Lexical Tone Perception in Mandarin Chinese Speakers With Aphasia

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Abstract

The brain localization debate of lexical tone processing concerns functional hypothesis that lexical tone, owing to its strong linguistic features, is dominant in the left hemisphere, and acoustic hypothesis that all pitch patterns, including lexical tone, are dominant in the right hemisphere due to their acoustic features. Lexical tone as a complex signal contains acoustic components that carry linguistic, paralinguistic, and nonlinguistic information. To examine these two hypotheses, the current study adopted triplet stimuli including Chinese characters, their corresponding *pinyin* with a diacritic, and the four diacritics representing Chinese lexical tones. The stimuli represent the variation of lexical tone for its linguistic and acoustic features. The results of a listening task by Mandarin Chinese speakers with and without aphasia support the functional hypothesis that pitch patterns are lateralized to different hemispheres of the brain depending on their functions, with lexical tone to the left hemisphere as a function of linguistic features.

Keywords: pitch, lexical tone, brain lateralization, Mandarin Chinese, **pinyin**

1. Introduction

Linguistic prosody utilizes physical features of frequency, intensity, and time, and their psychological counterparts of pitch, loudness, and duration (Cohen & Hart, 1968), to reveal linguistic and affective information during speech. These cues convey linguistic information at

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all levels in grammar, for example, word stress in the lexicon, tone in the phonology, and phrase marking in the syntax (Emmorey, 1987), and lexical tone is the contrastive function of fundamental frequency at word level (Lehiste, 1970).

Lexical tone processing in the brain is debatable on its hemispheric localization. It is believed that the left hemisphere (LH) of the brain is dominant in language processing, while the right hemisphere (RH) is dominant in emotion processing. The debate of brain localization for lexical tone processing concerns whether lexical tone, owing to its strong linguistic features, is dominant in the LH of the brain, or whether all pitch patterns, including lexical tone, are dominant in the RH. In other words, if the function served by a stimulus determines the laterality of processing, one would predict LH involvement for linguistic prosody and RH involvement for emotional prosody. An alternative is that the acoustic cue itself determines the lateralization of prosodic processing. That is, if the RH processes musical or nonlinguistic pitch, it may also be involved in the processing of linguistic information conveyed by pitch (Emmorey, 1987). The former view is also known as functional hypothesis, and the latter known as acoustic hypothesis.

The functional hypothesis posits that pitch patterns are lateralized to different hemispheres of the brain depending on their functions. Those pitch patterns that carry greater linguistic load (e. g., lexical tones) are lateralized to the LH, while those that carry less linguistic load (e.g., intonation patterns signaling affective moods) are lateralized to the RH (Wong, 2002). Van Lancker (1980) proposed a scale of hemispheric specialization associated with different domains (segment, syllable, word, phrase, sentence) of functional pitch contrasts. The most linguistically structured pitch contrasts, such as Chinese lexical tone, are associated with LH lateralization, while the least linguistically structured pitch contrasts, such as emotional tone, are associated with RH lateralization. She firstly adopted a dichotic listening technique and studied five lexical tones in Thai, and found a significant right ear advantage (REA). The conclusion was that "highly structured pitch contrasts are associated with left cerebral processing" (Van Lancker, 1980, p. 201). Gandour (2006) explained the REA in the way that the contralateral auditory pathways suppress the ipsilateral pathways at the level of brain stem, thus favoring the right ear input to the language-dominant LH. The REA, therefore, represents the LH dominance. Wang et al. (2001), using dichotic listening of monosyllabic Chinese words, studied 20 adult native Chinese speakers and 20 adult native American English speakers. They found that the Chinese listeners showed a significant REA while the American listeners did not. This implies that lexical tone perception is lateralized to the LH, as lexical tone possesses strong linguistic information to Chinese speakers but only acoustic signal to American listeners. Li and Peng (2004) recruited 32 college students, 12 males, and 20 females, who were required to finish a dichotic listening test with 48 monosyllabic Chinese words. Their results showed that the reaction time of the right ear is significantly faster than the left ear, implying the LH advantage.

