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Hemispheric processing of Mandarin tones by Chinese and American listeners*

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The hemispheric processing of Mandarin tones by native and nonnative listeners was examined using the dichotic listening paradigm. Twenty American listeners with no tone language background as well as twenty Chinese listeners were asked to identify the dichotically presented tone pairs by indicating which tone they heard in each ear. For the Chinese listeners, 57% of the total errors were due to the left ear, indicating a significant right ear advantage (REA). However, the American listeners revealed no significant ear preference, with 48% of the errors attributable to the left ear. These results indicated that Mandarin tones are predominantly processed in the left hemisphere by native speakers, suggesting that left hemisphere lateralization of tone may be more language-universal than was previously recognized.

1 Introduction

It has generally been hypothesized that brain function is distributed between both hemispheres, with the left hemisphere dominant for "analytic" processing and the right hemisphere for "holistic" processing (Bever, 1975; Bever and Chiarello, 1974); thus the left hemisphere is more linguistically sophisticated, while the right hemisphere is more adept at affective functions. Previous research has supported the hypothesis that the left hemisphere appears better at recognizing linguistic stimuli, such as real words and synthesized syllables (Kimura, 1961; Shankweiler and Studdert-Kennedy, 1967; Studdert-Kennedy and Shankweiler, 1970), whereas the right hemisphere appears better at recognizing non-linguistic stimuli such as music, pitch contours, and prosody associated with affective meaning (Kimura, 1964; Curry, 1967; Bryden, 1982).

While fundamental frequency (F0) based stimuli have generally been found to be lateralized to the right hemisphere (e.g., Goodglass and Calderon, 1977, for musical notes; Blumstein and Cooper, 1974, for intonation contours; Mazzucchi, Parma, and Cattelani, 1981, for synthesized tones), the processing of linguistic tones poses an

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interesting question. On the one hand, tones are used to make linguistic contrasts, assumed to be a function of the left hemisphere; on the other hand, they are a local modulation of F0, generally found to be the domain of the right hemisphere (Ryalls and Reinvang, 1986). Therefore, linguistic tone is a useful medium for studying hemispheric specialization.

1.1 Dichotic perception of linguistic tones

One research paradigm used to investigate the possible functional lateralization is that of dichotic listening. In most cases, a right ear advantage (REA) is found in connection with linguistic stimuli. For example, an REA has been found for segmental stimuli such as stop consonants and liquids (Cutting, 1974), nasals and fricatives (Bryden and Murray, 1985), and vowels (Dwyer, Blumstein, and Ryalls, 1982).

Initial research on the dichotic perception of linguistic tones was conducted by Van Lancker and Fromkin (1973). In this study, native speakers of a tone language, Thai, and those of a non-tone language, English, were tested in a dichotic listening task to compare ear preferences for three sets of stimuli: linguistic stimuli with pitch differences (Thai words differing only in tone, i.e., tone-words), linguistic stimuli without pitch differences (Thai words on the same tone, contrasting only in initial consonants, i.e., consonant-words), and pitch differences alone (hums of the Thai tones). Van Lancker and Fromkin (1973) found that the Thai speakers revealed a significant REA for both tone-words and consonant-words, but no ear difference for hums. In contrast, the English speakers only showed an REA for the consonant-words. The authors concluded that the perception of tones was lateralized to the left hemisphere by native speakers of Thai. They inferred that the Thai speakers were processing the feature contrasts in both the consonants and tones as language, whereas the hums were not linguistically relevant, and thus yielded no significant ear effects. According to them, a left hemisphere advantage occurred when pitch differences are processed linguistically.

In a follow-up study with both musically trained and untrained English speakers, as well as native Thai speakers, Van Lancker and Fromkin (1978) addressed whether the REA found in the Thai speakers was due to the linguistic system of these speakers, or whether it could have been due to greater familiarity with pitch contrasts. The results indicated that all three groups revealed an expected REA for the consonant-words, and no group revealed an REA for the hums. For the tone-words, an REA occurred only in the Thai group, with neither the musically-trained nor the musically-untrained English group showing an REA for the tone words, indicating that left hemisphere specialization for tones occurs only when they are part of the speaker's linguistic system.

