvoiced stops in Chinese, with the lexical tone being confined to the high level). The /pa/–/ta/ contrast is a kind of place of articulation contrast that has also been widely used to examine dyslexic children's speech perception abilities in alphabetic languages. In addition, it had been demonstrated that 5-year-olds show adaptation effects, with the synthetic /ba/–/da/ contrast as the test stimuli and the endpoint /da/ as the adapting stimulus (Sussman, 1993a). There were two adapting stimuli; one was the synthetic sound /ta/, which was isomorphic to the endpoint /ta/ in the test continuum, and the other was the synthetic sound /te/. Although both /t(a)/ and /t(e)/ can be perceived as the same phoneme undoubtedly by native Chinese speakers, the onset frequencies of formant transitions were different for /t(a)/ and /t(e)/ (see "Materials" section below); that is, the acoustic differences between /t(a)/ and /t(e)/ belong to a kind of allophonic mode. With the endpoint /ta/ as adaptor, we expected that children with phonological dyslexia would show similar adaptation effects to control groups. However, with the sound /te/ as adaptor, we expected that children with phonological dyslexia would show smaller adaptation effects than control groups if they perceived speech in an allophonic mode and were more sensitive to the subtle acoustic differences between /t(a)/ and /t(e)/, which would reduce adaptation effects of the /te/ sound to a /pa/–/ta/ continuum.

Finally, to test the unique contribution of speech perception abilities to phonological awareness and reading skill, the relation among speech perception, phonological awareness, and character recognition measures was examined by correlation and regression analyses. In summary, the current study investigated the relation between dyslexia and speech perception deficits in Chinese. With the homogeneous sample, we expected to find evidence of speech perception deficits and the allophonic perception mode in Chinese children with phonological dyslexia.

Methods

Participants

Three screening tests were administered to 586 third graders, fourth graders, and fifth graders from an elementary school in Tianjin, China. The first one was the phonological awareness test, which consisted of three subtests. Onset detection and rhyme detection subtests were first administered to the children in groups. In each trial of both subtests, the children heard three Chinese syllables presented through a loudspeaker connected to a computer, and then they were asked to indicate which one of the three syllables was different from the other two syllables in onset unit or rhyme unit, for example, /k^{h}æi^{55}/, /k^{h}uŋ^{55}/, /kua^{55}/ in onset detection and /luo^{51}/, /tou^{51}/, /tsuo^{51}/ in rhyme detection. There were 2 practice items and 16 test items in each subtest. A sound deletion subtest was administered individually. There were 2 practice items and 18 test items. In each trial, the children heard one syllable and were then asked to say what the resulting sound of a syllable would be if a given sound in the syllable were deleted (e.g., saying what /suan^{55}/ would be without the /u/ sound). The internal consistency reliabilities of the onset detection, rhyme detection, and sound deletion subtests were .73, .76, and .82, respectively. The second test was the Character Recognition Measure and Assessment Scale for Primary School (Wang & Tao, 1993), which is a standardized test of Chinese character recognition ability that has been widely used for screening Chinese children with dyslexia (Shu et al., 2006). The third test was Raven's Standard Progressive Matrices, which is a standardized test of nonverbal intelligence for which local norms were established by Zhang and Wang (1985). The test consisted of five sets of 12 items. Each item was composed of a target matrix with one part missing. Participants were asked to select one from six or eight alternatives to complete the matrix.

Based on the results of three tests administered to all 586 children, the children with phonological dyslexia and the age-matched normal readers were selected. In addition, a group of adult participants was also selected. The screening procedures for each group were as follows.

For *children with phonological dyslexia* (PD group), the raw scores of each child on the onset detection, rhyme detection, and sound deletion subtests were converted to standard scores (z scores) based on the grade sample. The z scores of the three subtests were added to form the composite score of phonological awareness (PA) for each child. The children who scored one standard deviation or more below the grade mean on both the PA composite score and the character recognition test were selected as the candidates of children with phonological dyslexia. Next, those children who scored below the 15th percentile on the Raven's matrices test were excluded from the candidates, and those children with hearing problems (binaural pure tone average threshold at 500, 1000, and 2000 Hz above 25 dB), neurological impairments, or attention deficit/hyperactivity disorder were also excluded from the candidates. Finally, 25 children were selected as the children with phonological dyslexia: 9 third graders, 7 fourth graders, and 9 fifth graders. The ratio of boys to girls was 3 to 2.

For the *chronological age control group* (CA group), the children who scored above the grade mean on both the composite PA score and the character recognition test were selected as the candidates. Children who were matched individually to the children with phonological dyslexia on age, sex, and score on the Raven's matrices test were selected from the candidates. After excluding some children with attention, hearing, or neurological disorders, 25 children were selected as the chronological age control group: 9 third graders, 7 fourth graders, and 9 fifth graders. The ratio of boys to girls was 3 to 2.

For the *adult control group,* 25 undergraduates (11 men and 14 women) were selected as the adult participants. They had neither brain damage nor hearing impairment, and their average age was 21.2 years.

Mean scores and standard deviations on the screening variables for the PD and CA groups are presented in Table 1. A series of *t* tests indicated that the PD group had significantly lower scores than the CA group on the Chinese character recognition test and phonological awareness test (including each subtest and the composite score of PA). The group difference was not significant for age and the Raven's matrices test.

