Research in Developmental Disabilities 86 (2019) 53–61

Contents lists available at ScienceDirect

Research in Developmental Disabilities

journal homepage: www.elsevier.com/locate/redevdis

Auditory identification of frequency-modulated sweeps and reading difficulties in Chinese

Hsiao-Lan Sharon Wang[a,*], Natalie Yu-Hsien Wang[b], I-Chen Chen[c], Yu Tsao[b]

[a] Department of Special Education, National Taiwan Normal University, Taipei, Taiwan
[b] Research Center for Information Technology Innovation (CITI), Academia Sinica, Taipei, Taiwan
[c] Department of Special Education, University of Taipei, Taipei, Taiwan

ARTICLE INFO

Number of reviews completed is 2
This paper belongs to the regular issue

Keywords:
Auditory processing
Frequency modulated sweeps
Reading difficulties
Chinese Mandarin

ABSTRACT

Background: In Chinese Mandarin, lexical tones play an important role of providing contrasts in word meaning. They are pitch patterns expressed by frequency-modulated (FM) signals. Yet, few studies have looked at the relationship between low-level auditory processing of frequency signals and Chinese reading skills.
Aims: The study aims to identify the role of auditory frequency processing in Chinese lexical tone awareness as well as character recognition in Chinese-speaking children.
Methods: Children with ($N = 28$) and without ($N = 27$) developmental dyslexia (DD) were recruited. All participants completed two linguistic tasks, Chinese character recognition and lexical tone awareness, and two auditory frequency processing tasks, frequency discrimination and FM sweep direction identification.
Results: The results revealed that Chinese-speaking children with DD were significantly poorer at all tasks. Particularly, Chinese character recognition was significantly related to FM sweep identification. Lexical tone awareness was significantly associated with both auditory frequency processing tasks. Regression analyses suggested the influence of FM sweep identification on Chinese character recognition contributed through lexical tone awareness.
Conclusions and implication: This study suggests that poor auditory frequency processing may associate with Chinese developmental dyslexia with phonological deficits. In support of the phonological deficit hypothesis, what underlies phonological deficit is likely to be auditory-basis. A potential clinical implication is to reinforce auditory perception and sensitivity through intervention for phonological processing.

What this paper adds?

The study is the first to identify the role of auditory frequency processing in Chinese lexical tone awareness as well as character recognition in Chinese-speaking children. The study provides evidence supporting the hypothesis that Chinese-speaking children with DD have impaired processing of suprasegmental pitch. Accordingly, what underlies phonological deficit is likely to be auditory-basis in Chinese reading difficulties. A clinical implication is that this finding suggests the importance of intervention to reinforce auditory perception and sensitivity. For optimal transfer of learning it could be most beneficial within a linguistic context; for example, games highlighting the frequency oscillation patterns of the native language (e.g. Up-Down pitch in Mandarin).

* Corresponding author.
E-mail addresses: hlw36@ntnu.edu.tw (H.-L.S. Wang), nataliewang@citi.sinica.edu.tw (N.Y.-H. Wang), g10605204@go.utaipei.edu.tw (I.-C. Chen), yu.tsao@citi.sinica.edu.tw (Y. Tsao).

https://doi.org/10.1016/j.ridd.2019.01.006
Received 24 September 2017; Received in revised form 31 December 2018; Accepted 12 January 2019
0891-4222/

1. Introduction

Developmental dyslexia (DD) is defined as a learning difficulty affecting word recognition, decoding, and spelling abilities, despite intelligence within the typical range and adequate education (Catts & Kamhi, 2005). According to the phonological deficit hypothesis (Ho, Law, & Ng, 2000; Ziegler & Goswami, 2005), impaired processing of segmental as well as suprasegmental phonological information is the root cause of reading failure. It is suggested that individuals with DD may have deficits in encoding and decoding basic phonological units (e.g. syllable & phoneme) and, therefore, have difficulties in forming more abstract and meaningful representations of speech (for a review, see Castles & Friedmann, 2014). Indeed, cross-linguistic evidence shows that children with DD have reduced phonological awareness, compared to typically developing children (Moll et al., 2014; Ziegler & Goswami, 2005). For instance, using a naming and a rhyme oddity task, Goswami, Fosker, Huss, Mead, and Szűcs (2011) have demonstrated reduced phonological awareness, the ability to identify and/or manipulate the component sounds in speech, in English, Spanish, and Chinese speakers with DD. Poor phonological awareness has also been found in Japanese children with dyslexia by Seki, Kassai, Uchiyama, and Koeda (2008); children with dyslexia performed significantly worse on the Japanese letter rhyming task compared to their age-matched typically developing children. It is notable that, in tonal language systems (e.g. Chinese Mandarin and Cantonese), the deficits of phonological processing have been found in both segmental (e.g. phoneme) and suprasegmental (e.g. lexical tone) level. In Chinese, lexical tone is crucial for conveying the meanings of Chinese characters through change of the pitch patterns. As a result, in children with Chinese DD, reduced lexical tone awareness has been identified as a persistent linguistic characteristic of profound influence on reading development (Tong, Tong, & King Yiu, 2017; Wang, Liu, Chung, & Yang, 2017).