Using a similar dichotic listening paradigm, Baudoin-Chial (1986) investigated the hemispheric lateralization of Mandarin Chinese to determine whether the REA results obtained by Van Lancker and Fromkin (1973, 1978) could be generalized to other tone languages. Native Chinese listeners, as well as French controls, participated in the dichotic listening tests with three sets of stimuli: four Mandarin tone-words, four Mandarin consonant-words, and hums of the four tones. The results from the Chinese speakers showed no significant ear preference in any of the three types of stimuli. However, the French listeners revealed an REA for consonant-words, a left ear advantage (LEA) for tone-words, and no significant ear difference for hums. The fact that the Chinese speakers did not reveal an REA for tone-words failed to support the hypothesis that tones would be predominantly processed by the left hemisphere because they are linguistic. However, given that they did not show an REA for consonant-words either, Baudoin-Chial (1986) speculated that phonemic stimuli for Chinese speakers might be equally processed by both hemispheres; i.e., the processing of linguistic materials could be less lateralized than previously thought. In comparison with the Van Lancker and Fromkin (1973, 1978) studies, Baudoin-Chial concluded that Thai and Chinese invoke different types of hemispheric processing, which are language dependent.

The hemispheric processing of tone has also been investigated for Norwegian. Moen (1993) examined the dichotic perception of the two Norwegian tones. When native Norwegian listeners were either aware or unaware of the dichotic nature of the stimuli, the words presented to the right ear were more frequently and correctly reported than those presented to the left ear. The results consistently revealed left-hemisphere dominance for the Norwegian word tones.

1.2 The current study

Inconsistent with studies on Thai and Norwegian, Baudoin-Chial (1986) failed to show an REA for Mandarin tones when they were perceived dichotically, suggesting language-dependent hemispheric processing of tones. However, other dichotic studies with Chinese listeners (e.g., Cai, 1992; Ip and Hoosain, 1993) did find an REA for Mandarin, although the stimuli tested in these studies were words (syllable plus tone) rather than tones *per se*. Furthermore, evidence from studies of aphasic speakers indicated that for Mandarin aphasics (Naeser and Chan, 1980; Packard, 1986), as well as for Thai (Gandour and Dardarananda, 1983; Gandour, Petty, and Dardarananda, 1988) and Norwegian (Ryalls and Reinvang, 1986) aphasics, damage to the left hemisphere (rather than to the right hemisphere) impairs both tone production and perception, clearly demonstrating the left-hemisphere dominance for linguistic tone processing.

These findings cast some doubt on the generalizability of Baudoin-Chial's (1986) results for Mandarin Chinese. As was also recognized by Baudoin-Chial herself, other factors, such as a ceiling effect, might account for the absence of an REA. Although Baudoin-Chial does not present any specific data to this effect, she does mention that the Chinese listeners' overall correct identification for tone words reached over 90%. In her study, the total number of stimuli for tone-words was 48 (1 syllable x 12 tone pairs x 4 repetitions), indicating that over 90% correct identification would result from an average of only four errors for each listener for each ear. This small number of errors may account for the absence of an REA in her study. Indeed, a ceiling effect is not uncommon in dichotic tone perception experiments. As was pointed out by Weiss and House (1973), an REA is expected only when the listening conditions are appropriately challenging. For instance, Van Lancker and Fromkin (1973) resorted to shortening the interval between every other stimulus-pair in order to induce errors, given that the first two Thai listeners showed few or no errors in identifying the tones.

Given these findings, it seems that the dichotic perception of Mandarin tones is worthy of re-examination, when conditions induce sufficient errors. The present study sought to examine the dichotic perception of Mandarin tones by native listeners of

Mandarin Chinese, and compare these results to the perception of tone by native listeners of American English with no prior knowledge of Mandarin or any other tone language in an attempt to address whether the hemispheric lateralization of Mandarin tones is similar to that of other tone languages.