Neuroimaging studies in recent decades have demonstrated that lexical tone perception may span a broad range in brain, involving a dynamic interplay among widely distributed brain regions within the two hemispheres. For example, Jia et al. (2015) used event-related potential experiments to investigate whether Cantonese lexical tones are processed with general auditory perception mechanisms and/or a special speech module. Their findings suggested that the processing of lexical tone relies on both acoustic and linguistic processes. When particular information in sound signal is decoded, those with linguistic information are processed majorly in LH, while those with nonlinguistic information are handled dominantly in RH. For instance, Wong and colleagues (Wong et al., 2004) used positron emission tomography (PET) to compare the neural correlates underlying lexical tone perception between Mandarin Chinese natives and native English speakers. Their task was a tone judgment on Chinese syllable pairs. Relative to passive listening of Chinese syllables, lexical tone judgment in native Mandarin speakers induced stronger activation in the left insular cortex, putamen, thalamus, fusiform gyrus, and medial frontal gyrus. Activation in the RH was also observed in the middle frontal gyrus, and the post-central gyrus. Gandour and his colleagues have conducted several functional imaging studies to elucidate the neural mechanisms dedicated to Mandarin lexical tone processing. In their experiments, participants were presented a list of three to five monosyllables consecutively (Gandour et al., 2003; Hsieh et al., 2000; Li & Peng, 2004; Li et al., 2010); they were asked to make tone judgments of the two syllables located first and last in the sequence on each trial; to match the last item in the sequence with the probe; or to match the probe with the target syllable within the sequence in random positions. Tonal processing yielded greater brain activations in bilateral frontal-parietal networks, including the inferior prefrontal cortex, posterior inferior frontal gyrus, middle frontal gyrus , and the inferior parietal lobule.

On the other hand, the acoustic hypothesis assumes that all pitch patterns, regardless of their functions, are lateralized to one hemisphere. This view regards lexical tone processing as being in the scope of general pitch processing, which is lateralized particularly to the RH. For instance, Snow (2000) argued that linguistic and emotional intonation have a common foundation in emotions, and studies of patients with brain damage suggest that linguistic and emotional intonation share a common neural basis in the RH. Bradvik et al. (1990) tested the ability to perceive and express prosodic qualities of speech in 21 patients with a single focal ischaemic disturbance of the RH, 14 patients having an infarct, and 7 transient ischaemic attacks, and in 21 age-matched controls. They did not discriminate between the patients and the controls, although some patients had large right-sided lesions. Bradvik et al. (1991) tested the ability to perceive and express emotional, as well as linguistic prosodic qualities of speech in 20 Swedish-speaking patients with right-sided cortical, as well as purely subcortical brain infarcts, and in 18 participants as the control group. The results demonstrated that prosodic impairment could be linguistic in nature, and not secondary to affective disorder. These findings indicate that the RH is dominant in both affective prosody and linguistic pitch contrasts.

Studies in neuropathology also provide evidence supporting either of the two views. Naeser and Chan (1980) studied a female Cantonese with nonfluent aphasia and found her tone perception was impaired, with only 55% correctness in a listening identification test compared with 100% correctness by a control participant without aphasia. A CT scan showed that she had suffered an intracerebral bleed resulting in extensive cortical and subcortical damage to the LH. They concluded that the LH damage caused her tone perception impairment. Gandour et al. (1998) used PET in a cross-linguistic study to compare pitch processing in native speakers of English with those of Thai. When discriminating pitch patterns in Thai words, only Thai subjects showed activation in the left frontal operculum. Activation of this region near the classically defined Broca's area suggests that the brain recognizes functional properties, rather than simply acoustic properties, of complex auditory cues in accessing language-specific mechanisms in pitch perception. Hsieh et al. (2001) studied adult native Chinese speakers and adult native American English speakers but using PET. The results implied that when pitch patterns are phonologically significant to the listeners, the pitch processing is lateralized to the LH. Gandour et al. (2002) used fMRI to examine how the brain processes linguistically relevant pitch patterns (spectral vs. temporal cues) in tonal language speakers. Participants were required to make same-different judgments on the syllable pairs they heard. Same stimuli were used for the spectral (i.e., lexical tone) and temporal (i. e., vowel length) conditions, and the syllable pairs were monosyllabic Thai pseudowords. They found that native Thai speakers showed greater activation in the left inferior prefrontal gyrus in discriminating Thai tone relative to non-speech pitch.