Materials

/pa/–/p^{h}a/ series

Stimuli in the /pa/–/p^{h}a/ continuum were constructed by progressively cross-splicing more /p^{h}a/ into /pa/. The syllables /pa/ and /p^{h}a/ were produced with a high-flat tone in a soundproof chamber by a Chinese male adult who spoke normal Mandarin. The syllables were recorded at a 22-kHz sampling rate with 16-bit resolution and were stored on computer disk. Each syllable was 260 ms in duration. The syllable /pa/ had 0 ms VOT, and /p^{h}a/ had 70 ms VOT. The syllable /pa/ served as the /pa/ endpoint stimulus of the /pa/–/p^{h}a/ continuum. Intermediate stimuli and the /p^{h}a/ endpoint in the series were created by successively replacing the acoustic segments of periodic energy from /pa/ with the equally long acoustic segments of aperiodic energy taken from /p^{h}a/. For example, the first intermediate token was constructed by replacing the 10-ms acoustic segments taken from the onset of /pa/ with the 10-ms aperiodic segment started from the release burst of /p^{h}a/. Subsequent tokens were created by increasing the replaced duration successively in 10-ms steps until 70 ms. It resulted in an eight-step /pa/–/p^{h}a/ series. All cuts were made at a zero crossing so that there was no audible indication that the stimuli had been made by digitally splicing two different syllables.

Selective adaptation task

An eight-step /pa/–/ta/ continuum was synthesized using the Klatt synthesizer on a PC (SenSyn 1.1, Sensimetrics). Each stimulus was 210 ms in duration and did not contain release burst. The eight-step continuum was constructed by varying the onset frequency of the second formant (F2) transition from 900 to 1600 Hz in 100-Hz steps and varying the onset frequency of the third formant (F3) transition

Table 1
Descriptive statistics for PD and CA groups.

	PD group	CA group	*t*(48)
Age (years)	10.42 (1.35)	10.21 (1.02)	0.61
Character recognition[a]	1959.94 (412.98)	2947.44 (375.73)	8.84***
Raven's Standard Progressive Matrices[b]	78.60 (22.09)	86.92 (11.20)	1.68
Onset detection[a]	9.40 (1.98)	13.72 (1.88)	7.91***
Rhyme detection[a]	8.00 (2.93)	12.96 (1.77)	7.25***
Sound deletion[a]	7.36 (3.24)	14.28 (1.75)	9.41***
Composite score of PA[c]	−3.44 (0.76)	2.70 (0.58)	32.05***

Note. Standard deviations are in parentheses.

*** $p < .001$.

[a] Raw scores.

[b] Percentiles.

[c] Standard scores.

from 2450 to 2800 Hz in 50-Hz steps. After 50-ms formant transitions, F2 and F3 reached the steady-state frequencies at 1200 and 2600 Hz, respectively. The first, fourth, and fifth formants were the same for each stimulus in the continuum. F1 had an onset frequency of 710 Hz and a 50-ms transition up to a steady-state frequency of 950 Hz. F4 and F5 remained constant at 3500 and 4400 Hz, respectively, for all stimuli. Fundamental frequency (F0) gradually fell from 140 to 130 Hz during the entire 210 ms. The stimuli were stored as 16-bit, 11-kHz .wav files. The adaptor /ta/ was identical to the endpoint /ta/ in the test continuum. The adaptor /te/ was synthesized by the Klatt synthesizer. The acoustic parameters were as follows: The onset frequencies of F1, F2, and F3 were 500, 1680, and 2450 Hz and changed linearly across a 50-ms transition period to reach the steady-state frequencies at 560, 1280, and 2350 Hz, respectively; F4 and F5 were steady-state at 3600 and 4460 Hz, respectively, during the 210 ms; and the F0 contour was consistent with the adaptor /ta/. Fig. 1 shows the formant contours of the adaptors /ta/ and /te/. One can see the subtle differences in formant transitions between /t(a)/ and /t(e)/.

Procedure

Identification of /pa/–/p^{h}a/ series

Participants were tested individually in a soundproof room. They were first given six practice items with feedback consisting of the endpoint stimuli. During experimental trials, participants listened to six presentations of each stimulus in three blocks of 48 trials. All stimuli were presented in semirandom order, and no feedback was given. Stimulus presentation was controlled by Praat software (Boersma & Weenink, 2006) running on a Hewlett–Packard (HP) laptop computer. Participants listened to the stimuli over AKG K501 headphones at a comfortable hearing level. They were told that they would hear either /pa/ or /p^{h}a/, and their job was to identify each item verbally as /pa/ or /p^{h}a/. The experimenter recorded each participant's responses.

Selective adaptation task

First, all participants completed the identification of the /pa/–/ta/ continuum in the unadapted state so as to obtain baseline identification functions. Participants were given six practice items with feedback consisting of the endpoint stimuli. The experimental trials consisted of six presentations of each stimulus for a total of 48 trials. The stimuli were presented in semi-random order and no feedback was given. Participants were asked to identify each item verbally as /pa/ or /ta/.