2 Method

Stimuli were presented dichotically to both Chinese and American listeners. To remedy possible ceiling effects present in previous studies, three manipulations were introduced to increase task difficulty for the Chinese listeners. First, following a commonly-used technique to induce errors (e.g., Weiss and House, 1973; Cullen, Thompson, Hughes, Berlin, and Samson, 1974; Schouten, van Dalen, and Klein, 1985; Shipley-Brown, Dingwall, Berlin, Yeni-Komshian, and Gordon-Salant, 1988), the dichotic stimuli were embedded in white noise. Second, trials were presented in rapid succession with a short (two second) inter-stimulus-interval (ISI). Finally, the total number of stimuli was increased by including four different syllables (rather than just one, as in Baudoin-Chial, 1986). For the American listeners, levels were set to ensure comparable task difficulty to the Chinese listeners.

2.1 Participants

Twenty adult native listeners of Mandarin Chinese (11 females, 9 males), and twenty adult native listeners of American English (11 females, 9 males) from the Cornell University population participated in the experiment. None of the listeners had any known history of speech and hearing impairments, and all were right-handed according to an assessment with the Edinburgh Handedness Inventory (Oldfield, 1971). An effort was made to keep the number of female and male listeners as comparable as possible to avoid gender bias. Although some studies found no gender difference in the magnitude of an REA (e.g., Minami, 1995), others claim that language is more bilaterally processed for females than males (e.g., Shaywitz, Shaywitz, and Pugh, 1995; Weekes, Zaidel, and Zaidel, 1995).

The Chinese listeners were all native speakers of Mandarin. Ten of the participants were also speakers of one of the (tonal) dialects of Chinese. The listeners all had some previous exposure to English, with eight years of class instruction in China, and less than six years of residence in the US. In addition, three of them also had some exposure to French, German, or Japanese. The American participants had no knowledge of Mandarin Chinese or any other tonal languages prior to the present experiment. Twelve of them had some exposure to French, German, or Spanish.

2.2 Stimuli

The stimuli were sixteen commonly used monosyllabic Mandarin words, consisting of four different syllables (*fan, guo, hui, shi*) each combined with the four tones, resulting in four tone quadruplets. The target stimuli are listed in Table 1.

Table 1. The sixteen target stimuli (4 syllables x 4 tones).

Character[a]	Pinyin	Tone	English gloss[b]
帆	*fan1*	1	sail
烦	*fan2*	2	annoy
反	*fan3*	3	reverse
饭	*fan4*	4	meal
锅	*guo1*	1	pan
国	*guo2*	2	country
果	*guo3*	3	fruit
过	*guo4*	4	pass
灰	*hui1*	1	gray
回	*hui2*	2	return
毁	*hui3*	3	destroy
会	*hui4*	4	meeting
师	*shi1*	1	teacher
十	*shi2*	2	ten
史	*shi3*	3	history
是	*shi4*	4	right

a. In most cases, a syllable-tone combination results in a number of homophones. One of the most commonly used characters is listed here, and was presented to the Chinese listeners on the instruction sheet. b. In most cases, a character represents a number of homonyms. One of the most common meanings is used here.

The stimuli were provided by a female native speaker of Mandarin Chinese, who was recorded in a sound-proof booth in the Cornell Phonetics Laboratory, using a cardioid microphone (Electrovoice RE 20) and a cassette recorder (Carver TD-1700). The sixteen target words were produced in isolation. Twenty repetitions of each target word were produced at a variety of speaking rates. The recordings were then digitized at 11.025 kHz after low-pass filtering at 5 kHz, using WAVES+/ESPS speech analysis software running on a SUN SPARCstation.

The F0 contours of the target words *guo1, guo2, guo3, guo4* produced by the speaker are shown in Figure 1, illustrating the four Mandarin tones.

