Tone Lateralization under Noisy Conditions

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Abstract

This paper presents a dichotic listening experiment on the perception of Mandarin tones under clean and noisy conditions. We examine the enhancing role of noise on the lateralization patterns of tones. We discover that the lateralization patterns of different tones are inconsistent: the perception of tone 1 exhibits a left ear advantage, while that of tone 2 or tone 4 has a right ear advantage. These different lateralization patterns may result from different tone features and the fast or slow change of the tone pitch. Moreover, a gender difference in tone perception is detected in our experimental results.

1. Introduction

Tone lateralization has been of great interest for many decades ever since Van Lancker and Fromkin did a dichotic listening experiment on Thai tones [11]. In their experiment, the ear advantages of Thai tones in both Thai and English speakers were compared and a right ear advantage (left hemisphere advantage, according to [6]) for Thai tones in Thai speakers was discovered. This is supportive evidence for the “function” view of human brains [12] which states that human brains are organized according to various functions. Tone is lateralized to the left hemisphere because it is a part of the language system for providing meaning contrasts in words.

However the physical property of tone, such as the pitch variation within several hundreds of milliseconds, suggests that it should be right hemisphere lateralized [16]. The hypothesis of the right hemisphere lateralization of pitch has been supported by both behavioral and brain imaging studies (e.g., [5], [10]).

Besides these various viewpoints on tone lateralization, the empirical results of tone dichotic listening experiment did not show a consistent right ear advantage for tones. For example, Baudoin-Chial failed to find any ear advantage on Mandarin tones [1]. However, Wang et al. [14], based on a dichotic listening experiment on Mandarin tones, found a right ear advantage in Mandarin speakers. They also discovered that the English speakers had no right ear advantage for Mandarin tones.

Although both in [11] and [14], a right ear advantage in tonal language native speakers was found and compared with non-tonal language speakers who did not show tone lateralization, the experimental conditions are different for native and non-native speakers in their tone dichotic listening experiments. In [11], two consecutive dichotic trials were used for native Thai speakers in half of their trials; while for non-native speakers, only isolated dichotic trials were used. In [14], the white noise with -10dB S/N ratio was introduced for native Mandarin speakers, but non-native speakers only heard clean speech. Without a systematic study of the tone lateralization patterns under noisy conditions, directly introducing noise may affect the lateralization results since the noise may act as a confounding variable. In addition, both experiments did not report the hearing ability differences in left and right ears of subjects.

In this paper, we propose a dichotic listening experiment on tone lateralization under clean and noisy conditions. First, this experiment began with testing of the hearing ability of subjects in left and right ears. Whereas the authors of [14] intended the noise to induce errors, we find that this condition actually enhanced hemispheric lateralization, though differently for different tones. Moreover, our experimental results show that subjects exhibit different lateralization patterns toward different tones, and we propose two factors to explain these various lateralization patterns. Finally, the individual and gender differences among subjects are discussed, which is one of the significant factors to study the variety in human behaviors (e.g., [3]) and is usually neglected in some previous studies.

The rest of the paper is organized as follows: Section 2 introduces our dichotic listening experiment; Section 3 illustrates and discusses the experiment results; and finally, Section 4 gives conclusions and future directions.

2. Tone lateralization under noisy conditions

2.1. Method

To find out the effect of noise on tone lateralization, we imbedded the tone dichotic trials in white noise under three different S/N ratios. We also compared the lateralization patterns in noisy dichotic trials with those in clean dichotic trials.

2.1.1. Participants

Twenty-four native Mandarin speakers were enrolled in this experiment. Ten of them are qualified to take the experiment based on the Edinburgh Handedness Test [7], the Hearing Threshold Level (HTL) test and the pretest. These 10 subjects include 5 males and 5 females, whose average age is 25.5 (±2.32). And all of them are strongly right-handed.

2.1.2. Stimuli

In this experiment, the testing materials consist of 16 monosyllabic Mandarin words, which are formed by four syllables (*fan*), (*guo*), (*hui*) and (*shi*) combined with 4 tones (adopted from [14]). Table 1 lists these 16 words, their Pinyin spellings, tones and English glosses. And the F0 contours of the four Mandarin tones are shown in Figure 1, as spoken by author LS and analyzed by PRAAT software.