On the contrary, Zatorre et al. (1992) measured cerebral activation in ten adult volunteers by PET with the paired-image subtraction paradigm. Stimuli were paired noise bursts and paired consonant-vowel-consonant real speech syllables. The vowels in any given syllable pair were always different, but the final consonant differed in half of the pairs; also, the second syllable had a higher fundamental frequency in half of the pairs and a lower frequency in the other half. The results showed that processing changes in pitch produced activation of the right prefrontal cortex, consistent with the importance of right-hemisphere mechanisms in pitch perception. Li et al. (2010) used fMRI to identify neuroanatomical substrates underlying phonological processing of segmental (consonant, rhyme) and suprasegmental (tone) units. Native speakers of Mandarin Chinese were required to match a phonological unit that occurs in a list of three syllables to the corresponding unit of a following probe. The results showed that hemispheric asymmetries arose depending on the type of phonological unit. In direct contrasts between phonological units, tones yield increased activation in frontoparietal areas of the RH.

2. Lexical Tones and *Pinyin* in Mandarin Chinese

Chinese is a tonal language, in which lexical tone can change the core meaning of the word (Yip, 2002). The spoken forms of the Chinese language exhibit a high degree of diversity in its geographical variants, while the written form is shared by all the geographical variants, and the standardized form of modern spoken Chinese in China is *putonghua*, or Mandarin, of which the phonology is based mainly on Beijing Mandarin, and the grammar loosely on the subdialects of Northern China (Fung, 2009).

Mandarin Chinese has four lexical tones, which are language signals with linguistic features, possessing characteristics of melodic acoustics as well. Based on tone value from 1 to 5 proposed by Chao (1934), Mandarin Chinese tones are divided into high level tone (e.g., 妈 ma^{55}, "mother or mom"), high rise tone (e.g., 麻 ma^{35}, "fiber"), low tone (e.g., 马 ma^{214}, "horse"), and high fall tone (e.g., 骂 ma^{51}, "blame or curse"). These tones are also named tone 1, tone 2, tone 3, and tone 4 respectively for convenience. When listening to each of the above examples, one perceives the linguistic information combining a consonant /m/ and a vowel /a/, as well as the acoustic information of the pitch variation. Lexical tones are always attached to lexicon, as defined by Lehiste (1970) that suprasegmentals are secondary to, and overlaid function of segmental features.

Chinese *pinyin* is an alphabetic system for the phonological representation of Chinese characters. For example, the aforementioned Chinese characters 妈 (mom), 麻 (fiber), 马 (horse), and 骂 (blame or curse) have their *pinyin* with diacritics as "mā," "má," "mǎ," and "mà" respectively. The diacritics on top of the vowel /a/ represent the four lexical tones. Without ideographical cues, one may expect that *pinyin* with a diacritic possesses fewer linguistic features than its corresponding Chinese character, yet more linguistic features than the pure diacritic, which is a more acoustic representation.

3. Disorders of Lexical Tone in Mandarin Chinese Speakers With Aphasia

Aphasia refers to a family of clinically diverse disorders that affect the ability to communicate by oral or written language, or both, following brain damage (Goodglass, 1993). Kemmerer (2015) further explained that aphasia is an impairment in the ability of language production, comprehension, and repetition, which results from an acquired brain injury such as a stroke, head injury, or progressive degenerative disease. For language production, some people with aphasia have difficulty retrieving words for objects or actions and may struggle with phonological production. Others have trouble dealing with grammatical structures of words, phrases, and sentences. For language comprehension, the impairments could be in phoneme perception, word recognition, and syntactic parsing. As for language repetition, many people with aphasia have difficulty reproducing sentences that are said to them; others cannot even repeat single words accurately.

Chinese speakers with aphasia are found with lexical tone perception deficits. Yiu and Fok (1995) studied the nature of tonal disruption in brain-damaged subjects who speak Cantonese, a Chinese dialect spoken in southern China with six lexical tones, and found that lexical tone disruption is a generalized sign in aphasia, with the perceptual ability more severe. Wang (2004) studied one case of a Chinese male with aphasia and found that his lexical tone disorders were independent of phonemes perception. In a listening task, he made 8 mistakes out of 28 for disyllabic words tone recognition, and 8 mistakes out of 28 for tri-syllabic words tone recognition. Liang (2009) investigated 14 Chinese with aphasia and compared with 30 controls without aphasia, and found Chinese with aphasia took almost twice as long as the controls to identify lexical tones. In addition, time pressure had little effect on accuracy for controls, yet reduced accuracy for those with aphasia. Their conclusion was that lexical tone impairment involves both structural deficits and processing limitations. Packard (1986) suggested that in tone languages, lexical specification of tone contour information results in

LH lateralization of that information, thus making the tonal phonemes vulnerable to LH damage.