1.1. Lexical tone in relation to reading development

The ability to accurately perceive lexical tone is developed around the first birthday in Chinese-speaking children (Tsao, 2017). The early development of speech perception is influential on later language abilities. For instance, Tsao, Liu, and Kuhl (2004) have revealed that, in six-month-old infant whose mother tongue is Chinese, the speech discrimination performance significantly predicts spoken word understanding, word production, and phrase understanding at the age of two. According to Ciocca and Lui (2003), lexical tone representations in tonal language speakers do not reach full maturation until about age ten. However, evidence from various age groups demonstrated strong correlation between lexical tone awareness and reading acquisition (McBride-Chang et al., 2008; Shu, Peng, & McBride-Chang, 2008). For instance, McBride-Chang et al. (2008) demonstrated that both morphological and lexical tone awareness significantly correlated with Chinese preschoolers' single word recognition performance. Further, McBride-Chang et al. reported that, when age and visuospatial skills are controlled, morphological and lexical tone awareness accounted for 5% and 3% of unique variance in Chinese word recognition respectively. Their findings highlight the importance of lexical tone awareness in reading development.

Mounting evidence has shown strong correlation between lexical tone awareness and reading skills in Chinese-speaking children with and without DD (Li & Ho, 2011; Liu & Tsao, 2017). Using a tone discrimination and a tone production task, Li and Ho demonstrated that Chinese-speaking children with DD have significantly worse lexical tone awareness, compared to typically developing children. The correlation analyses further revealed significant correlations between Chinese word recognition and the two lexical tone processing tasks [tone discrimination ($r = 0.28$) & tone production ($r = 0.27$)] respectively. Moreover, the correlation between reading skills and lexical tone awareness ae not restricted to word level. Liu and Tsao (2017) reported that lexical tone awareness, assessed with a tone discrimination task, significantly correlated with Chinese-speaking children's character recognition ability ($r = 0.38$), vocabulary size ($r = 0.56$), and reading comprehension ($r = 0.58$). The findings highlighted the importance of lexical tone awareness in the development of early literacy skills at character level and how it affects, relatively, high-level comprehension, which is essential for becoming an efficient reader.

In addition to the indicative and predictive role of lexical tone awareness in DD, interventions targeting lexical tone awareness have been reported to significantly improve Chinese character recognition (Wang et al., 2017; Zhou, McBride-Chang, Fong, Wong, & Cheung, 2012). To further explore the association between Chinese lexical tone awareness and character reading, Wang et al. (2017) assessed lexical tone awareness and character reading performance after the children with DD (from grade two, four & six) received sixteen fifteen-minute lexical tone training sessions over a four-week period. In each session, the children with DD were repeatedly exposed to different lexical tone pairs and the task was to judge the lexical tones in the pairs to see if they were the same or different. Positive training outcomes were restricted to the second grader group, showing that lexical tone awareness could significantly account for early reading development in particular.

Moreover, evidence drawing from alphabetic language systems has suggested that phonological deficits are closely linked with detecting certain auditory stimuli directly. It implied that the sensitivity to spectro-temporal acoustic cues reflect one's phonological processing (Talcott et al., 2000; Witton, Stein, Stoodley, Rosner, & Talcott, 2002) and further affects reading skills (Witton et al., 1998). However, little research has explored low-level auditory processing in relation to lexical tone awareness and reading skills in Chinese, which might be language specific.

1.2. Spectro-temporal acoustic cues and Chinese lexical tone

Natural speech consists of spectral and temporal modulated patterns, which change constantly within a period of time. Segmental information (i.e. syllable boundary) is temporal modulated whilst formant and pitch are spectral modulated; formant transition is a spetro-temporal modulated pattern (Liberman, 1996; Zheng, Escabí, & Litovsky, 2017). In a tonal language, variations in fundamental frequency (F0), such voice-pitch, at syllable level define lexical tone and distinguish word meanings (Liang, 1963). Lexical tone is a suprasegmental feature of a tonal language linked to a syllable. Similar to the concept of prosody in English, lexical tone cannot be easily analyzed without phonological segments, such as phonemes, consonants, and vowels (Zhang & McBride-Chang, 2010). Accordingly, lexical tone processing involves sensitivity to spectro-temporal acoustic cues.

All Chinese characters are monosyllabic and some comprise of identical phonetic segments; the meanings of the monosyllabic characters change according to the lexical tones (Tong, Tong, & McBride-Chang, 2015). For instance, in Mandarin, when the syllable "ba" is pronounced with Tone 1, it means *eight* [八]; with T2, it means *pull* [拔]; with Tone 3, it means *target* [靶]; with Tone 4, it means *father* [爸]. The four lexical tones in Mandarin vary in fundamental frequency (F0) and frequency contour, which is defined by the variations of pitch height (high, mid, & low) and pitch sweep (level, falling, & rising) (Ploquin, 2013; Yip, 2002). Tone 1 is a high-level pitch with an average frequency of 174 Hz; Tone 2 is a high-rising pitch, with the pitch sweep starting and ending at approximately 113 Hz and 193 Hz respectively; Tone 3 is a falling-rising pitch, the initial frequency falls from 114 to 87 Hz before rising to 147 Hz; Tone 4 is a high-falling pitch, falling from 189 to 85 Hz (Xu, Tsai, & Pfingst, 2002).