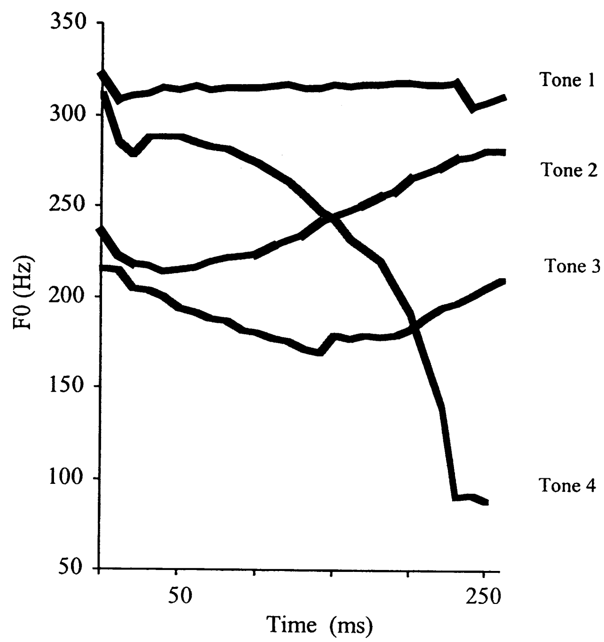

Figure 1. F0 contours for the four Mandarin tones, each combined with the syllable *guo*.

In order to create dichotic pairs which were matched in terms of duration and intensity, the recorded tokens were selected in two different ways. First, among the twenty repetitions of each word, the tone quadruplets (for each syllable) were selected such that their durational difference was under 10%, the approximate JND (Just Noticable Difference) for these durations (Lehiste, 1970). The duration range was 467–474 ms for *fan* words, 377–392 ms for *guo* words, 403-437 ms for *hui* words, and 444–488 ms for *shi* words. Next, the intensity of the sixteen selected words was equalized such that the RMS amplitude of all the resulting stimuli was the same.

A pilot study with four Chinese listeners using dichotic stimuli presented in the clear showed a low error rate of 5% on average. To induce errors, the target stimuli were each embedded in Gaussian noise with the same duration as the corresponding stimulus. The appropriate signal-to-noise (S/N) ratio was established empirically by testing two different Chinese listeners, at each of the following S/N values: 0 dB, −3 dB, −6 dB, and −10 dB. A S/N ratio of −10 dB was found to generate a sufficient number of errors (35% error rate; at the other S/N ratios, errors ranged from 5% to 7%). Therefore, the S/N ratio for the Chinese listeners was set to −10 dB. The stimuli for the American listeners were also embedded in noise in the same fashion, except that the S/N ratio was 0 dB, at which a comparable amount of errors (31%) was generated, as tested with two native English pilot listeners. The pilot study also suggested an ISI of two seconds for the Chinese listeners. For the American listeners, ISI was increased to four seconds to achieve an error rate comparable to that of the Chinese listeners.

These tokens were then transferred to a PC for pairing and presentation of the dichotic stimuli, using the BLISS system (Mertus, 1989). A total of 48 dichotic pairs (12 pairs x 4 syllables) were generated with all possible pairings for each syllable, except for identical pairings. The segmental composition was always the same for each pair. These 48 dichotic pairs were repeated four times, resulting in a total of 192 pairs for the dichotic test.

2.3 Procedure

The experiment was conducted in the Cornell Phonetics Laboratory, where listeners were tested individually over SONY MDR-V6 headphones.

Prior to the dichotic test, the Chinese listeners were submitted to a pretest with the sixteen target stimuli presented binaurally in the clear in a random order. The listeners in this study all met the criterion of perfect identification of the four tones. The American listeners received a short training program (about 30 minutes) before the pretest, to familiarize them with the four Mandarin tones. They were only presented with the sixteen target stimuli in isolation, produced by the same speaker as in the test. No attempt was made to have them associate these stimuli with any meaning. Only listeners who could identify 75% or more of the tones correctly at pretest were retained in the dichotic test (three out of 23 American listeners did not reach this criterion).