In the current study, we proposed the triplet stimuli of Chinese characters, their *pinyin* with a diacritic, and pure diacritics, such as 妈, “mā,” and “ˉ,” to compare lexical tone perception between Mandarin Chinese speakers with and without aphasia, as well as examining functional hypothesis versus acoustic hypothesis. Compared with Chinese characters, *pinyin* with a diacritic and a pure diacritic have less linguistic information. Based on the functional hypothesis that those pitch patterns carrying greater linguistic load are lateralized to the LH, when the language dominant LH is damaged as in aphasia, it is not expected to see an advantage of processing lexical tone in Chinese characters over that in *pinyin* with a diacritic, nor over that in the pure diacritics. That is, LH lesion leads to a reduced lexical tone processing in Chinese characters. Therefore, it is reasonable to assume that Mandarin Chinese speakers with aphasia cannot show more accurate and faster processing of lexical tones in Chinese characters than the other two stimuli as those without aphasia can.

On the contrary, if the acoustic hypothesis holds the position, we shall observe a non-influenced perception pattern of the lexical tone no matter whether in the Chinese character, *pinyin* with a diacritic, or a pure diacritic, because RH is dominantly responsible for all pitch patterns process including the lexical tone. Therefore, the pattern of the lexical tone perception among Mandarin Chinese speakers with aphasia shall not be different from Mandarin Chinese speakers without aphasia.

4. Experiment Design

4.1 Participants

Fifteen Mandarin Chinese native speakers with aphasia volunteered in the experiment, eight females and seven males, with the average age of 46.7. As shown in Table 1, 9 of them were diagnosed with the nonfluent type of aphasia and 6 with the fluent type of aphasia, according to China Rehabilitation Research Center Aphasia Examination (CRRCAE). Their aphasic severity varied from mild to moderate. CT brain images demonstrated that all participants had their lesions in the LH. None of them had any hearing and visual problems, nor other neurological conditions. They all possessed the fundamental knowledge of *pinyin*.

The control group consisted of 31 Mandarin Chinese native speakers who were randomly selected as volunteers in the experiment. They possessed normal hearing and vision, as well as normal neurological conditions. Mandarin Chinese was their native language, and their dialects were controlled such that participants speaking Cantonese with six tones were excluded.

4.2 Materials

Three types of tone representations were used. Chinese characters, *pinyin* with a diacritic

Table 1. *Demographic Information of Participants With Aphasia*

Participant	Gender	Age	Type of aphasia
1	F	56	Nonfluent
2	M	43	Nonfluent
3	M	45	Nonfluent
4	F	62	Nonfluent
5	F	51	Nonfluent
6	F	54	Nonfluent
7	F	34	Nonfluent
8	M	53	Nonfluent
9	F	47	Nonfluent
10	M	55	Fluent
11	F	36	Fluent
12	M	42	Fluent
13	M	19	Fluent
14	M	46	Fluent
15	F	58	Fluent

and pure diacritics. Based on the Character Frequency List of Modern Chinese (Da, 2004), 40 high frequency single noun characters were selected, 10 for each tone. The sound stimuli were produced and standardized by Goldwave (v6.21), a free software program, within the range of the average female fundamental frequency (Moore & Jongman, 1997; Wu, 1986). Altogether there were 40 sound stimuli, 40 target Chinese characters, 40 target *pinyin* with a diacritic, and 4 pure diacritics from tone 1 to tone 4. Besides, there were 103 Chinese character fillers and 103 *pinyin* with diacritics fillers correspondingly. The following are examples of the Chinese characters and their corresponding *pinyin* stimuli (target stimulus: fillers):

Tone 1 包: 雹宝报; bāo: báo, bǎo, bào
Tone 2 牛: 妞扭拗; niú: niū, niǔ, niù
Tone 3 尺: 吃迟翅; chǐ: chī, chí, chì
Tone 4 树: 舒塾薯; shù: shū, shú, shǔ

4.3 Procedure

A self-paced listening task was run through the E-prime program (version 2.0). Participants listened to a sound stimulus; at the same time on a monitor appeared a Chinese character, a *pinyin* with a diacritic, or a pure diacritic. If the lexical tone that the participants heard matched the representation that they saw on the screen, "F" was pressed for "yes," otherwise "J" for "no." Participants could have a rest in the middle of the process. Accuracy and reaction time were recorded. The reaction time measured in millisecond (ms) began at the onset of the sound stimulus and the representation on the monitor and ended at the moment when the participant pressed the key.