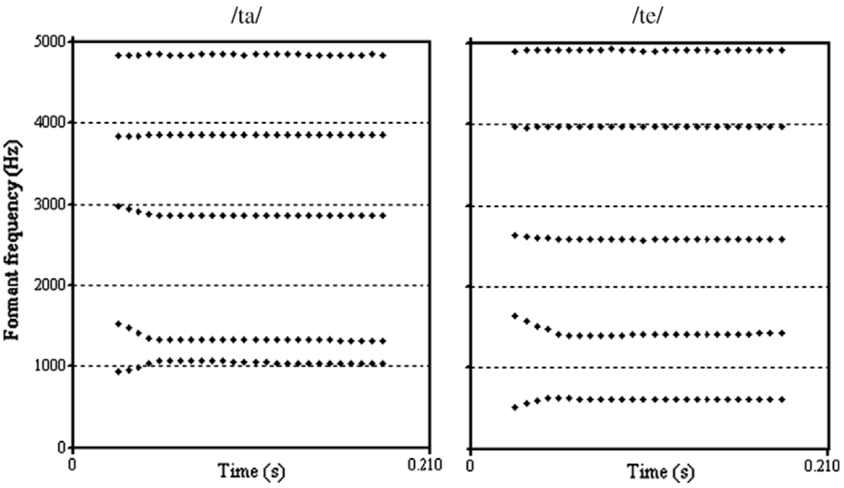

Fig. 1. Formant contours of the adaptors /ta/ and /te/.

Next, participants completed two adaptation sessions. The two sessions were separated by at least 1 day. In each group, approximately one half of the participants (12 or 13) first completed the /ta/ adapting session, and the other half first completed the /te/ adapting session. Each session consisted of six blocks. In each block, participants first heard 100 repetitions of the adaptor (/ta/ or /te/) separated by 300-ms interstimulus intervals (approximately 1 min presentation). Following the 1-min presentation and a 2-s pause, eight stimuli from the test continuum were presented in random order and participants were asked to identify each stimulus verbally as /pa/ or /ta/. Six blocks of 1-min adaptation periods followed by identification of eight stimuli (the test continuum) were completed for each adaptor, resulting in 48 labeled responses for each participant in each adapting condition.

Participants were tested individually in a soundproof room. The stimuli were presented with an HP laptop computer. Participants listened to the stimuli over AKG K501 headphones at a comfortable hearing level. They were asked to identify each test item verbally as /pa/ or /ta/. The experimenter controlled the presentation of the adaptor and test stimuli and also recorded each participant's responses.

Results

Identification of /pa/–/p^{h}a/ series

Group comparison

Identification functions of the /pa/–/p^{h}a/ series were obtained by calculating the percentage of /p^{h}a/ responses for each stimulus along the eight-step continuum. Fig. 2A shows the mean identification curves for the PD group and two control groups. The identification function of the PD group appeared to be less categorical than the identification functions of the control groups. Before comparing the differences among children with phonological dyslexia and the control groups, the Grade (third, fourth, or fifth) × Group (PD vs. CA) interaction was first analyzed with the percentage of /p^{h}a/ responses as the dependent variable. The analysis showed that the interaction was not significant, $F(2,44) = 0.92$, $p < .50$, so the data from the three grades were collapsed for the PD and CA groups. The percentage of /p^{h}a/ responses was entered into a 3 (Group) × 8 (Stimulus) mixed-design analysis of variance (ANOVA) with group as the between-participants factor and stimulus as the within-participant factor. The analysis revealed that the main effect of group was significant, $F(2,72) = 14.93$, $p < .001$, $\eta_p^2 = .29$, the main effect of stimulus was significant, $F(7,504) = 391.89$, $p < .0001$, $\eta_p^2 = .84$,

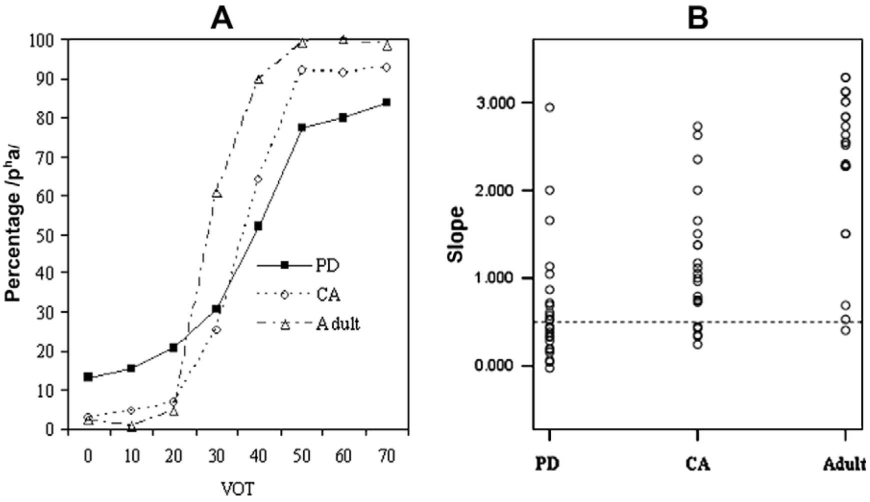

Fig. 2. (A) Identification functions for the PD group and two control groups. (B) Individual slope value on the /pa/–/p^{h}a/ series for the PD group and two control groups.

