Revisiting Hemispheric Lateralization for Cantonese Lexical Tone Processing in Dichotic Listening

Gaoyuan Zhang[1], *Jing Shao*[1], *Yubin Zhang*[1] *and Caicai Zhang*[1, 2]

[1] Department of Chinese and Bilingual Studies, the Hong Kong Polytechnic University
[2]Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences

gynzhang@polyu.edu.hk, jing.shao@polyu.edu.hk, yubin.zhang@polyu.edu.hk, caicai.zhang@polyu.edu.hk

Abstract

In this study, we aim to re-examine the issue of hemispheric lateralization for Cantonese lexical tone processing in dichotic listening. We are particularly interested in testing whether the previously reported the right-hemisphere advantage in Cantonese lexical tone processing in dichotic listening [1] is replicable. More importantly, we aim to explore whether the brain lateralization pattern for tone processing is influenced by tone awareness. Sixteen native Cantonese speakers that were proficient in *Jyutping* and eighteen matched controls were asked to discriminate and identify Cantonese tones in dichotic listening. A right-hemisphere advantage was found in the discrimination task but not in the identification task. Findings from the discrimination task were generally consistent with [1] and supported the acoustic hypothesis of brain lateralization in lexical tone processing. However, the identification task might require more higher-level linguistic processing in the left hemisphere, resulting in more bilateral processing. No differences in hemispheric advantage were found between the two groups, although the *Jyutping* group outperformed controls in tone discrimination and identification in some conditions. The temporary conclusion is that late learning of *Jyutping* in adulthood may have limited effect on reshaping the brain lateralization of Cantonese lexical tone processing.

Index Terms: dichotic listening, hemispheric lateralization, lexical tone processing, Cantonese, tone awareness.

1. Introduction

Since Paul Broca's seminal works revealed a left hemispheric lateralization for speech production, much effort has been dedicated to the hotly debated topic of brain function lateralization [2]. The two hemispheres of the brain are regarded as having different functions [3]. Generally speaking, the left hemisphere (LH) is believed to be related to analytic processing and the right hemisphere (RH) is considered to be concerned with holistic processing [3, 4]. For example, the LH is dominant for speech processing [5-7], whereas RH is better at music processing [8], face recognition [9], etc.

There are two major hypotheses regarding the brain lateralization for processing auditory stimuli – the functional hypothesis and the acoustic hypothesis [10]. The functional hypothesis assumes that brain lateralization is dependent on the functional role of the auditory signal, that is, whether the incoming stimuli are speech or not. This view predicts that speech stimuli are primarily processed in LH, since in right-handed people the LH is typically considered as the "language brain", whereas other non-speech signals are processed primarily in the RH. The acoustic hypothesis focuses on low-level acoustic properties of the stimuli. According to this view, spectral processing, like pitch-related information is lateralized to the RH while fast temporal processing, like fast spectral changes, induces more LH activations.

Lexical tones, where fundamental frequency (F0) patterns systematically distinguish lexical meanings in tonal languages like Chinese, stand as an interesting case for examining the hemispheric lateralization of auditory stimuli. The two aforementioned hypotheses give different predictions on the brain lateralization of lexical tone processing. The functional hypothesis predicts LH dominance for processing lexical tones because lexical tones have key linguistic functions [11]. On the other hand, the acoustic hypothesis predicts that lexical tone is processed primarily in the RH, as the RH is in charge of processing spectral information like F0 [1].

Several behavioral studies using the dichotic listening paradigm provided evidence for the functional view [12-15]. For example, an early study from van Lancker and Fromkin [14] examined the dichotic listening of lexical tones and reported a right ear advantage for Thai tones in native Thai speaker. In a similar vein, Wang [12] found a significant right ear superiority/LH advantage for tone processing in native Mandarin speakers. There are also some neuroimaging studies supporting the functional hypothesis [16, 17].

The acoustic hypothesis has also gained some empirical support in dichotic listening studies. For example, Jia et al. [1] reported a RH advantage for Cantonese tone processing in Cantonese native speakers, in contrast to the LH advantage for tone processing in Thai and Mandarin speakers mentioned above. The authors explained that the discrepancy between the results of LH advantage [14-17] mentioned before and their findings might be related to differences in phonological awareness, especially tone awareness.