4.4 Statistical Analysis

Summary statistics were computed and the data displayed to identify outliers and/or impossible or implausible values, to summarize the data and check for distributional forms. Groups with and without aphasia were compared on numerical data using independent samples *t*-test. Within each group, comparisons were made using one-way ANOVA analysis. For each statistically significant main or interaction effect having more than two levels, Tukey post hoc pairwise comparisons were performed to examine which levels of that factor were significantly different from each other. All assumptions were examined for the validity of the test. A two-tailed alpha of .05 was set as the level of significance for all tests. IBM SPSS Statistics 22 was utilized for all data management and statistical analyses. Abnormal data were transformed when necessary to stabilize variances and normalize distributional forms.

5. Results

Table 2 shows the statistics for both participant groups with and without aphasia. When comparing the accuracy and reaction time between the two groups, Mandarin Chinese speakers with aphasia were significantly less accurate and slower. The results of independent samples *t*-test showed that there was a statistically significant difference between those with and without aphasia on accuracy for characters, $t(370.50) = 4.41$, $p < .01$, for *pinyin*, $t(397.62) = 4.48$, $p < .01$, and for diacritics, $t(438.87) = 3.11$, $p < .01$; and on reaction time, for characters, $t(379.27) = -7.90$, $p < .01$, for *pinyin*, $t(391.21) = -8.68$, $p < .01$, and for diacritics, $t(402.05) = -8.35$, $p < .01$.

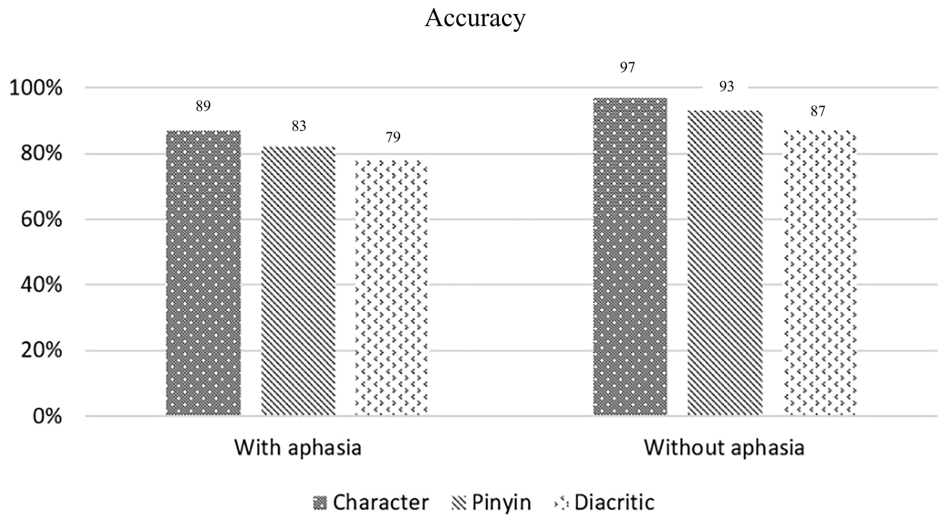
Table 2. *Statistics for Accuracy and Reaction Time: Mean (Standard Deviation)*

	Accuracy (%)		Reaction time (ms)	
	With aphasia	Without aphasia	With aphasia	Without aphasia
Character	89 (32)	97 (18)	1397 (981)	944 (585)
	$t(370.50) = 4.41$, $p < .01$		$t(379.27) = -7.90$, $p < .01$	
Pinyin	83 (38)	93 (25)	1450 (944)	968 (614)
	$t(397.62) = 4.48$, $p < .01$		$t(391.21) = -8.68$, $p < .01$	
Diacritic	79 (41)	87 (34)	1461 (842)	1045 (586)
	$t(438.87) = 3.11$, $p < .01$		$t(402.05) = -8.35$, $p < .01$	