Table 1: *The 16 monosyllabic words used in this experiment (adopted from [14]).*

Character	Pinyin	Tone	English gloss
帆	fān	1	sail
烦	fán	2	annoy
反	fǎn	3	reverse
饭	fàn	4	meal
锅	guō	1	pan
国	guó	2	country
果	guǒ	3	fruit
过	guò	4	pass
灰	huī	1	gray
回	huí	2	return
毁	huǐ	3	destroy
会	huì	4	meeting
师	shī	1	teacher
十	shí	2	ten
史	shǐ	3	history
是	shì	4	right

The recording was done in a sound-proof room in a digital speech processing lab using a SHURE microphone and digitized with a MACKIE 12-channel mixer at 44.1 kHz. Each word was produced separately. The lengths of the four tones of the same syllable were roughly the same, which were chosen from the three repeated recordings of each tone of this syllable.

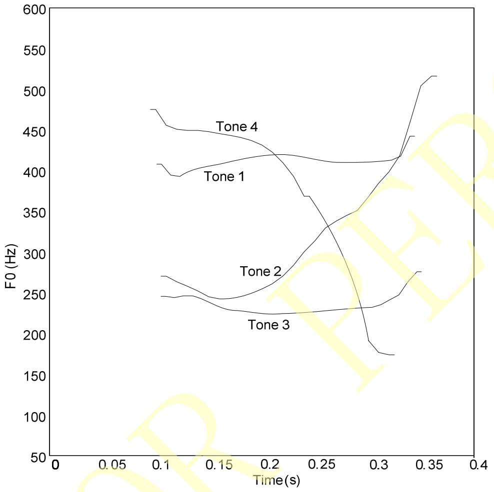

Figure 1: *The F0 contours of the four Mandarin tones, each combined with the syllable /fan/.*

Each target word lasted about 400ms. The target stimuli in each dichotic trial were either clean or embedded in white noise. The length of the noise was 1000ms. The three noisy conditions included 0dB, -10dB and -20dB S/N ratios. And the S/N ratio was measured during the 400ms in which the target word was presented (0.3ms~0.7ms in the noise sound file). The intensity profile of the noise is shown in Figure 2. After the target word has been imbedded in the white noise with the three noisy conditions, the intensity of the whole sound file was adjusted at 75dB using PRAAT software.

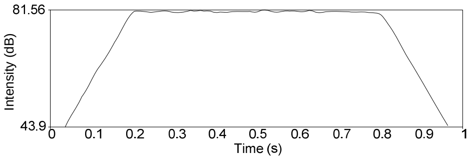

Figure 2: *The intensity profile of the noise.*

The ISI was set to 2 seconds. And a total of 192 dichotic pairs (12 pairs × 4 syllables × 4 conditions) were generated using MATLAB. Each pair contained two words with the same syllable but different tones. There were 4 blocks in the experiment, each consisting of a randomization of these 192 pairs of stimuli.

2.1.3. *Procedure*

The experiment was conducted in a sound-proof booth. All participants were tested individually with a headphone (SENNHEISER HD 280 Pro).

Before the experiment, participants were given the handedness test [7]. Those strongly right-handed participants were allowed to take the HTL test (1 of the 24 participants was not strongly right-handed). They were tested of their hearing ability under 125, 250, 500, 1000, 2000, 4000 and 8000 Hz. Participants whose left and right ears' HTLs differ more than 10dB or either of them exceeds 25dB at any frequency were excluded (6 of the 23 participants failed to meet this criterion).

Participants who passed the HTL test were given the pretest. During the pretest, participants were tested using 48 trials randomly chosen from the 192 dichotic trials in the real test. Participants who reached more than 50% correctness in both left and right ears were allowed to take the real test (7 of 17 participants didn't pass the pretest).

In the real dichotic test, four blocks were presented, each containing 192 randomized trials. The output volume of the two channels of the headphones was calibrated at 75dB using a sound level meter. Subjects were instructed that they would hear two different words (only differ in tones) simultaneously in their two ears. They were to identify the tones of both stimuli and write them down on an answer sheet using the four tone marks. Left ear and right ear response rows were counterbalanced across blocks to avoid order bias. Each block lasted around 8 minutes. Between the first two and the last two blocks, there was a 30-second rest. The two channels between these blocks were counterbalanced. Between the second and third blocks, there was a 2-minute break for the subject to take a rest and prepare for the reversed order of ear response rows in the answer sheet. The whole experiment lasted approximately 35 minutes.