Phonological awareness refers to the ability of analyzing the spoken language into smaller units such as phonemes [18]. It has been well established that learning an alphabetic script boosts phonological awareness at the phoneme level [19-21]. At the neural level, learning an alphabetic script not only causes functional reorganization of the left language network [22, 23], but also induces marked anatomical changes in the language regions of the LH [24, 25]. Most Mandarin speakers are skilled at an alphabetic script of Chinese (i.e., *pinyin*) whereas the majority of Cantonese speakers in Hong Kong are only literate in logographic Chinese. It has been found that experience with *pinyin* leads to enhanced phonological awareness [21], which may be related to more left-lateralized tone processing in Mandarin speakers.

In the present study, we firstly aimed at replicating Jia et al.'s [1] results on RH lateralization for Cantonese tone processing. More importantly, we aimed to test the hypothesis that tone awareness associated with learning an alphabetic script leads to more left-lateralized tone processing in Cantonese speakers. To this end, we compared a group of Cantonese speakers who were proficient in *Jyutping*, which is a Romanization system of Cantonese, and a control group with low *Jyutping* proficiency on Cantonese tone identification and discrimination in dichotic listening.

2. Method

2.1. Participants

18 control participants (8M, 10F) and 16 *Jyutping* participants (9M, 7F) were recruited for this experiment. One *Jyutping* subject was excluded because he always responded according the information from his left ear. All of them were native speakers of Hong Kong Cantonese. None of them reported any hearing deficits, brain injuries, and long-term professional musical training. The two groups were matched in age and they were all right-handed as assessed by the Edinburgh Handedness Inventory [26]. The *Jyutping* participants were selected based on a *Jyutping* transcription test, which contained 20 disyllabic words in Chinese characters. Subjects were instructed to write down the *Jyutping* transcription of these words in an answer sheet as fast as possible. Participants who achieved above 50% accuracy on tone transcription in the test were assigned to the *Jyutping* group (M = 72.94%, Range: 52.5%-97.5%). The control group scored 50% or below on the same task (M = 29.13%, Range: 10%-45%).

2.2. Stimuli

There were two types of materials: speech and pure tone. Five syllables (/fɐn/, /jɐu/, /wɐi/, /nga/ and /ji/) with six lexical tones in Cantonese (T1-high level tone, T2-high rising tone, T3-mid level tone, T4-low falling tone, T5-low rising tone, and T6-low level tone) were selected. These syllables were recorded by a female native Hong Kong Cantonese speaker. Every stimulus was normalized in duration to 620 ms and in average intensity to 60 dB. The pure tone stimuli were non-speech analogues of lexical tones. F0 contours in syllables (/ji/ and /nga/) with six Cantonese tones were extracted to generate the pure tone stimuli using Praat. The duration of each pure tone stimulus was also 620 ms, while the mean intensity of the pure tone sound was changed to 75 dB, because the pure tone materials sounded softer. Level tones (T1, T3, T6) and contour tones (T2, T4, T5) were divided and presented separately.

2.3. Procedure

This study included three stimulus conditions: high-variation condition, low-variation condition and pure-tone condition. Each condition consisted of a discrimination task and an identification task. The high-variation condition that required relatively high-level phonological processing of lexical tones was mainly designed to test the effect of phonological/tone awareness on brain lateralization in tone processing.

The procedure of the discrimination task largely followed that of Jia et al. [1]. There were two dichotic pairs (the target-mask pair and the probe-mask pair) in one trial. The target and probe tones were presented sequentially in the same ear which was the testing ear. The two masking tones were presented in the other ear. Subjects were told to pay full attention to the tones in the testing ear and judge whether the target and probe tones were the same or different by pressing corresponding buttons on the keyboard. They were asked to ignore the distraction caused by masking tones in the other ear.

The three conditions were presented in different sessions. Two types of tones (contour tone and level tone) and two ears in one session were presented in separate blocks. There were 12 blocks in total. Take the low-variation condition as an example, there were four blocks: contour tone × left ear as the testing ear, contour tone × right ear as the testing ear, level tone × left ear as the testing ear, and level tone × right ear as the testing ear. Considering contour tones in the low-variation condition, there were six different target-probe tone pairs (T2-T4, T4-T2, T2-T5, T5-T2, T4-T5, and T5-T4) and three identical tone pairs (T2-T2, T4-T4, and T5-T5). All pairs were intermixed and presented randomly.