Amplitude modulation (AM) cues corresponding to the relatively slow amplitude variations over time; FM cues corresponding to the oscillations in instantaneous frequency close to the center frequency of the band (Cabrera, Tsao, Gnansia, Bertoncini, & Lorenzi, 2014). Studies (e.g. Smith, Delgutte, & Oxenham, 2002) have revealed that AM cues convey speech rhythm information whilst FM cues carry pitch information. Therefore, lexical tone identification is largely based on FM cues (Xu & Pfingst, 2008). A series of cross-linguistic studies by Cabrera et al. (2014, 2015) have further demonstrated different sensitivity to spectro-temporal modulated cues in speakers of alphabetic (French) and tonal (Chinese) languages. For instance, Cabrera et al. (2014) developed two-tone discrimination tasks with stimuli derived from three Thai tones (rising, falling, & low). For 'vocoded lexical tone' discrimination, the tones were manipulated by reducing the fine spectral details and FM cues. In the 'click trains' discrimination task, click trains were created by extracting the F0 of a tone and superimposed the extracted-F0 on the F0 of a pure tone. The participants' task was to discriminate whether the two auditory stimuli of a pair sounded the same or different. The Chinese speakers outperformed the French speakers on discriminating click trains but scored lower in vocoded lexical tone discrimination. The findings showed that Chinese speakers were highly dependent on the spectro-temporal modulated cues, including both FM and fine spectral structures, to process lexical tones.

Since Chinese lexical tone is frequency modulated, it is likely that the reduced sensitivity of lexical tone observed among Chinese-speaking children with DD is resulting from low-level auditory processing deficits. However, this issue has been overlooked and few have investigated the possibility. An event-related potential study by Meng et al. (2005) has looked at whether Chinese-speaking children with and without DD differed in processing pure tone. Despite reduced lexical tone awareness, the event-related potential results demonstrated that the children with DD did not differ from the controls in pure tone processing. Yet, the pure tone stimuli used in the study had a fixed frequency, which did not reflect the reality of lexical tone processing, during which the frequency sweeps change with time. Therefore, the relationships between Chinese reading skills, auditory frequency processing, and lexical tone awareness require further investigation.

1.3. Aims of the study

Lexical tone itself is frequency modulated (FM); different lexical tones have different frequency contour. However, the relationship between lexical tone awareness and auditory FM processing and how they are reflected in Chinese reading remain unclear. Therefore, this study employed a Chinese word recognition task, a lexical tone awareness task, and two auditory frequency tasks to further explore how the phonological and auditory frequency processing contribute to Chinese attainment. The study focuses on the following research questions:

1) To see whether children with Chinese DD demonstrate lexical tone processing difficulties as well as auditory FM processing impairment?
2) To see whether lexical tone awareness and/or auditory FM processing contribute(s) to Chinese word recognition?

2. Methods

2.1. Participants

Twenty-eight children with developmental dyslexia (DD) in 3rd grade and 4th grade of primary school were screened from the database of the Special Education Division, Department of Education of Taipei City Government (21 males; average age = 112.64 months), and recruited for this study. Children with DD must have demonstrated sufficient Chinese word decoding failures and have been behind typically developing children over one year, particularly in the Graded Chinese Character Recognition Test (Huang, 2001). In this study, significant character recognition problems and phonological deficits with 1.5 standard deviations below in the tests were part of the inclusion criteria for children with dyslexia. However, it is notable that these children may also demonstrate difficulties in reading comprehension.

On the other hand, twenty-seven age-matched typically developing children from local primary schools volunteered for the study as the controls (CA; 17 males; average age = 114.26 months). No reading or learning difficulty of any type was reported by their school teachers and parents. Their reading performance is well above the cut-off score (3rd grade = 50; 4th grade = 60) defined by the Graded Chinese Character Recognition Test. None of the participants had any other neurological or psychiatric disorders and

Table 1
Mean participant characteristics.

	CA controls (N = 27) Mean (SD)	Dyslexics (N = 28) Mean (SD)	*t*(53)
Age (month)	114.26 (8.14)	112.64 (12.18)	.576
WISC-IV	104.51 (5.20)	101.11 (9.46)	1.383
Chinese character recognition	102.89 (16.18)	61.79 (20.03)	8.355***
Lexical tone awareness task (20)	16.30 (2.60)	12.36 (4.08)	4.283***
Auditory Assessments			
Frequency discrimination	4.56 (1.27)	10.17 (8.11)	−3.556**
Frequency-modulated sweeps direction identification	135.04 (7.24)	115.32 (24.47)	4.083***

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

hearing impairment. Participant characteristics are listed in Table 1.

2.2. Measures

The participants' intelligence quotient (IQ) was examined using the Abbreviated Wechsler Intelligence Scale for Children. The children's scores of Graded Chinese Character Recognition Test were especially reported from the Diagnostic Tool for the statistical analysis. The independent-sample *t*-tests showed a significant group difference in Chinese character recognition [t (53) = 8.355, $p < .001$] and lexical tone awareness [t (53) = 4.283, $p < .001$]. In addition to the IQ test, all participants completed two linguistic tasks, Chinese character recognition and lexical tone awareness, and two auditory frequency processing tasks, frequency discrimination and frequency-modulated (FM) sweep direction identification. The auditory stimuli were set at 75 dB and presented binaurally through calibrated circumaural headphones.