2.1.4. *Data analysis*

We measure the Percentage of Errors (POE) to indicate the lateralization. POE is defined as $(P_L/(P_R + P_L)) \times 100$, where P_L is percentage errors in the left ear and P_R is percentage errors in the right ear. POE greater than 50% indicates a right ear advantage or left hemisphere advantage, and POE smaller than 50% a left ear advantage or right hemisphere advantage. In our experiment, the POE of all stimuli and POE of each of the four Mandarin tones were calculated.

3. Results and Discussion

3.1. Overall correctness and POE

The overall correctness of the 384 stimuli (192 pairs) is 72.5%. The average POE of the 10 subjects is 52.4%, which is lower than the POE (57%) reported in [14]. However, they did not report the hearing ability differences in left and right ears as in this experiment. And there is a possibility that the unbalanced hearing ability may affect the ear advantages. Besides the overall correctness and POE, the correctness and POE under the clean and three noisy conditions are listed in Table 2.

Table 2: *The Correctness and POE under the clean and noisy conditions.*

Condition	Correctness (%)	POE (%)
Clean	81.8	51.2
0dB	79.6	53.6
-10dB	73.5	53.4
-20dB	55	51.7

As shown in Table 2, POE increases under the noisy conditions compared with the clean condition, though under the -20dB S/N ratio noisy condition, the increase of POE was not as significant as those under 0dB and -10dB S/N ratio conditions. This is because that under the -20dB condition subjects may not clearly identify the tones in both ears, which is indicated by the abrupt drop of correctness compared with the other three conditions.

In [14], the authors introduced white noise at -10dB S/N ratio to increase errors and avoid ceiling effect to find the lateralization. However, they did not consider that the noisy condition may affect the result of lateralization. Our experimental results suggest that a certain degree of white noise can increase the right ear advantage in a certain degree in the tone dichotic listening experiment. And the white noise may act as a confounding in comparing ear advantages of tonal and non-tonal speakers in [14].

There is functional neuroimaging evidence to support that the low S/N ratio increases the left hemisphere activation in speech processing (e.g., [2], [17]). These fMRI results show that Broca's area has an enhanced activation when the S/N ratio decreases [2], and under a very low S/N ratio, only the left BA44 area activates significantly compared with other regions that correlate with speech processing [17]. The possible explanation of this phenomenon is that the Broca's area may compensate for the loss of the sensory information by enhancing the internal speech sound presentations and serve to improve performance under low S/N ratio. The above evidence that the left hemisphere activates more under low S/N ratio is consistent with our finding that the left lateralization increases when the S/N ratio decreases.

3.2. POE of the four tones

Subjects show different lateralization patterns with respect to the four tones. The one-way ANOVA shows the main effect of tone ($F(3,12) = 11.893$, $p < .001$). Table 3 lists the POEs of the four tones, in which tone 1 exhibits a left ear advantage; tone 2 and tone 4 have a strong right ear advantage. Tone 3 has a right ear advantage under 0dB and -10dB S/N ratios, a left ear advantage under the clean condition, but under the -20dB S/N ratio noisy conditions, the ear advantage is inexplicit.

Table 3: *The POE of four tones under different conditions.*

	Tone 1	Tone 2	Tone 3	Tone 4
Clean	44.8%	55.3%	47.3%	60.3%
0dB	44.9%	53.4%	56.6%	58.8%
-10dB	46.5%	57.3%	53.7%	55.0%
-20dB	48.3%	54.0%	49.9%	54.4%

We propose two explanations for the different tone lateralization patterns.