In the high-variation condition, three syllables (/fɐn/, /jɐu/, /wɐi/) with six different Cantonese tones were presented as target and probe items and the syllable /nga/ with six Cantonese tones was the mask. Each target-probe tone pair was always associated with different syllables. We used two sets of syllables in this condition to keep the duration of the experiment short. Set A consisted of three syllable pairs (/fɐn/-/jɐu/, /wɐi/-/fɐn/, /jɐu/-/wɐi/) and set B included the same syllable pairs in reversed order (/jɐu/-/fɐn/, /fɐn/-/wɐi/, /wɐi/-/jɐu/). Half of subjects in each group were randomly assigned to set A and the other half to set B. In the low-variation condition, six words based on the syllable /ji/ served as target-probe tone pairs and six words based on the syllable /nga/ were the masking tones. In the pure-tone condition, pure tone stimuli generated from the syllable /ji/ were target-probe items and pure tone stimuli generated from the syllable /nga/ were used as masking items.

The procedure of the identification task also largely followed that of Jia et al. [1]. In each trial, there was a dichotic pair presented to the two ears simultaneously. Subjects were asked to select the tone of the stimulus they heard most clearly by pressing buttons 1-6 on the keyboard. There were also three conditions, namely high-variation, low-variation and pure-tone condition, in the identification task. Level tones and contour tones were presented separately into two blocks as in the discrimination task. There were in total six blocks. In the high-variation condition, three syllables (/fɐn/, /jɐu/, /wɐi/) carrying six tones occurred in one block and each dichotic pair was carried by two different syllables (e.g. /fɐn55/-/wɐi22/). In the low-variation condition, the syllable /ji/ with six tones was presented in one block. In the pure-tone condition, pure tone stimuli mimicking six lexical tones carried by the syllable /ji/ were presented in one block.

Practice sessions were provided before both discrimination and identification tasks to familiarize the subjects with the procedure. All subjects did the identification task first and the presentation order of blocks in each task was counterbalanced across subjects as much as possible. Stimulus presentation and data recording were implemented by E-prime 1.0. Accuracy and reaction time (RT) in all tasks were collected.

2.4. Data analysis

For the discrimination task, the sensitivity index d' and RT (ms) were analyzed. The d' was computed as the z-score value of the hit rate (the proportion of "different" responses to different tone pairs) minus that of the false alarm rate (the proportion of "different" response to the same tone pairs) [29]. As for RT analysis, incorrect trials and trials with RT exceeding three standard deviations (0.3%) were discarded.

For the identification task, accuracy and RT were analyzed. Accuracy was the percentage of correct responses of each condition per participant. RT analysis was similar to that of the discrimination task. Four-way (*group* × *stimulus type* × *tone type* × *ear*) repeated measures ANOVAs were conducted on the sensitivity index d', discrimination RT, identification accuracy and identification RT, respectively.

3. Results

Figure 1 and 2 show the sensitivity index d' of the discrimination task and the accuracy of the identification task. The RT data were not displayed due to space limit. For the d' in the discrimination task, there was a significant main effect of *stimulus type* (F (1.670, 53.428) = 43.795, p < 0.001). Post hoc tests suggested that the d' score in the low-variation condition (M = 3.879, SD = 0.117) was significantly higher than that in the pure-tone condition (M = 3.354, SD = 0.106) and the high-variation condition (M =2.752, SD =0.12), and the d' score in the pure-tone condition was also significantly higher than that in the high-variation condition ($ps \leq 0.001$). The main effect of *tone type* (F (1, 32) = 32.070, p < 0.001) was also significant, suggesting a higher sensitivity for discriminating level tones (M = 3.509, SD = 0.095) than contour tones (M = 3.148, SD = 0.098). There was also a significant main effect of *group* (F (1, 32) = 6.561, p = 0.015), where the performance of the *Jyutping* group (M = 3.561, SD = 0.132) was significantly better than that of the control group (M = 3.095, SD = 0.125). There was a marginally significant main effect of *ear* (F (1, 32) = 3.789, p = 0.060), indicating left ear/RH advantage (M = 3.410, SD = 0.084 vs. M = 3.246, SD = 0.114). There was also a significant two-way interaction between *tone type* and *stimulus type* (F (1.744, 55.795) = 6.049, p = 0.006), which reflects that the difference in d' scores between level and contour tones was the largest in the pure-tone condition. No other effects were significant.