2.2.1. Graded Chinese character recognition test

This timed test developed by Huang (2001) involves the participants reading aloud a series of 200 Chinese character. As the test proceeded, the printed word frequency decreased and, therefore, the recognition difficulty increased. All the characters are real Chinese characters but semantically unrelated. The recognition accuracy was recorded. The split-test reliability coefficient of this test was .99.

2.2.2. Lexical tone awareness task

Lexical tone reflects phonological awareness among Chinese speakers. This test consisted of twenty experiment trials. Each trial contained three different syllables, each corresponded to a visually presented cartoon character. After the three syllables were presented, the participants were asked to select the syllable with the odd tone. Prior to the task, four practice trials with feedback were available for familiarizing the participants with the task. No feedback was given for the experiment trials. Fig. 1 demonstrates the experiment interface shown on the computer screen. The green square surrounding cartoon item 1 indicates that the cartoon item

Fig. 1. The experiment interface of each trial. A trial is initiated by clicking on the 'start' option on the screen. The participants can listen to the syllables more than once using 'start'. The next trial would not appear until the participants give their answer and press the 'go to next' option.

is pronouncing the first syllable(/xi2/) in the trial. Once cartoon item 1 finishes, the green square moves to cartoon item 2; meanwhile, the second syllable (/lu2/) of the trial is presented by cartoon item 2. The same procedure applies for cartoon item 3, which presents the third syllable (/che3/) of the trial. Each syllable was only pronounced once in a trial; all trials can be repeated if the participants wish to listen to the pronunciations more than once. After all three cartoon items presented their corresponding syllables, the participants were to identify which cartoon item produced the syllable with an odd tone. For this example, shown in Fig. 1, the correct answer is cartoon item 3, which pronounces a syllable with Tone 3 while the other two cartoon items pronounce syllables with Tone 2. Each correct response earns one point; the maximum score is twenty. The coefficient of internal consistency (Cronbach's α) in the test was .75; the effect size of this task is 1.15 (Cohen's *d*).

2.2.3. Frequency discrimination test

This task was modified from the *frequency variation task* in Wang, Huss, Hämäläinen, and Goswami (2012). The current task employed the two alternative forced choice paradigms. There were five practice trials and a maximum of forty experiment trails in this auditory task. Feedback was provided for the practice but not the experiment trials. Therefore, an interval comprised of two trials. In one trial, a cartoon item sang rhythmically with high and low pitches (alternative sound); in the other trial, a different cartoon item sang a series of identical pitches (standard sound). The participants were asked to identify which cartoon item sang the alternative sound. All sound sequences were composed of five serial sounds. The standard sound had a frequency of 500 Hz and a duration of 200 ms; the inter-stimuli-interval (ISI) between each sound was 50 ms. The alternative sound sequence changed in a continuum of 40 stimuli ranging from 500 to 510 Hz logarithmic scale and the ISI between the five sounds was 50 ms. The volume of the stimuli was all set at 75 dB level.

An adaptive staircase method (Levitt, 1971) involving two up/one down or three up/one down procedure was used to measure the task performance. The participants started with three up/one down procedure. After three responses, the procedure was changed to two up/one down. A Probit function was fitted in the computer program to estimate the auditory sensitivity threshold. This estimation of auditory sensitivity could reach about 79% of accuracy (Wang et al., 2012). The threshold value of 40 was set as the maximum value. The effect size of this task is 0.95 (Cohen's *d*).

2.2.4. Frequency-modulated (FM) sweep direction identification test

The task was a modified form Luo, Boemio, Gordon, and Poeppel (2007). LabVIEW 2009 Service Pack 1 (NI Ltd., USA) was used to generate linear frequency-modulated (FM) tone sweeps sampled at 44.1 kHz with 16 bits of resolution. Both upward (UP) and downward (DOWN) FM sweeps were created. Pure and complex FM sweeps were generated with the frequency range of 600–900 and 85–200 respectively. A linear rise and fall time of 2 ms was set in all FM sweeps to minimize spectral splatter. Fourteen FM sweeps were created accordingly, including seven with UP direction and seven with DOWN direction. Each UP/DOWN FM sweep had a corresponding duration of 5, 10, 20, 30, 40, 50, or 80 ms.

The test contained 140 trials that were divided into seven blocks. Each block took about 15–20 minutes to complete. For each trial, the participants were presented with three cartoon items, each associated with a FM sweep. All three FM sweeps had the same duration; two of the sweeps were identical and the other contained a different FM sweep direction. The participants were asked to identify which cartoon item sounded differently; that is, identifying the FM sweep with an odd direction. The response accuracy was recorded and the maximum score was 140. The effect size of this task is 1.10 (Cohen's *d*).