and the Group × Stimulus interaction was significant, $F(14,504) = 11.28$, $p < .001$, $\eta_p^2 = .24$. To further investigate the interaction, the effect of group was tested at each stimulus level. This revealed that the effect of group was significant at all stimulus levels, $Fs(2,72) \geqslant 6.55$, $ps < .01$, $\eta_p^2s \geqslant .15$. Post hoc Tukey's HSD tests showed that for 0-, 10-, and 20-ms VOT stimuli, the PD group had significantly more /p^{h}a/ responses than the CA group ($ps < .05$) and the adult group ($ps < .01$). For 30- and 40-ms VOT stimuli, both the PD and CA groups obtained significantly fewer /p^{h}a/ responses than the adult group ($ps < .01$). For 50-, 60-, and 70-ms VOT stimuli, the PD group was less likely to label them as /p^{h}a/ than the CA group ($ps < .05$) and the adult group ($ps < .01$).

Next, the identification data of the PD group and control groups were submitted to probit analysis, from which the values of phoneme boundary and slope were obtained. Probit analysis fits a cumulative normal curve to probability estimates as a function of stimulus level. Phoneme boundary is the 50% identification crossover point, and the slope serves as an index of identification consistency. The Grade (third, fourth, or fifth) × Group (PD vs. CA) interaction was analyzed with the slope and phoneme boundary as dependent variables. Because the results showed that neither of the interactions was significant, for the slope, $F(2,44) = 0.19$, $p < .70$, for the phoneme boundary, $F(2,44) = 2.10$, $p < .20$, the data from the three grades were pooled for the PD and CA groups. The mean slope values for the PD, CA, and adult groups were 0.67 ($SD = 0.67$), 1.09 ($SD = 0.72$), and 2.36 ($SD = 0.83$), respectively. A one-way ANOVA indicated that the group difference was significant, $F(2,72) = 34.94$, $p < .001$, $\eta_p^2 = .49$. Post hoc Tukey's tests showed that both the PD and CA groups had significantly lower slopes than the adult group ($ps < .001$) and that the difference between the PD group and the CA group did not reach significance ($p = .12$). The mean phoneme boundaries (expressed in VOT units) for the PD, CA, and adult groups were 41.41 ($SD = 14.64$), 37.42 ($SD = 4.17$), and 29.75 ($SD = 5.59$), respectively. The group difference for phoneme boundary was significant, $F(2, 72) = 10.03$, $p < .001$, $\eta_p^2 = .22$. Post hoc tests revealed that the PD group obtained a higher category boundary than the adult group ($p < .001$) and that the CA group also had a higher boundary than the adult group ($p < .05$).

Individual analysis

Several studies have demonstrated that not all participants with dyslexia show the categorical perception deficit; even children with phonological dyslexia also exhibit individual variability with respect to categorical perception ability (Joanisse et al., 2000; Manis et al., 1997). The individual identification function of the /pa/–/p^{h}a/ series was also examined in this study. Scatter plots of individual identification function slope for each group are shown in Fig. 2B. Each group exhibited interparticipant variability. For the PD group, several children even obtained higher slope values than the mean level of the CA group; however, most children had relatively lower slope values. Of the 25 children with phonological dyslexia, 20 had slope values lower than 1 (and 12 of these had slope values lower than 0.5). In the CA group, 13 children obtained slope values lower than 1 (and 7 of these had slope values lower than 0.5). Most adult participants had slope value higher than 1.

Selective adaptation task

Because the Grade (third, fourth, or fifth) × Group (PD vs. CA) interaction (with unadapted slope as the dependent variable) was not significant, $F(2,44) = 0.43$, $p < .70$, the data from the three grades were pooled for the PD and CA groups. The mean identification slopes in the baseline condition for the PD, CA, and adult groups were 0.94 ($SD = 0.66$), 1.68 ($SD = 0.85$), and 2.06 ($SD = 0.72$), respectively. A one-way ANOVA indicated that the group difference was significant, $F(2,72) = 14.58$, $p < .001$, $\eta_p^2 = .29$. Post hoc tests showed that the PD group had a lower slope than both the CA group ($p < .01$) and the adult group ($p < .001$). For the analysis of adaptation effects, first, the percentages of /ta/ responses in the baseline and adapted conditions were compared with a paired-samples *t* test for each group. The significant decrease of /ta/ responses in the adapted condition showed the occurrence of adaptation effects. ANOVA was also used to determine differences of adaptation effects among the PD group and control groups. Second, the phoneme boundaries of identification functions in the unadapted and adapted conditions were compared with a paired-samples *t* test for each group, and ANOVA was used to analyze the differences among participant groups. The significant boundary shift in the adapted conditions indicated the emergence of adaptation effects.