The first explanation deals with the feature differences of these 4 tones. Wang [13] assigned 7 features for different tones, and these features include CONTOUR, HIGH, CENTRAL, MID, RISING, FALLING and CONVEX. According to these features, tone 1 differs from the other 3 tones in CONTOUR. In addition, tone 2 and tone 4 differ from tone 3 in HIGH. And the different tone features may cause different lateralization patterns of the four tones. This explanation and our experimental results may further reveal a neural mechanism in the auditory system that works similarly as that in the visual system. For instance, in the primary visual cortex of cat, there are "complex" cells that only respond to specific orientation of light bars [4], indicating that certain neurons in the visual cortex can extract different orientation features from the visual stimuli. Similarly, our experiment shows that different pitch contours in tones may correspond to different brain mechanisms. However, whether there are such pitch contour feature extraction neurons in the auditory cortex of humans or other animals still needs to be discovered.

Besides the explanation concerning the pitch contours of tones as clarified by different tone features, our second explanation concerns the fast or slow changes of the pitches of tones. As shown in Figure 1, the pitch contour of tone 1 is flat and its frequency throughout the whole word changes slowly, however tone 2 and tone 4 have fast frequency changes throughout the pitch contours. Our results indicate that the fast or slow changes of the fundamental frequencies of different tones may cause different lateralization patterns, such that tone 1 has a left ear (right hemisphere) advantage while tone 2 or tone 4 have right ear (left hemisphere) advantage during the perception of tone 2 or tone 4. This finding partially matches Poeppel's hypothesis on the lateralization [8], which states that the left hemisphere is more sensitive to the fast physical property changes and the right hemisphere is more sensitive to the slow physical property changes, though the time window in [8] does not exactly matches that of ours.

Finally, as for tone 3, its pitch contour undergoes a falling rising change, but this change is not fast enough compared with that of tone 2 or tone 4. Therefore, the lateralization pattern of tone 3 in the clean condition is similar to that of tone 1 (left ear advantage). However, under the 0dB and -10dB S/N ratios noisy conditions, the lateralization pattern of tone 3 is reversed, which is consistent with our discussion in Section 3.1 that certain degree of white noise can increase the right ear advantage. It is also consistent with the finding in [14] that tone 3 has a strong right ear advantage in noisy condition. Nonetheless, the underlying brain mechanisms of the different lateralization patterns of tone 3 under clean and noisy conditions remain unexplained.

3.3. Individual difference and gender difference

The individual and gender differences among subjects are indicated by the individual POE. Table 4 lists the correctness and POE of each subject, in which M1 to M5 are male subjects and F1 to F5 are female subjects. As shown in Table 4, different subjects show different degrees of lateralization, two female subjects even have a reversed lateralization pattern compared with others. In addition, the average POE of all male subjects is 56.7% and the average POE of all female subjects is 47.5%. Based on a T-test, we detect a significant gender difference of the POE ($t(8) = 2.696$, $p < .027$). This gender difference indicates that tones are more bilaterally processed for females than males. A similar gender difference has also been found in some other studies (e.g. [9], [15]).

Table 4: *The correctness and POE of each subject.*

	Correctness (%)	POE (%)
M1	89.6	56.0
M2	69.1	54.9
M3	54.4	58.8
M4	65.4	52.9
M5	76.1	61.6
F1	71.0	51.5
F2	68.6	38.6
F3	80.7	52.9
F4	64.3	47.3
F5	85.4	52.4

4. Conclusions

In this paper, we conducted a Mandarin tone dichotic listening experiment to study tone lateralization under clean and noisy conditions. Based on a hearing test, the subjects of the experiment were well controlled of their left and right ears' HTLs. Apart from the clean condition, three noisy conditions were introduced, and the lateralization patterns of the four Mandarin tones under these conditions were compared. We found that certain noisy conditions such as those under the 0dB and -10dB S/N ratios may limitedly increase the average POE and the right ear advantage of tone 3. In addition, subjects show different ear advantages for different tones: the perception of tone 2 and tone 4 shows a right ear advantage, while that of tone 1 shows a left ear advantage. We suggested that two physical properties, the tone features such as CONTOUR and HIGH, and the fast or slow changes of the fundamental frequencies of different tones, may cause these different tone lateralization patterns. Moreover, we detect a gender difference of POE, which suggests that there could be some differences in the underlying mechanisms of tone perception in male and female speakers.

In this experiment, the lateralization pattern of tone 3 is different in clean and noisy conditions, which cannot be explained by the above two physical properties we proposed. Besides these physical properties, other factors may play a role in affecting the lateralization pattern of tone 3, and we will explore these linguistic or nonlinguistic factors in the future work.

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