RT analysis in the discrimination task revealed a significant main effect of *stimulus type* (F (1.598, 51.125) = 63.537, p < 0.001). Post hoc tests indicated that the RT in the high-variation condition (M = 1378, SD = 39.269) was significantly longer than that in the pure-tone condition (M = 1154, SD = 35.245) and the low-variation condition (M = 1115, SD = 33.397, ps < 0.001). The main effect of *tone type* (F (1, 32) = 61.942, p < 0.001) was also significant, revealing that RT for discriminating level tones (M = 1144, SD = 34.961) was significantly shorter than that for contour tones (M = 1288, SD = 33.504,). There was also a significant main effect of *ear* (F (1, 32) = 8.110, p = 0.008), indicating a left ear/RH advantage (M = 1195, SD = 33.63 vs. M = 1237, SD = 34). There was a three-way interaction among *ear*, *tone type* and *group* (F (1, 32) = 4.675, p = 0.038). We conducted a two-way *ear* × *tone type* ANOVA for each *group*. In the *Jyutping* group, there was only a main effect of *tone type* (F (1, 47) = 93.28, p < 0.001), suggesting that they responded faster to level tones (M = 1156, SD = 37.273 vs. M = 1283, SD = 33.529). In the control group, there were significant main effects of *tone type* (F (1, 53) = 51.266, p < 0.001) and *ear* (F (1, 53) = 13.505, p = 0.001), as well as a two-way interaction between *tone type* and *ear* (F (1, 53) = 5,093, p = 0.028). Independent sample t-tests conducted to analyze the effect of *tone type* within each *ear*. We found significant *tone type* differences in the left ear (t (105.995) = 2.776, p = 0.007) and the right ear (t (105.913) = 3.597, p < 0.001). T-tests conducted to analyze the effect of *ear* within each *tone type* did not reveal any significant effects. The results suggested that contour tones generally elicited longer RT than level tones, but the difference between contour and level tones was smaller in the left ear for the control group.

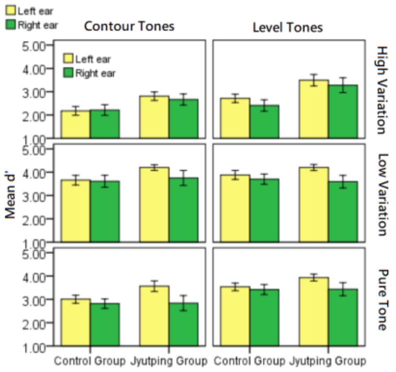

Figure 1: *Sensitivity index d' of discrimination task.*

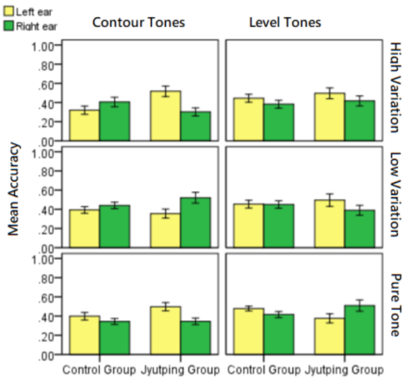

Figure 2: *Accuracy of identification task.*

For the identification accuracy, there was a significant main effect of *stimulus type* (F (1.883, 60.258) = 5.014, p = 0.011). Post hoc tests suggested that the accuracy in the low-variation condition (M = 0.435, SD = 0.007) was significantly higher than that in the high-variation condition (M = 0.409, SD = 0.008, p = 0.004). The main effect of *tone type* (F (1, 32) = 18.426, p < 0.001) was also significant, showing a higher accuracy for level tones than contour tones (M =0.441, SD = 0.008 vs. M = 0.401, SD = 0.009). There was also a significant three-way interaction among *ear*, *tone type* and *group* (F (1, 32) = 4.267, p = 0.047). We conducted a two-way ANOVA *ear* × *group* within each *tone type* to examine group differences. In contour tones, there was only a main effect of *group* (F (1, 103) = 8.526, p = 0.004), which showed that the performance of the *Jyutping* group was better than the control group. In level tones, there were no significant effects.