/ta/ adaptation

The average identification functions in the baseline and /ta/ adaptation conditions for the PD, CA, and adult groups are shown in Fig. 3. Percentage /ta/ responses in the unadapted and adapted conditions were compared for each group with a paired-samples *t* test. For the PD group, $t(24) = -0.54$, $p < .60$; for the CA group, $t(24) = 4.37$, $p < .001$; for the adult group, $t(24) = 9.01$, $p < .001$. Because the Grade (third, fourth, or fifth) × Group (PD vs. CA) interaction (with percentage of /ta/ responses as the dependent variable) was not significant, $F(2,44) = 2.26$, $p < .20$, the data from the three grades were pooled for the PD and CA groups. The percentage of /ta/ responses was entered into a 3 (Group) × 2 (Adaptation Condition: unadapted vs. /ta/ adaptation) mixed-design ANOVA. Results showed a significant main effect for group, $F(2,72) = 5.21$, $p < .01$, $\eta_p^2 = .13$, a significant main effect for adaptation condition, $F(1,72) = 65.07$, $p < .001$, $\eta_p^2 = .48$, and a significant interaction, $F(2,72) = 24.59$, $p < .001$, $\eta_p^2 = .41$. Further tests of simple effects revealed that the baseline percentages were equivalent across all participant groups; the group difference was significant in the /ta/ adaptation condition, $F(2,72) = 18.11$, $p < .001$, $\eta_p^2 = .33$, with post hoc tests showing that the PD group had more /ta/ responses than both the CA group ($p < .05$) and the adult group ($p < .001$) and that the CA group had more /ta/ responses than the adult group ($p < .01$).

Next, the phoneme boundaries in the unadapted and adapted conditions were computed for each group. The results are shown in Table 2. A paired-samples *t* test showed that the difference of phoneme boundaries between the unadapted condition and the adapted condition was significant for the CA group, $t(24) = 4.53$, $p < .001$, and for the adult group, $t(24) = 8.95$, $p < .001$, but not for the PD group, $t(24) = -0.20$, $p < .90$. Because the Grade (third, fourth, or fifth) × Group (PD vs. CA) interaction (with phoneme boundary as the dependent variable) was not significant, $F(2,44) = 0.93$, $p < .50$, the data from the three grades were pooled for the PD and CA groups. The 3 (Group) × 2 (Adaptation Condition) ANOVA showed a significant main effect for adaptation condition, $F(1,72) = 38.38$, $p < .001$, $\eta_p^2 = .35$, and a significant interaction, $F(2,72) = 10.45$, $p < .001$, $\eta_p^2 = .22$. The tests of simple effects revealed that the group difference in the baseline condition was not significant; the group difference was significant in the /ta/ adaptation condition, $F(2,72) = 6.27$, $p < .01$, $\eta_p^2 = .15$, with post hoc tests showing that the PD group differed significantly from the adult group ($p < .01$), the difference between the CA group and the adult group approached significance ($p < .09$), and the difference between the PD group and the CA group did not reach significance.

/te/ adaptation

The average identification functions in the /te/ adaptation condition for the PD, CA, and adult groups are shown in Fig. 3. The difference in percentage of /ta/ responses between the unadapted

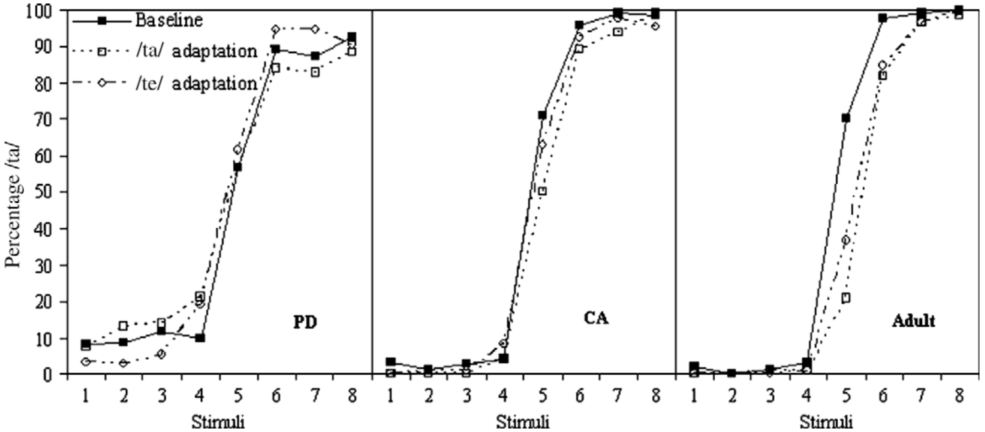

Fig. 3. Averaged identification functions in the baseline, /ta/ adaptation, and /te/ adaptation conditions for the PD, CA, and adult groups.

Table 2
Phoneme boundaries in the baseline, /ta/ adaptation, and /te/ adaptation conditions for the PD and control groups.

	Baseline	/ta/ adaptation	/te/ adaptation
PD	4.91 (0.46)	4.94 (0.85)	4.80 (0.46)
CA	4.73 (0.35)	5.15 (0.29)	4.96 (0.37)
Adult	4.76 (0.38)	5.51 (0.42)	5.33 (0.57)

Note. Phoneme boundaries are expressed in stimulus units. Standard deviations are in parentheses.

condition and the /te/ adaptation condition was significant for the adult group, $t(24) = 5.97$, $p < .001$, and approached significance for the CA group, $t(24) = 1.93$, $p < .07$, but not for the PD group, $t(24) = -0.89$, $p < .40$. Because the Grade (third, fourth, or fifth) × Group (PD vs. CA) interaction (with percentage of /ta/ responses as the dependent variable) was not significant, $F(2,44) = 0.34$, $p < .80$, the data from the three grades were pooled for the PD and CA groups. The percentage /ta/ responses were entered into a 3 (Group) × 2 (Adaptation Condition) ANOVA. Results showed a significant main effect of adaptation condition, $F(1,72) = 18.04$, $p < .001$, $\eta_p^2 = .20$, and a significant interaction, $F(2,72) = 12.35$, $p < .001$, $\eta_p^2 = .26$. The tests of simple effects revealed that the group difference was significant only in the /te/ adaptation condition, $F(2,72) = 9.04$, $p < .001$, $\eta_p^2 = .20$. Post hoc tests showed that the PD group had more /ta/ responses than the adult group ($p < .001$) and that the CA group also had more /ta/ responses than the adult group ($p < .05$).