The dichotic test contained four randomized blocks (i.e., four repetitions) of 48 dichotic pairs each. For each listener, the output volume of the two channels of the headphones was calibrated with a sound level meter such that it was always 75 dB for both channels. Thus equal intensity was maintained for both ears. Listeners were instructed that they would be hearing two different tones (with the same segmental components) simultaneously over the headphones, one in the right ear and the other in the left ear. They were to identify both stimuli on an answer sheet. Right ear and left ear response rows (each with four numerical tone marks) were counter-balanced across blocks to avoid order bias. In addition, to eliminate channel effects, the headphones were reversed after two blocks. Headphone channels were counter-balanced across listeners.

The instructions and answer sheets were presented in Chinese to the Chinese listeners, and in English to the American listeners. Only one listener was tested at a time. The test lasted approximately 30 minutes for the Chinese listeners, while the test and training lasted approximately 60 minutes for the American listeners. To avoid fatigue, the American listeners took a short break between training and the dichotic test.

2.4 Data analysis

In previous studies, various criteria have been employed to measure the magnitude of ear asymmetry, hence the degree of hemispheric lateralization. The most straightforward and widely used measure is simply the difference in the number of errors (or correct responses) made on the left and the right ear (e.g., Kimura, 1961; Weiss and House, 1973; Schouten et al, 1985; Shipley-Brown et al, 1988; Ke, 1992; Cai, 1992; Ip and Hoosain, 1993). For the present study, the difference between left and right ear errors was also calculated.

However, since this measurement fails to take into account overall performance, direct comparisons across listeners, tests, and experimental conditions are more difficult (Repp, 1977). One alternative index that has been proposed is percentage of errors (POE) (Studdert-Kennedy and Shankweiler, 1970; Harshman and Krashen, 1972). This measure has been widely adopted (e.g., van Lancker and Fromkin, 1973; Blumstein and Cooper, 1974; Blumstein, Goodglass, and Tartter, 1975; Wexler and Halwes, 1983), as it has a lower correlation with overall performance (Harshman and Krashen, 1972). Repp (1977) has further pointed out that POE is a particularly precise measure when the percentage overall correct responses (averaged for both ears) is over 50%, and it can also compensate for the problem of guessing. Therefore, in addition to the number of errors, POE was calculated in the present study. POE is defined as $[P_L / (P_R + P_L)] \times 100$, where P_R is percentage errors in the right ear, and P_L is percentage errors in the left ear. A POE value of 60%, therefore, means the left ear makes 60% of the total errors. The index ranges from 0% (perfect LEA), to 50% (no ear advantage), to 100% (perfect REA), thus indicating the degree of laterality.

In calculating number of errors and POE, both-ear errors in a dichotic pair (i.e., neither tone is identified correctly) were not included, as previous research indicated that only those trials in which listeners identify one item correctly, and fail to identify the other, provide accurate information about laterality (Bryden, 1988). Both-ear errors are analyzed and discussed separately.

3 Results

3.1 Overall results

Overall, out of a total of 384 stimuli (192 pairs) for each subject, the Chinese listeners made an average of 174 errors (45% error rate), and the American listeners made an average of 177 errors (46% error rate). The similarity of error rates for both groups of listeners suggests that the manipulation of S/N ratio and ISI was highly successful in matching error rates. Out of the 192 pairs, for the Chinese listeners, 39 are left-ear errors, 31 are right-ear errors, 52 are both-ear errors, and the number of correct responses in both ears is 70. For the American listeners, 34 are left-ear errors, 37 are right-ear errors, 53 are both-ear errors, and the number of correct responses in both ears is 68. Table 2 lists the number and distribution of correct and incorrect responses for the Chinese and American listeners.

Table 2. Number and distribution of correct and incorrect responses for the 192 pairs of stimuli for Chinese and American listeners.