RT analysis for the identification task revealed a significant main effect of *stimulus type* (F (1.439, 46.036) = 93, p < 0.001). Post hoc tests indicated that the RT in the high-variation condition (M = 2352, SD = 86.636) was significantly longer than that in the pure-tone condition (M = 1768, SD = 77.34) and the low-variation condition (M = 1737, SD = 59.656, ps < 0.001). The main effect of *tone type* (F (1, 32) = 6.404, p = 0.016) was also significant, which could be attributed to faster responses for level tones than for contour tones (M = 2050, SD = 75.988 vs. M = 1854, SD = 65.027). The two-way interaction between *tone type* and *stimulus type* was significant (*F* (1.950, 62.391) = 4.749, *p* = 0.012), which reflected that the difference in RT between level tones and contour tones were largest in the low-variation condition. There was also a significant two-way interaction between *group* and *stimulus type* (*F* (1.439, 46.036) = 8.678, *p* = 0.002). Independent sample t-tests were conducted to analyze the effect of *group* within each *stimulus type*. There was a marginally significant effect of *group* (*t* (66.033) = 1.982, *p* = 0.052) in the high-variation condition, where the *Jyutping* group showed a trend of faster RT (*M* = 2053, *SD* = 87.29) than the control group (*M* = 2282, *SD* = 75.37), but no significant effects in the other stimulus types. Then one-way ANOVAs were conducted to examine the effect of *stimulus type* within each *group*. There was a significant effect of *stimulus type* in both *Jyutping* group (*F* (2, 99) = 4.749, *p* < 0.001)) and control group (*F* (2, 105) = 27.431, *p* < 0.001), where showed that the RT in the high-variation condition was the largest among three conditions in both groups (*p*s < 0.001).

4. Discussion

The present study investigated brain lateralization in Cantonese tone processing during dichotic listening for speakers with high or limited *Jyutping* proficiency. Overall, our results indicated a left-ear/RH advantage in the discrimination task, but no ear preference was obtained in the identification task, suggesting more bilateral processing. Although the *Jyutping* group outperformed the control group in overall tone discrimination sensitivity as well as in tone identification accuracy and RT in difficult conditions (i.e., contour tones and high-variation condition), there was no significant difference in hemispheric lateralization in dichotic tone processing between control and *Jyutping* groups.

In the discrimination task, an RH advantage was observed in both groups, regardless of the *stimulus type.* This finding is largely consistent with Jia et al.'s [1] finding, supporting the acoustic hypothesis of brain lateralization in lexical tone processing [1, 27, 28]. Compared with the Mandarin tonal system, the Cantonese one is more complex and exploits the pitch height dimension more intensely [29]. Another explanation is that, tone discrimination may rely more on auditory pitch processing. These factors might explain why the RH, which is responsible for spectral processing, according to the acoustic hypothesis, is found to have an advantage in the discrimination of Cantonese tones.

However, there was no obvious hemispheric advantage in the identification task for both groups, which differed from Jia et al.'s [11] finding, but was consistent with Baudoin-Chial [5]. In the latter study, Chinese speakers showed no obvious hemispheric advantage in processing Mandarin tones and hums [5]. This finding can be explained by different demands on phonological processing that tone identification and discrimination impose. To be specific, the discrimination task relies more on low-level auditory processing, whereas the identification task involves more higher-level phonological processing, which requires the mapping of auditory input to phonological representations of tones [1]. As a result, the identification task might induce more LH activities than the discrimination task, leading to more bilateral processing.

The results also showed that there were no differences in ear advantage between *Jyutping* group and control group. Jia et al. [1] speculated that the discrepancy between Cantonese and Mandarin dichotic listening results might be attributed to the lack of tonal awareness in Hong Kong Cantonese-speaking adults. However, the present study found no differences in ear advantage between the *Jyutping* group and control group. There was no evidence that tone awareness could increase LH lateralization for lexical tone and pitch processing in Cantonese speakers in the current study. One explanation might be that *Jyutping* subjects tested in the current study learned *Jyutping* late in adulthood and had limited exposure to *Jyutping*, whereas Mandarin participants learned *pinyin* in early childhood. The impact of acquiring *Jyutping* on shaping the brain lateralization for tone processing is probably limited for Cantonese speakers who learned *Jyutping* late in life.