The mean phoneme boundary in the /te/ adaptation condition is shown for each group in Table 2. The difference in phoneme boundary between the unadapted condition and the /te/ adaptation condition was significant for the CA group, $t(24) = 2.17$, $p < .05$, and for the adult group, $t(24) = 6.35$, $p < .001$, but not for the PD group, $t(24) = 1.27$, $p < .30$. The Grade (third, fourth, or fifth) × Group (PD vs. CA) interaction (with phoneme boundary as the dependent variable) was not significant, $F(2,44) = 0.43$, $p < .70$, so the data from the three grades were pooled for the PD and CA groups. The 3 (Group) × 2 (Adaptation Condition) ANOVA showed a significant main effect for adaptation condition, $F(1,72) = 17.70$, $p < .001$, $\eta_p^2 = .20$, and a significant interaction, $F(2,72) = 13.28$, $p < .001$, $\eta_p^2 = .27$. The tests of simple effects revealed that the group difference was significant only in the /te/ adaptation condition, $F(2,72) = 8.17$, $p < .01$, $\eta_p^2 = .18$. Post hoc tests showed that the PD group differed significantly from the adult group ($p < .01$), the CA group differed significantly from the adult group ($p < .05$), and the difference between the PD group and the CA group did not reach significance.

Individual analysis in adaptation effects

The size of the phoneme boundary shift was computed for each participant as the index of adaptation effects. The size of the phoneme boundary shift was defined as the boundary difference between one adaptation condition and the baseline condition. The scatter plots of adaptation effects in the /ta/ and /te/ adaptation conditions are shown for each group in Fig. 4. Most participants in the CA and adult groups showed the positive boundary shift in both adaptation conditions. However, for the PD group, more than half of the participants had an adaptation effect size less than 0 in both adaptation conditions. With 0.3 as the cutoff value (approximately the average shift level of the CA group across the adaptation conditions, a significant boundary shift), the PD group had 20 and 18 children with boundary shifts less than 0.3 in the /ta/ and /te/ adaptation conditions, respectively, the CA group had 9 and 12 corresponding children, and the adult group had 2 and 5 corresponding participants.

Relationship among different measures

The intercorrelations among the character recognition, phonological awareness, and speech perception measures (only the /pa/–/p^{h}a/ and baseline /pa/–/ta/ identification slopes were included) were examined in the child groups, partialing for children's age and nonverbal intelligence. The data from the two child groups were pooled because most of the correlation coefficients in the CA and PD groups were not significant. The results are presented in Table 3. The slope of the /pa/–/p^{h}a/ function correlated significantly with onset detection ($r = .40$) and sound deletion ($r = .30$). The /pa/–/ta/ slope

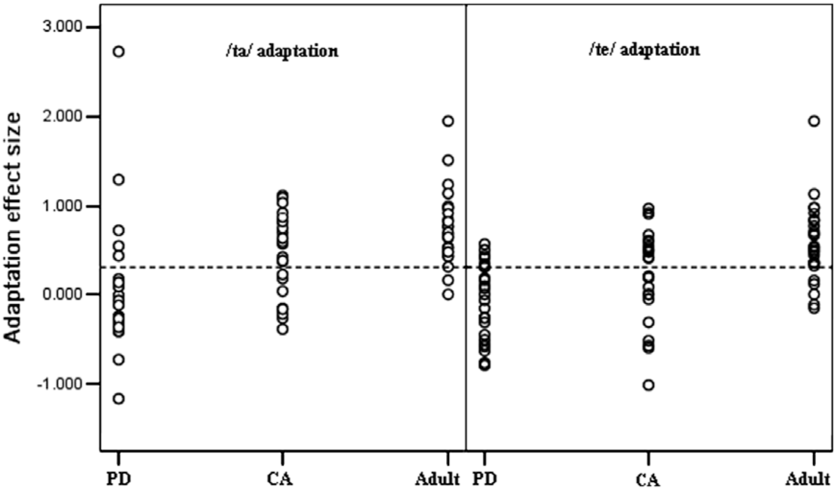

Fig. 4. Scatter plots of the adaptation effect size for the PD group and two control groups in the /ta/ and /te/ adaptation conditions.

correlated significantly with all reading and phonological awareness measures, especially with onset detection ($r = .52$). It seems that the categorization of consonants has more close association with awareness of consonant units.