Tone pair type	Chinese	American
Both ear wrong (LX[a]-RX[b])	52	53
Left ear wrong (LX-RC[c])	39	34
Right ear wrong (LC[d]-RX)	31	37
Both ear correct (LC-RC)	70	68
Total	**192**	**192**

a. LX: left ear wrong; b.RX: right ear wrong; c.RC: right ear correct; d.LC: left ear correct.

The average POE for the Chinese listeners is 57%, whereas that for the American listeners is 48%. The overall results were analyzed using a two-way ANOVA with POE as the dependent variable, and Listener Group (Chinese, American) and Gender (Female, Male) as factors. There was a significant main effect of Listener Group [$F(1, 38) = 7.4$, $p<.01$], indicating a significant difference in ear preference between the Chinese and the American listeners. No reliable difference in Gender was observed [$F(1, 38) = 0.02$, $p>.886$], nor was there a significant Listener Group by Gender interaction [$F(1, 38) = 0.5$, $p>.502$].

The Chinese and American listeners' performance in terms of the distribution of left and right ear errors is displayed in Figure 2. For the Chinese listeners, the percentage of errors for the left ear exceeds that for the right ear, indicating an REA. In contrast, for the American listeners, errors for the left and right ears are comparable, showing little ear differences.

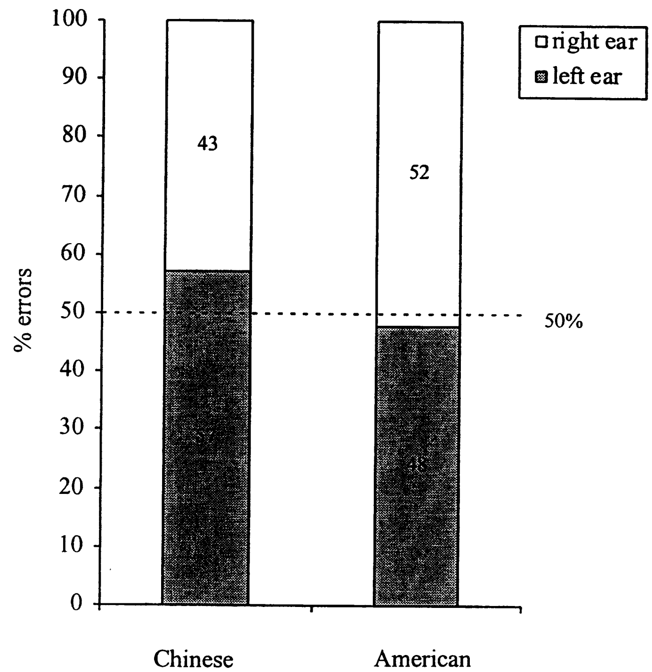

Figure 2. Distribution of left-ear errors and right-ear errors (in %) by the Chinese (n=20) and the American (n=20) listeners.

3.2 Chinese listeners

Individual Chinese listeners' performance in terms of POE and the number of errors made on each ear is shown in Table 3.

As shown in Table 3, fifteen out of twenty listeners exhibited an REA (with more errors on the left than on the right ear), and five listeners demonstrated an LEA. This difference in the number of listeners for the two ear advantage categories was significant [$\chi^2(1) = 5$, $p<.025$], indicating greater frequency of occurrence of an REA than an LEA.

Data were also analyzed in terms of individual tones. Table 4 presents the mean number of errors occurring in the left and right ear for each tone. A 2-way repeated measures ANOVA was calculated with the Number of Errors as the dependent variable, and Ear (left, right) and Tone (1,2,3,4) as within-subjects factors. As expected, a significant difference for Ear was obtained [$F(1,19) = 4.98$, $p<0.038$], revealing a significant ear asymmetry, with more left ear errors than right ear errors (39 left ear errors versus 31 right ear errors). There was also a significant main effect of Tone

[F(3, 57) = 42.51, p=.000], with a post hoc analysis (Tukey-HSD) indicating that, across ears, the number of errors for Tone 3 (40 errors) was significantly greater than for the other three tones (Tone 1: 11 errors, Tone 2: 11 errors, Tone 4: 8 errors). In addition, the interaction of Ear and Tone was also significant [F(3,58) = 3.33, p<.019], suggesting that listeners showed different degrees of ear preference for individual tones. That is, the magnitude of REA is greater for Tone 3 than for the other three tones.