Consistent with Jia et al. [1], we also found that level tones were discriminated and identified more accurately and faster than contour tones. Khouw and Ciocca [30] found that F0 height is the primary cue distinguishing Cantonese level tones and that the differences in F0 for level tones start from the beginning of the F0 curve. In contrast, both F0 height and F0 direction are involved in contour tone perception and F0 cues in the later portion of the F0 curve might be more critical for contour tone perception. Therefore, compared with level tones, subjects showed lower accuracy and longer RT when identifying and discriminating Cantonese contour tones.

It was also interesting to note that the high-variation condition was the hardest among the three conditions for both groups. That was because discrimination and identification in the high-variation condition required more higher-level phonological processing of Cantonese tones due to the increased acoustic variation in the tone stimuli. Furthermore, participants' performance in the low-variation condition was better than that in the pure tone condition. It might be related to their greater familiarity with the speech materials in the low variation condition when compared with non-linguistic tones. The meaning of the materials in the low-variation condition might also assist participants to perceive tones.

The *Jyutping* group seemed to show relatively better performance than controls in overall tone discrimination sensitivity as well as in tone identification accuracy and RT to some extent. The superior performance of *Jyutping* group in can be ascribed to their better phonological awareness, which presumably gives them an advantage in processing the tone dimension while ignoring variation in segmental information, especially in the high-variation condition and might facilitate discriminating tones irrespective of stimulus types.

5. Conclusions

To summarize, a RH advantage in the discrimination task and bilateral processing in the identification task were found in Cantonese tone processing using the dichotic listening paradigm. No differences was found in hemispheric lateralization between the *Jyuping* group and control group. These results supported the acoustic view of brain lateralization in tone discrimination and more involvement of LH activities in tone identification. It also suggests that late acquisition of *Jyutping* in adulthood may have limited effects on brain lateralization patterns in tone processing for native Cantonese speakers.

6. Acknowledgements

This work was supported by grants from the Research Grants Council of Hong Kong (ECS: 25603916), the National Natural Science Foundation of China (NSFC: 11504400), and the PolyU Start-up Fund for New Recruits (1-ZE4Y).

7. References

[1]. S. Jia, Y.-K. Tsang, J. Huang, and H.-C. Chen, "Right hemisphere advantage in processing Cantonese level and contour tones: evidence from dichotic listening," *Neuroscience letters,* vol. 556, pp. 135-139, 2013.

[2]. P. Broca, "Remarques sur le siège de la facultè du langage articulé, suivies d'une observation d'aphémie d'aphémie (perte de la parole)," *Bull. la Société Anat.*, vol. 6, pp. 330–357, 1961.

[3]. J. L. Bradshaw and N. C. Nettleton, "The nature of hemispheric specialization in man," *Behavioral and Brain Sciences,* vol. 4, no. 1, pp. 51-63, 1981.

[4]. M. Bryden, *Laterality functional asymmetry in the intact brain*. Elsevier, 2012.

[5]. S. Baudoin-Chial, "Hemispheric lateralization of modern standard Chinese tone processing," *Journal of Neurolinguistics,* vol. 2, no. 1-2, pp. 189-199, 1986.

[6]. R. J. Zatorre, A. C. Evans, E. Meyer, and A. Gjedde. "Lateralization of phonetic and pitch processing in speech perception." *Science,* vol. 256, pp. 846-849, 1992.

[7]. R. J. Zatorre, E. Meyer, A. Gjedde, and A. C. Evans, "PET studies of phonetic processing of speech: review, replication, and reanalysis," Cerebral cortex, vol. 6, no. 1, pp. 21-30, 1996.

[8]. D. Kimura, "Left-right differences in the perception of melodies," *Quarterly Journal of Experimental Psychology,* vol. 16, no. 4, pp. 355-358, 1964.

[9]. G. Geffen, J. Bradshaw, and G. Wallace, "Interhemispheric effects on reaction time to verbal and nonverbal visual stimuli," *Journal of experimental psychology,* vol. 87, no. 3, p. 415, 1971.

[10]. R. J. Zatorre and J. T. Gandour, "Neural specializations for speech and pitch: moving beyond the dichotomies," *Philos. Trans. R. Soc. B Biol. Sci.*, vol. 363, no. 1493, pp. 1087–1104, 2008.

[11]. A. M. Liberman and D. H. Whalen, "On the relation of speech to language," *Trends in cognitive sciences,* vol. 4, no. 5, pp. 187-196, 2000.