Hierarchical regression analyses were conducted to examine the unique contributions of speech perception measures to reading and phonological skills. Age and nonverbal intelligence were entered at steps 1 and 2, respectively, as control variables. The main predictor of reading ability was phonological awareness (composite score), which accounted for 38.8% of the variance as the last entered variable, $\Delta F(1,44) = 70.34$, $p < .001$. When entered before phonological awareness variables, the /pa/–/ta/ slope accounted for 12.2% of variance of reading ability, $\Delta F(1, 45) = 8.70$, $p < .01$. When entered after phonological awareness variables, neither the /pa/–/p^{h}a/ slope nor the /pa/–/ta/ slope accounted for unique variance of reading ability. Finally, the /pa/–/ta/ slope accounted for 16.9% of variance of phonological awareness (composite score), $\Delta F(1, 45) = 10.89$, $p < .01$.

Discussion

The present study examined speech perception abilities in Chinese children with phonological dyslexia. First, the results of the categorical identification task indicated that Chinese children with

Table 3
Intercorrelations among different measures.

Measure	1	2	3	4	5	6	7
1. Character recognition	–						
2. Onset detection	.69***	–					
3. Rhyme detection	.72***	.51***	–				
4. Sound deletion	.72***	.58***	.59***	–			
5. Composite score of PA	.83***	.76***	.80***	.83***	–		
6. /pa/–/p^{h}a/ slope	.27	.40**	.26	.30*	.24	–	
7. /pa/-/ta/slope	.46**	.52***	.32*	.47**	.49***	.34*	–

* $p < .05$.
** $p < .01$.
*** $p < .001$.

phonological dyslexia showed categorical perception deficits. Although the identification slope difference between the PD group and the CA group did not reach significance, the PD group was less consistent than both the CA and adult groups in categorizing the stimuli belonging to the same phonetic category. The individual analysis revealed that most children in the PD group had relatively low slope values, with approximately half of them showing severe categorization deficits. In addition, the CA group also had lower identification slopes than the adult group, and the category boundaries of both the PD and CA groups were different from the category boundary of the adult group. This indicates that the phonemic categorization ability of children is still under development (Hazan & Barrett, 2000).

These results are inconsistent with some studies that did not find categorical perception deficits in dyslexic children when the test stimuli were more natural speech sounds (Blomert & Mitterer, 2004; Blomert et al., 2004). For example, Blomert and Mitterer (2004) found that the deficits that dyslexic children showed in the perception of synthetic speech could not be generalized to the perception of more natural speech sounds. We suggest that differences in the dyslexic samples may be responsible for the inconsistency between the findings. The current study selected dyslexic children with phonological awareness deficits as participants. They constituted a more homogeneous group in which it might be more likely to find speech perception deficits. So, the inconsistency of findings about the relation between dyslexia and speech perception deficits may be attributed partly to the heterogeneity of the dyslexic samples used.

The second task compared adaptation effects of dyslexic children and control groups using the selective adaptation paradigm. The results indicated that the PD group did not show any significant adaptation effects in either the /ta/ or /te/ adaptation condition, the CA group showed significant adaptation effects in the /ta/ adaptation condition and the adaptation effects approached significance in the /te/ adaptation condition, and the adult group showed the greatest and most significant adaptation effects in both the /ta/ and /te/ adaptation conditions. Individual analysis indicated that most children in the PD group did not show significant adaptation effects in either of the adaptation conditions, more than half of the children in the CA group showed significant adaptation effects for both adapting stimuli, and most adult participants showed significant adaptation effects after exposure to both adaptors. In addition, the adaptation effects of the CA group were still less than those of the adult group. This, together with the lower categorization ability that the child groups showed in the identification of the /pa/–/p^{h}a/ continuum, indicates that speech perception skills in 10-year-olds are far from perfect. The time when children achieve adult-like levels remains to be answered.

Finally, correlation and regression analyses suggested that speech perception skills contributed to phonological awareness and reading ability, but the contribution of speech perception to reading was not significant when phonological awareness was involved. It seems that the effect of speech perception on word recognition is mediated by phonological awareness (McBride-Chang, Wagner, & Chang, 1997).

A novel aspect of the current study was that the selective adaptation paradigm was adopted to explore the underlying speech perception process in Chinese children with phonological dyslexia. The lack of /te/ adaptation effects in the PD group was in accordance with expectations. We expected that the PD group would show smaller adaptation effects than control groups in the /te/ adaptation condition because they perceived speech in an allophonic mode and were more sensitive to the formant transition differences between /t(a)/ and /t(e)/, which would lead to the decrease or lack of adaptation effects for the adaptor /te/. We also expected that the PD group should show normal adaptation effects when the endpoint /ta/ served as the adaptor. However, the results revealed that the PD group still lacked adaptation effects in the /ta/ adaptation condition. The lack of /ta/ adaptation effects cannot be predicted directly by the hypothesis of allophonic perception, which pertains to the point that children with dyslexia are more sensitive to the subtle acoustic differences within a phonetic category and are less sensitive to the acoustic changes across phonetic categories. Nevertheless, how children with dyslexia process the same sound stimulus still needs to be answered. The lack of /ta/ adaptation effects implies that children with phonological dyslexia process the repeatedly presented sound /ta/ in a different way from children without dyslexia. This adaptation mode actually seems to indicate that the PD group has a general deficit in representing and processing speech stimuli even for the same speech stimuli.