2.3. Procedure

Each participant attended four sessions in a quiet room in his/her school on different days. In the first session, IQ assessment was conducted prior to the linguistic/non-linguistic task. The order of the four tasks were counterbalanced among the participants. Every session lasted for approximately 40 to 60 min. The written consent forms were obtained from all the parents and children to ensure their understanding of the procedure of this study. This study was approved by the Research Ethics Committee at National Taiwan University (NTU-REC No. 201306EM020).

3. Results

3.1. Statistical analyses

The first step for data analysis was to screen the data set, including an examination of variable means and standard deviations and check for outliers to ensure that the data was appropriate for the planned statistical analyses. The independent *t*-test was used to understand whether a quantitative variable within two groups significantly differ from each other. The significant level was set at 0.05. There were no significant differences between CA and DD groups in age and IQ, but significant differences appeared in Chinese character recognition, $t\ (53) = 8.355$, $p < .001$. Partial correlation was used to measure the degree of association between two variables, with the effect of the controlling variables removed. Hierarchical regression analysis was performed to explore the unique contribution of auditory frequency processing to character recognition and lexical tone awareness in Mandarin Chinese.

Table 2
Partial correlations between Chinese character recognition, lexical tone awareness and auditory perception, controlling for age and IQ.

	1	2	3	4
1. Chinese character recognition	–	.471**	−.314	.337*
2. Lexical tone awareness		–	−.364*	.499**
3. Frequency discrimination			–	−.598***
4. Frequency-modulated sweeps direction identification				–

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

3.2. Descriptive statistics

3.2.1. Group comparisons of lexical tone awareness

Table 1 presented the mean score and the standard deviation of this task. *T*-test was conducted to examine the group effects upon individual tasks. Alpha level for all tests were 0.05.

The results showed that there was a significant group difference in lexical tone awareness. Children with DD were significantly poorer at lexical tone awareness, t (53) = 4.283, $p < .001$, compared to CA controls.

3.2.2. Group comparisons of auditory processing

Table 1 also showed the mean thresholds and standard deviations for the auditory assessments including frequency discriminations and identification of FM sweep direction.

Children with DD showed a higher discrimination threshold (t (53) = −3.556, $p < .001$) and lower identification accuracy (t (53) = 4.083, $p < .001$) than CA group in both tasks. The values reached the statistically significant level. It suggested that DD children might have poor auditory processing regarding sound frequency signals.

3.3. Relationships between literacy, lexical tone awareness and auditory processing skills

The partial correlations, controlling for age and IQ, between the measures of reading, lexical tone awareness and auditory processing across all participants, were present in Table 2.

The results showed that there was a strong correlation between Chinese character recognition and lexical tone awareness. Chinese character recognition was significantly associated with lexical tone awareness, r = 471, p = .004. Clearly, the better children performed in lexical tone awareness, the better performance on Chinese character recognition they could achieved.

In the examination of the relationship between Chinese character recognition and auditory frequency tests, the results showed that there was a significant link between Chinese character recognition and FM sweep direction identification only, r = .337, p = .048. Moreover, lexical tone awareness was found significantly related to both frequency discrimination (r = −.364, p = .034) and FM sweep direction identification (r = .499, p = .002).

3.4. Multiple regression analyses

Hierarchical regression analysis was performed to investigate the contribution of each auditory frequency test to Chinese character recognition and lexical tone awareness. In all regression analyses, age and IQ were entered first into the model. The results were shown in Table 3. FM sweep direction identification significantly explained up to 11% of additional variance in Chinese character recognition. However, when lexical tone awareness was controlled, none of the auditory frequency contributions was significant. In

Table 3
R^2 changes in separate linear regression equations examining the contribution of auditory perception to character recognition.

Step	Beta	R^2 changes
DV: Chinese character recognition		
1. Age	.189	.036
2. IQ	.051	.003
3. Frequency discrimination	−.330	.095
3. Frequency-modulated sweeps direction identification	.371	.109*
3. Lexical tone awareness	.529	.214**
4. Frequency discrimination	−.172	.022
4. Frequency-modulated sweeps direction identification	.149	.013

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

Table 4
R^2 changes in separate linear regression equations examining the contribution of auditory perception to lexical tone awareness.

Step	Beta	R^2 changes
DV: Lexical tone awareness		
1. Age	−.017	.000
2. IQ	.489	.235**
3. Frequency discrimination	−.340	.101*
3. Frequency-modulated sweeps direction identification	.490	.190**

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

terms of the degree that auditory processing contributed to lexical tone awareness, Table 4 demonstrated that both frequency discrimination and FM direction identification accounted for unique variance (10% and 19%) of lexical tone awareness.

4. Discussion

In the current study, we are interested in the relationship between auditory frequency processing, lexical tone awareness, and reading abilities in Chinese. We found significant group differences between children with and without DD in lexical tone awareness test and auditory frequency processing tasks. In our data, there was a strong correlation between Chinese character recognition, lexical tone awareness, and auditory FM sweeps direction identification. Auditory identification of FM sweep direction appears to be the best variable to explain the individual differences in both lexical tone awareness and Chinese character recognition. In addition, basic auditory discrimination of simple sound frequency also contributed significantly to lexical tone awareness.