[12]. Y. Wang, A. Jongman, and J. A. Sereno, "Dichotic perception of Mandarin tones by Chinese and American listeners," *Brain and Language,* vol. 78, no. 3, pp. 332-348, 2001.

[13]. Y. Wang, D. M. Behne, A. Jongman, and J. A. Sereno, "The role of linguistic experience in the hemispheric processing of lexical tone," *Applied Psycholinguistics,* vol. 25, no. 3, pp. 449-466, 2004.

[14]. D. Van Lancker and V. A. Fromkin, "Hemispheric specialization for pitch and "tone": Evidence from Thai," *Journal of Phonetics,* vol. 1, no. 2, pp. 101-109, 1973.

[15]. D. Van Lancker, "Cerebral lateralization of pitch cues in the linguistic signal," *Research on Language & Social Interaction,* vol. 13, no. 2, pp. 201-277, 1980.

[16]. L. Hsieh, J. Gandour, D. Wong, and G. D. Hutchins, "Functional heterogeneity of inferior frontal gyrus is shaped by linguistic experience," *Brain and language,* vol. 76, no. 3, pp. 227-252, 2001.

[17]. F. Gu, C. Zhang, A. Hu, and G. Zhao, "Left hemisphere lateralization for lexical and acoustic pitch processing in Cantonese speakers as revealed by mismatch negativity," *Neuroimage,* vol. 83, pp. 637-645, 2013.

[18]. I. Y. Liberman, D. Shankweiler, F. W. Fischer, and B. Carter, "Explicit syllable and phoneme segmentation in the young child," *J. Exp. Child Psychol.*, vol. 18, no. 2, pp. 201–212, 1974.

[19]. H. Cheung, H. C. Chen, C. Y. Lai, O. C. Wong, and M. Hills, "The development of phonological awareness: Effects of spoken language experience and orthography," *Cognition*, vol. 81, no. 3, pp. 227–241, 2001.

[20]. J. Morais, L. Cary, J. Alegria, and P. Bertelson, "Does awareness of speech as a sequence of phones arise spontaneously?," *Cognition,* vol. 7, no. 4, pp. 323–331, 1979.

[21]. H. Shu, H. Peng, and C. McBride-Chang, "Phonological awareness in young Chinese children," *Dev. Sci.*, vol. 11, no. 1, pp. 171–181, 2008.

[22]. C. Brennan, F. Cao, N. Pedroarena-leal, C. Mcnorgan, and J. R. Booth, "Reading Acquisition Reorganized the Phonological Awareness Network Only in Alphabetic Whiting Systems," *Hum. Brain Mapp.*, vol. 34, no. 12, pp. 1–24, 2013.

[23]. S. Dehaene *et al.*, "How Learning to Read Changes the Cortical Networks for Vision and Language," *Science (80-.).*, vol. 330, no. 6009, pp. 1359–1364, 2010.

[24]. M. Carreiras *et al.*, "An anatomical signature for literacy," *Nature*, vol. 461, no. 7266, pp. 983–986, 2009.

[25]. M. Thiebaut De Schotten, L. Cohen, E. Amemiya, L. W. Braga, and S. Dehaene, "Learning to read improves the structure of the arcuate fasciculus," *Cereb. Cortex*, vol. 24, no. 4, pp. 989–995, 2014

[26]. R. C. Oldfield, "The assessment and analysis of handedness: the Edinburgh inventory," *Neuropsychologia,* vol. 9, no. 1, pp. 97-113, 1971.

[27]. H. Luo *et al.*, "Opposite patterns of hemisphere dominance for early auditory processing of lexical tones and consonants," *Proceedings of the National Academy of Sciences,* vol. 103, no. 51, pp. 19558-19563, 2006.

[28]. G.-Q. Ren, Y. Yang, and X. Li, "Early cortical processing of linguistic pitch patterns as revealed by the mismatch negativity," *Neuroscience,* vol. 162, no. 1, pp. 87-95, 2009.

[29]. N. A. Macmillan and C. D. Creelman, *Detection Theory: A User's Guide*. Mahwah: Lawrence Erlbaum Associates, 2005.

[30]. E. Khouw and V. Ciocca, "Perceptual correlates of Cantonese tones," *Journal of Phonetics,* vol. 35, no. 1, pp. 104-117, 2007.