Ahissar and colleagues recently also found a lack of adaptation effects in children with dyslexia and phonological awareness deficits (Ahissar, Lubin, Putter-Katz, & Banai, 2006). They administered auditory frequency discrimination and pseudoword perception tasks to a dyslexic group and control groups. The results indicated that children with dyslexia did not benefit from stimulus-specific repetitions. For example, in a frequency discrimination task, participants were asked to judge which one of two sequentially presented tones had the higher pitch. In one condition, a standard tone (1000 Hz) was presented as the fixed reference tone in each trial; in the other condition, there was no fixed reference. The task revealed that the dyslexic group performed as well as the control group in the no-reference condition. However, in the reference condition, the performance of the dyslexic group was lower than that of normal readers. Ahissar and colleagues suggested that dyslexic children cannot benefit from stimulus-specific repetitions and have difficulty in forming perceptual anchors, perhaps reflecting a deficient stimulus-specific adaptation mechanism (Ahissar, 2007; Ahissar et al., 2006).

The difficulty in forming perceptual anchors seems to be consistent with the results obtained in the selective adaptation task. After exposure to the repeatedly presented sound /ta/, children with phonological dyslexia failed to form a perceptual anchor and did not show significant adaptation effects. The anchoring and adaptation paradigms actually share the same underlying process (Simon & Studdert-Kennedy, 1978). What, then, is the underlying mechanism responsible for the anchoring deficit?

The sound perception mode in children with dyslexia (especially phonological dyslexia) can be summarized as follows. First, they show categorical perception deficits in perceiving native phonetic categories; that is, they are more sensitive to acoustic differences within a given phonetic category and less sensitive to acoustic changes across phonetic categories. Serniclaes and his colleagues (2004) put forward the allophonic perception hypothesis to explain this perception mode. Second, dyslexic children cannot show adaptation effects after exposure to a repeatedly presented sound stimulus. Ahissar and colleagues suggested that the anchoring deficit hypothesis accounts for the lack of adaptation effects (Ahissar, 2007; Ahissar et al., 2006). We think that both the allophonic perception mode and the anchoring deficit shown by children with dyslexia are reflections of a general deficit in representing and processing sound stimuli; the representations of sound stimuli in dyslexics are more diffused and less consistent than those in normal readers. That is, the activations of sound stimuli in dyslexics' cortical neural networks are more dispersed; even the activations of the same sound stimulus overlap less than those in normal readers. The diffused activations of sound stimuli result in the allophonic perception mode, and the diffused activations also lead to the difficulty in forming cohesive activation networks after exposure to a repeatedly presented sound stimulus and, furthermore, to the failure to form a perceptual anchor.

The brain activation patterns revealed by normal participants when listening to phonetic categories provide some evidence for the diffused activation hypothesis in phonological dyslexia. Normal participants show more cohesive cortical activations when processing speech sounds from the center of a native phonetic category and show more diffused brain activations when processing stimuli away from the category center or belonging to nonnative categories (Guenther & Bohland, 2002; Guenther, Nieto-Castanon, Ghosh, & Tourville, 2004; Zhang, Kuhl, Imada, Kotani, & Tohkura, 2005). However, considering the speech perception modes in which dyslexic children show, for example, similar sensitivity to native and nonnative categories (Serniclaes et al., 2004), they seem to have diffused and inconsistent neural network activations for all sound stimuli.

How do the diffused sound representations affect phonological awareness skills and reading acquisition? Phonological awareness skills reflect one's ability to segment and manipulate phonetic categories consciously (Anthony & Francis, 2005; Wagner & Torgesen, 1987). If the underlying phonetic category representations in one's brain are diffused and inconsistent, it must interrupt the conscious segmentation and manipulation administered to these phonetic categories. As suggested by Morais and Kolinsky (1994), the activation of unconscious phonemic representations ultimately constrains the elaboration of conscious manipulations. For the influence of impaired phonological representation on reading acquisition, Harm and Seidenberg (1999) provided a computational account using connectionist models. They showed that the phonologically impaired models developed more diverse representations for words with orthographic and phonological commonalities (neighborhood words such as *meat, eat,* and *treat*); in contrast, the normal model formed very similar representations for these words. The modeling results seem to be consistent with the hypothesis that children with phonological dyslexia develop more diffused representations for phonological stimuli that may result in less overlap representations for neighborhood words. As for Chinese characters, we know that they lack the grapheme–phoneme correspondence rules, but reading Chinese characters also requires establishing mapping between orthography and phonology, and Chinese children experience a phonological phase before becoming skilled readers, just like their counterparts learning alphabetic scripts (Ho & Bryant, 1997a; Siok & Fletcher, 2001). The diverse phonological representations will also cause Chinese children to develop more specific phonological output for each character, even for the prevalent homophones. So, despite the differences between alphabetic scripts and logographic scripts, the influence of diffused phonological representations on reading acquisition should be similar. The cross-linguistic consistency of phonological deficits in dyslexia has demonstrated this point clearly.

In sum, the current study provides further evidence for the close relation between phonological dyslexia and speech perception deficits, and the relation seems to have cross-language consistency. Furthermore, the current results show that children with phonological dyslexia have a general deficit in processing and representing speech stimuli. We suggest that the representations of sound stimuli in phonological dyslexics' brains are more diffused and less consistent, which may result in difficulties with phonological awareness and reading acquisition. The brain activations of children with phonological dyslexia when perceiving sound stimuli can be examined by functional brain imaging technologies to validate the hypothesis.

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