Our study is consistent with previous work, showing the nature of lexical tone deficit in Chinese children with dyslexia. For example, Li and Ho (2011) compared 20 Cantonese-speaking children with Chinese dyslexia aged 7–10 with typical-reading children. The data indicated that 35% of dyslexic children were poor at the discrimination of tones with real syllables while 50% of them demonstrated reduced performance on tone production. This problem may affect their paired-associate learning of Chinese character recognition and pronunciation. Recently, Wang et al. (2017) examined 270 schooling children across 2^{nd} to 6^{th} grade children in Taiwan and found that, for Chinese-speaking children with DD, the performance of their tone awareness was always worse than children with typical reading development. Across all children of different reading levels, the test of lexical tone awareness was significantly associated with onset-rime awareness, verbal short-term memory, and rapid naming tasks. Lexical tone detection even serves as a strong early predictor to distinguish Chinese children at risk of DD from typically developing children (McBride-Chang et al., 2008). Our findings, again, support the assumption that DD is a result of underspecified phonological representations and insensitive perception of prosodic information in native speech (Goswami, Gerson, & Astruc, 2010; Tong et al., 2017; Wang et al., 2012).

Because lexical tone is one of the suprasegmental properties in Chinese, we look at the possible influence of lower-level auditory processing of suprasegmental structure on reading difficulties. In the study, we found that Chinese-speaking children with DD had inferior auditory discrimination of alternative frequency discrimination (i.e. pure tones with alternately high and low pitches) and auditory identification of FM sweep directions. This auditory problem may link to their poor development of tone awareness. It may also suggest that, since tonal language is phonologically contrastive, for its speakers, basic auditory frequency discrimination was significantly associated with lexical tone identification, as both of our auditory frequency processing tasks were significantly related to lexical tone awareness. In fact, studies have found that when we are very young, at the infant stage, tonal language learners are able to develop better perceptual sensitivity for lexical tones. Such auditory processing mechanism is language-specific and could be reorganized according to the language-specific experience. A study conducted by Cabrera et al. (2015) investigated whether one's native language experience affected the auditory perceptual sensitivity of spectro-temporal cues in speech modulations. A significant developmental change in perceptual weighting of speech modulation cues were found by the comparisons between French and Mandarin infants. Moreover, another study by Tsao (2017) examined one hundred and twenty 6–12 month-old Mandarin-learning infants and revealed a significant developmental improvement of auditory sensitivity to pitch contrasts with similar frequency contours like lexical tones. It seems that the language environment could boost the perceptual reorganization related to the native phonological properties. These findings are in line with our present behavioral results, showing a strong connection between auditory frequency processing and lexical tone awareness in Chinese-speaking children. As in our data, significant correlations between tone awareness, auditory frequency discrimination and auditory FM identification were demonstrated. In addition, the regression analysis pointed out that 19% of the variance in the assessment of lexical tone awareness was explained by auditory FM sweeps identification. The value was higher than simple auditory frequency discrimination. We thus suspect that tones awareness may require a more complex analysis of frequency modulation, such as frequency-modulated (FM) glides.

The present study further suggested that measurements using the simple pure tones aforementioned might not be consistent in reflecting the sensory and perceptual discrimination of lexical tones toward Chinese reading. In our data, Chinese character recognition was significantly related to auditory identification of FM sweeps only. The regression analysis indicated that 11% of the variance in the assessment of Chinese character recognition was explained by FM sweeps identification. Therefore, dynamic frequency modulation appears to be an important acoustic correlate of both lexical tones and Chinese reading. However, when tone awareness was entered into the model, the contribution of auditory identification of FM sweeps to Chinese character recognition did not reach the statistical significant level. It may imply that this auditory influence upon Chinese character recognition was made through lexical tone processing. This inference needs to be examined in the future.

Our data was preliminary to indicate the significance of decoding FM signals for lexical tone identification and Chinese character recognition. To account for the importance of auditory FM sweeps identification in tone awareness and Chinese reading, one reliable explanation is that Chinese Mandarin is a tonal language that requires more sensitive pitch perception in speech (Fu, Zeng, Shannon, & Soli, 1998). Although it has been suspected that Chinese-speaking children with DD may have impaired simple frequency discrimination in previous research (Meng et al., 2005; Zhang & McBride-Chang, 2010), it should be noted that these experiments usually adopted pure-tone frequency stimuli to assess the accuracy of individual's auditory perception. While lexical tones are pitch contours, which are primarily determined by the fundamental frequency (F0), some temporal information can also serve as acoustic cues (Wang, Jongman, & Sereno, 2003). It seems that both spectral and temporal information through FM signals must be considered in determining pitch differ. For example, pitch movement (rising or falling) and pitch height/level (high, middle or low) together determine four different lexical tones in Chinese Mandarin. A study by Gandour (1981) has also suggested three perceptual dimensions labeled 'height', 'direction', and 'contour' that are related to listeners' perception of Cantonese tones. Similar to Cantonese tones, Mandarin Chinese tones also differ in 'height', 'direction', and 'contour' in perception. Among these dimensions, the direction of F0 change is crucial to distinguish contour tones (Tone 2, Tone 3 and Tone 4) and the level tone (Tone 1). In a word, instead of simple frequency discrimination, perception of different dimensions of pitch may be applied for listeners to perceive tonal contrasts. As a result, the ability to detect the gradually changed pitch associated with tones is worthy of investigation.