5.1 Accuracy

The mean accuracy percentage in both groups decreased from character, to *pinyin* and to diacritic as illustrated in Figure 1. One-way ANOVA test results demonstrated that there was a significant difference between the three types of stimuli on accuracy among Mandarin Chinese speakers with aphasia, $F(2, 957) = 5.28$, $p < .01$. Post hoc testing showed that there was a significant difference between character and diacritic, $MD = .09$, 95% CI [.03 to .16], $p < .01$; but not between character and *pinyin*, $MD = .06$, 95% CI [-.01 to .12], $p = .10$, nor between *pinyin* and diacritic, $MD = .04$, 95% CI [-.03 to .11], $p = .40$. Among Mandarin Chinese speakers without aphasia, one-way ANOVA test results showed that there was a statistically significant difference between the three types of stimuli on accuracy, $F(2, 3717) = 44.01$, $p < .01$. Post hoc testing showed that there was a significant difference between character and *pinyin*, $MD = .04$, 95% CI [.01 to .06], $p < .01$, between character and diacritic, $MD = .10$, 95% CI [.07 to .12], $p < .01$, and between *pinyin* and diacritic, $MD = .06$, 95% CI [.04 to .09], $p < .01$.

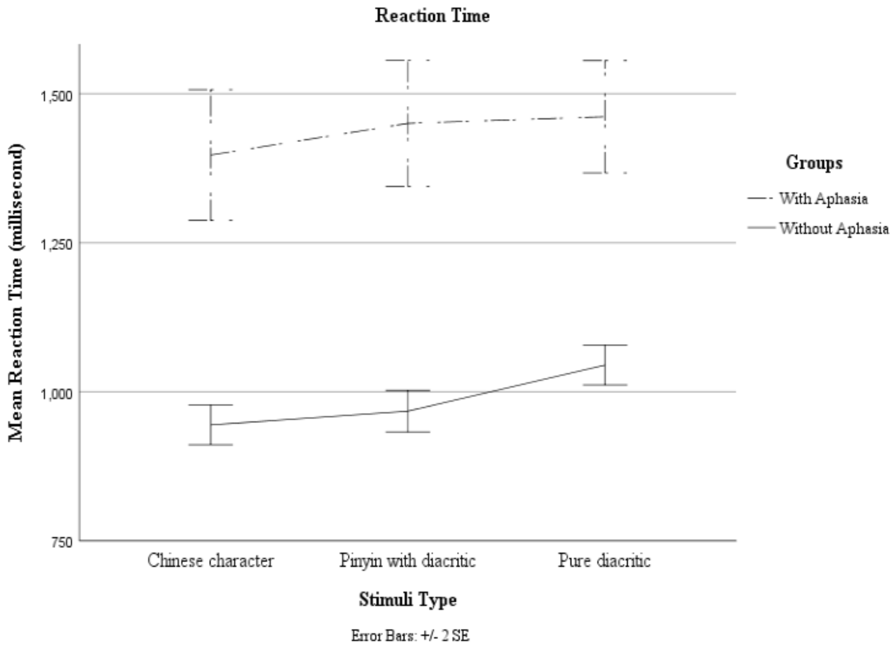
Figure 1. *Mean Accuracy of Lexical Tone in Listening Judgment*



5.2. Reaction Time

Figure 2. illustrated the mean reaction time (in milliseconds) of three stimuli among Mandarin Chinese speakers with and without aphasia. There was a statistically significant difference between those with and without aphasia on reaction time, for characters, $t(379.27) = -7.90$, $p < .01$, for *pinyin*, $t(391.21) = -8.68$, $p < .01$, and for diacritics, $t(402.05) = -8.35$, $p < .01$. In addition, one-way ANOVA test results demonstrated that, among those without aphasia, there was a statistically significant difference, $F(2, 3717) = 11.11$, $p < .01$. Post hoc testing showed that there was a significant difference between character and diacritic, $MD = 103.44$, 95% CI [49.68 to 157.19], $p < .01$; between *pinyin* and diacritic, $MD = 78.91$, 95% CI [25.15 to 132.66], $p < .01$; but not between character and *pinyin*, $MD = 24.53$, 95% CI [-29.23 to 78.28], $p = .53$. There was no statistically significant difference between the three types of stimuli on reaction time among Mandarin Chinese speakers with aphasia, $F(2, 1017) = .013$, $p = .99$.