Although the results obtained in our analyses here have provided some novel information regarding spectro-temporal information processing in the auditory system, there is still much work to be done. With respect to Chinese-speaking children with DD, it is hoped that more work can be done to properly question the causality between auditory frequency processing, phonological and reading abilities in Chinese language. Some work should involve a longitudinal study to examine auditory, phonological and reading performance in a large group of children across many developmental years. It will then be able to explore the developmental trajectory of auditory perception and whether this low-level temporal modulation cue is a characteristic of Chinese reading difficulties with significant tone awareness problems. In addition, some future intervention studies may be able to describe the influence of auditory training on frequency sensitivity described here and to examine whether this effect will help Chinese-speaking children process phonological information. Finally, we suggest that exploration of this auditory mechanism should be investigated with more ecologically valid linguistic and non-linguistic stimuli also with methodology that can better assess the nature of reading impairment at the neuronal level.

Our findings again point to the hypothesis that an auditory processing deficit was a possible cause of phonological problems in children with DD. In Chinese, accurate tracking of frequency changes is exactly what is needed for the perception of Mandarin speech, which is characterized both by information of spectral and temporal variations (Kong & Zeng, 2006). Since speech perception is the basis to develop phonological skills, it is therefore likely that impairments in the identification of FM signals affect tone awareness development and sensitivity via speech perception. A clinical implication is that this finding suggests the importance of intervention to reinforce auditory perception and sensitivity. For optimal transfer of learning it could be most beneficial within a linguistic context; for example, games highlighting the frequency oscillation patterns of the native language (e.g. Up-Down pitch in Mandarin). Further applied studies are required to examine these possibilities.

In conclusion, the current research found group-level differences between Chinese-speaking children with and without DD on character recognition, lexical tone awareness, and auditory frequency processing. We propose that auditory identification of FM signals might be related to Chinese reading difficulties specifically. Our evidence may provide support to the hypothesis that Chinese-speaking children with DD have impaired processing of suprasegmental pitch. Accordingly, what underlies phonological deficit is likely to be auditory-basis in Chinese reading difficulties.

Acknowledgements

We thank all our participants, their schools, and their parents. H.L.S.W. was supported by the Minister of Science and Technology (MOST103-2420-H-003-008-MY3).

References

Cabrera, L., Tsao, F. M., Gnansia, D., Bertoncini, J., & Lorenzi, C. (2014). The role of spectro-temporal fine structure cues in lexical-tone discrimination for French and Mandarin listeners. *The Journal of the Acoustical Society of America, 136*(2), 877–882.

Cabrera, L., Tsao, F. M., Liu, H. M., Li, L. Y., Hu, Y. H., Lorenzi, C., ... Bertoncini, J. (2015). The perception of speech modulation cues in lexical tones is guided by early language-specific experience. *Frontiers in Psychology, 6*, 1290.

Castles, A., & Friedmann, N. (2014). Developmental dyslexia and the phonological deficit hypothesis. *Mind & Language, 29*(3), 270–285.

Catts, H. W., & Kamhi, A. G. (2005). *The connections between language and reading disabilities.* UK: Psychology Press.

Ciocca, V., & Lui, J. (2003). The development of the perception of Cantonese lexical tones. *Journal of Multilingual Communication Disorders, 1*(2), 141–147.

Fu, Q. J., Zeng, F. G., Shannon, R. V., & Soli, S. D. (1998). Importance of tonal envelope cues in Chinese speech recognition. *The Journal of the Acoustical Society of America, 104*(1), 505–510.

Gandour, J. (1981). Perceptual dimensions of tone: Evidence from Cantonese. *Journal of Chinese Linguistics, 9*(1), 20–36.

Goswami, U., Fosker, T., Huss, M., Mead, N., & Szűcs, D. (2011). Rise time and formant transition duration in the discrimination of speech sounds: the Ba–Wa distinction in developmental dyslexia. *Developmental Science, 14*(1), 34–43.

Goswami, U., Gerson, D., & Astruc, L. (2010). Amplitude envelope perception, phonology and prosodic sensitivity in children with developmental dyslexia. *Reading and Writing, 23*(8), 995–1019.