Figure 2. *Mean Reaction Time of Lexical Tone in Listening Judgment*



6. Discussion

The current study was conducted to examine the two hypotheses in the brain lateralization debate of processing lexical tone. Three types of stimuli were proposed to represent a continuum of variation of the linguistic and acoustic information in the lexical tone, with Chinese characters representing the lexical tone with strong linguistic features on the one side, and the pure diacritics representing the lexical tone with strong acoustic features on the other side. The current experiment results demonstrated that participants with aphasia had a significantly reduced ability in processing lexical tones, comparing with those without aphasia. In addition, although participants with aphasia processed Chinese characters more accurately than the pure diacritic, they did not show an advantage of processing the lexical tone in Chinese characters over *pinyin* with a diacritic or the pure diacritic as those without aphasia did in term of reaction time.

The functional hypothesis of lexical tone lateralization in brain was supported by the results in the current study. According to the functional hypothesis, when the lexical tone possesses the strong linguistic features, its processing is in LH, the language dominant hemisphere. This was demonstrated in both groups with and without aphasia. The participants without aphasia showed more accurate and faster processing of the Chinese character than *pinyin* with a diacritic and the pure diacritic. When LH was compromised, the participants with aphasia demonstrated less accuracy and slower processing than those without aphasia.

Although the participants with aphasia did not show more accurate and faster processing of the pure diacritic as assumed due to the intact RH, it was probably because the participants with aphasia still tried to match the pure diacritic with the heard stimuli by applying their linguistic knowledge. The listening judgment task in the current experiment was highly demanding for linguistic competence of the lexical tone. Stimuli such as Chinese characters possessed the most linguistic information related to the lexical tone. *Pinyin* with a diacritic, although with less linguistic information, was still competitive because of the phonological cues of alphabetic letters and diacritics indicating the lexical tones. The pure diacritics possessed the least linguistic information, yet their indication of the pitch patterns could possibly be related to the heard stimuli. For the participants with LH lesions who had a reduced ability in linguistic information processing, none of the three stimuli could stand out in regard to reaction time.

The results in the current study were against the acoustic hypothesis. According to the acoustic hypothesis, all the pitch patterns, including the lexical tone, are dominant in RH. Therefore, two assumptions could be made based on the acoustic hypothesis in the current study: 1) there was no significant difference between the two groups of participants with and without aphasia, as all of the participants had intact RH that was responsible for the processing of the lexical tone; 2) the processing of the lexical tone in the Chinese character by the participants with aphasia was significantly more accurate and faster than the other two stimuli. However, neither of the two assumptions could find supportive evidence in the results of this study.

The lexical tone is a complex signal, containing acoustic components that carry linguistic, paralinguistic, and nonlinguistic information (Braun & Johnson, 2011). The major function of the lexical tone is to deliver linguistic information such as linguistically meaningful contrasts (e.g. Cutler & Chen, 1997), syntactic constituency (e.g., Price et al., 1991). In addition, the lexical tone also delivers paralinguistic information, such as attitudes and emotions (e.g., Scherer et al., 1984), and nonlinguistic information, such as age and gender (Fujisaki, 2004). During the processing of the lexical tone, the linguistic features are dominant in LH, while the paralinguistic and nonlinguistic features are dominant in RH. The function of the lexical tone determines its dominant hemisphere. There have already been studies demonstrating the activation of both hemispheres in processing the lexical tone, but in different temporal and spatial sequence (e.g., Krishnan et al., 2016; Krishnan et al., 2017; Kwok et al., 2016; Kwok et al., 2019). In the future, more and more evidence may appear with the advancement in brain and neurosciences.

7. Conclusion

By comparing perception of lexical tone in Chinese character, *pinyin* with diacritics and pure diacritics in Mandarin Chinese speakers with and without aphasia, the current study demonstrated the functional features of the lexical tone, supporting the functional hypothesis in the debate of brain lateralization during the lexical tone processing. Yet more evidence is needed to explore the functions of the lexical tone and its perception in the brain.

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