Ho, C. S. H., Law, T. P. S., & Ng, P. M. (2000). The phonological deficit hypothesis in Chinese developmental dyslexia. *Reading and Writing, 13*(1-2), 57–79.
Huang, H. S. (2001). *Graded Chinese character recognition test.* Taiwan: Psychology Publication.
Kong, Y. Y., & Zeng, F. G. (2006). Temporal and spectral cues in Mandarin tone recognition. *The Journal of the Acoustical Society of America, 120*(5), 2830–2840.
Levitt, H. C. C. H. (1971). Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical Society of America, 49*(2B), 467–477.
Li, W. S., & Ho, C. S. H. (2011). Lexical tone awareness among Chinese children with developmental dyslexia. *Journal of Child Language, 38*(4), 793–808.
Liang, Z. A. (1963). The auditory perception of Mandarin tones. *Acta Physica Sinica, 26*, 85–91.
Liberman, A. M. (1996). *Speech: A special code.* MA: MIT Press.
Liu, H. M., & Tsao, F. M. (2017). Speech perception deficits in Mandarin-speaking school-aged children with poor reading comprehension. *Frontiers in Psychology, 8*, 2144.
Luo, H., Boemio, A., Gordon, M., & Poeppel, D. (2007). The perception of FM sweeps by Chinese and English listeners. *Hearing Research, 224*(1–2), 75–83.
McBride-Chang, C., Lam, F., Lam, C., Doo, S., Wong, S. W., & Chow, Y. Y. (2008). Word recognition and cognitive profiles of Chinese pre-school children at risk for dyslexia through language delay or familial history of dyslexia. *Journal of Child Psychology and Psychiatry, 49*(2), 211–218.
Meng, X., Sai, X., Wang, C., Wang, J., Sha, S., & Zhou, X. (2005). Auditory and speech processing and reading development in Chinese school children: Behavioural and ERP evidence. *Dyslexia, 11*(4), 292–310.
Moll, K., Ramus, F., Bartling, J., Bruder, J., Kunze, S., Neuhoff, N., ... Tóth, D. (2014). Cognitive mechanisms underlying reading and spelling development in five European orthographies. *Learning and Instruction, 29*, 65–77.
Ploquin, M. (2013). Prosodic transfer: From Chinese lexical tone to English pitch accent. *Advances in Language and Literary Studies, 4*(1), 68–77.
Seki, A., Kassai, K., Uchiyama, H., & Koeda, T. (2008). Reading ability and phonological awareness in Japanese children with dyslexia. *Brain & Development, 30*(3), 179–188.
Shu, H., Peng, H., & McBride-Chang, C. (2008). Phonological awareness in young Chinese children. *Developmental Science, 11*(1), 171–181.
Smith, Z. M., Delgutte, B., & Oxenham, A. J. (2002). Chimaeric sounds reveal dichotomies in auditory perception. *Nature, 416*(6876), 87–90.
Talcott, J. B., Witton, C., McLean, M. F., Hansen, P. C., Rees, A., Green, G. G., ... Stein, J. F. (2000). Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences of the United States of America, 97*(6), 2952–2957.
Tong, X., Tong, X., & King Yiu, F. (2017). Beyond auditory sensory processing deficits: Lexical tone perception deficits in Chinese children with developmental dyslexia. *Journal of Learning Disabilities, 51*(3), 293–301.
Tong, X., Tong, X., & McBride-Chang, C. (2015). Tune in to the tone: Lexical tone identification is associated with vocabulary and word recognition abilities in young Chinese children. *Language and Speech, 58*(4), 441–458.
Tsao, F. M. (2017). Perceptual Improvement of lexical tones in infants: Effects of tone language experience. *Frontiers in Psychology, 8*, 558.
Tsao, F. M., Liu, H. M., & Kuhl, P. K. (2004). Speech perception in infancy predicts language development in the second year of life: A longitudinal study. *Child Development, 75*(4), 1067–1084.
Wang, H. L. S., Huss, M., Hämäläinen, J. A., & Goswami, U. (2012). Basic auditory processing and developmental dyslexia in Chinese. *Reading and Writing, 25*(2), 509–536.
Wang, Y., Jongman, A., & Sereno, J. A. (2003). Acoustic and perceptual evaluation of Mandarin tone productions before and after perceptual training. *The Journal of the Acoustical Society of America, 113*(2), 1033–1043.
Wang, L. C., Liu, D., Chung, K. K. H., & Yang, H. M. (2017). Development of lexical tone awareness in Chinese children with and without dyslexia. *Contemporary Educational Psychology, 49*, 203–214.
Witton, C., Stein, J. F., Stoodley, C. J., Rosner, B. S., & Talcott, J. B. (2002). Separate influences of acoustic AM and FM sensitivity on the phonological decoding skills of impaired and normal readers. *Journal of Cognitive Neuroscience, 14*(6), 866–874.
Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A., ... Green, G. G. R. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current Biology, 8*(14), 791–797.
Xu, L., & Pfingst, B. E. (2008). Spectral and temporal cues for speech recognition: Implications for auditory prostheses. *Hearing Research, 242*(1–2), 132–140.
Xu, L., Tsai, Y., & Pfingst, B. E. (2002). Features of stimulation affecting tonal-speech perception: Implications for cochlear prostheses. *The Journal of the Acoustical Society of America, 112*(1), 247–258.
Yip, M. (2002). *Tone.* UK: Cambridge University Press.
Zhang, J., & McBride-Chang, C. (2010). Auditory sensitivity, speech perception, and reading development and impairment. *Educational Psychology Review, 22*(3), 323–338.
Zheng, Y., Escabí, M., & Litovsky, R. Y. (2017). Spectro-temporal cues enhance modulation sensitivity in cochlear implant users. *Hearing Research, 351*, 45–54.
Zhou, Y. L., McBride-Chang, C., Fong, C. Y. C., Wong, T. T. Y., & Cheung, S. K. (2012). A comparison of phonological awareness, lexical compounding, and homophone training for Chinese word reading in Hong Kong kindergartners. *Early Education and Development, 23*(4), 475–492.
Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131*(1), 3–29.