Table 3. Individual Chinese listeners' performance in the dichotic test in terms of the difference in errors made on the left and right ears, and the degree of laterality (POE).

Listener	Gender	Total[a]	Left[b]	Right[c]	Difference[d]	POE[e]
1	M	86	44	6	+38	88%
2	M	107	61	20	+41	81%
3	F	189	22	10	+12	71%
4	M	148	34	19	+15	64%
5	F	172	36	21	+15	64%
6	F	174	42	24	+18	63%
7	F	111	43	27	+16	62%
8	F	108	44	29	+15	60%
9	F	146	75	54	+14	58%
10	M	165	16	13	+3	56%
11	F	140	48	40	+8	54%
12	M	94	38	33	+5	53%
13	F	162	75	69	+6	52%
14	F	157	24	23	+1	52%
15	M	106	35	34	+1	51%
16	F	127	48	53	-5	48%
17	M	181	42	50	-8	45%
18	M	163	25	33	-8	43%
19	M	159	11	18	-7	39%
20	F	107	26	54	-28	32%
Mean		**140**	**39**	**31**	**+8**	**57%**
(SD)		(32)	(17)	(16)	(16)	(13)

a.Total number of stimuli excluding both-ear errors; b.Left ear errors; c.Right ear errors; d.Left minus right ear errors; e.Percentage of errors made on the left ear.

Table 4. Chinese listeners' (n=20) mean errors for the left and right ears for the four individual tones, with SD in parentheses.

	Left ear errors	Right ear errors
Tone 1	6 (5)	5 (3)
Tone 2	6 (4)	5 (4)
Tone 3	22 (12)	18 (11)
Tone 4	5 (3)	3 (2)

3.3 American listeners

Individual American listeners' performance in terms of number of errors and POE is listed in Table 5. The degree of ear asymmetry was much smaller compared to the Chinese listeners (cf. Table 3). Eight of the listeners revealed a slight tendency towards an REA, while twelve showed an LEA. The number of listeners with left or right ear preference was not significantly different [$\chi^2(1)=0.8$, $p>.371$]. For the American listeners, as shown in Table 6, ear preference was not consistent across the four tones, a pattern distinct from that observed for the Chinese listeners (cf. Table 4).

A 2-way repeated measures ANOVA was conducted for the American listeners in which the within-subjects factors were Ear and Tone, and the dependent variable was the Number of Errors. There was no significant main effect for Ear [$F(1,19) = 3.08$, $p>.096$], nor was there a significant Ear by Tone interaction [$F(3,57) = 2.55$, $p>.065$]. However, a main effect of Tone was observed [$F(3,57) = 9.18$, $p=.000$], and a post hoc analysis (Tukey-HSD) showed that for both ears, the number of errors for Tone 4 (24 errors) was significantly greater than for Tone 1 (12 errors) and Tone 3 (15 errors).

These results indicate that, as opposed to the Chinese listeners who demonstrated a significant REA, the American listeners presented no consistent ear asymmetry. However, regardless of ear, the American listeners did exhibit a difference in overall identification of the four tones. Unlike the Chinese data, in which Tone 3 was most frequently mistaken, the most difficult tone for the American listeners was Tone 4.

Table 5. Individual American listeners' performance in the dichotic test in terms of the difference in errors made on the left and right ears, and the degree of laterality (POE).

Listener	Gender	Total[a]	Left[b]	Right[c]	Difference[d]	POE[e]
1	F	163	29	21	+8	58%
2	M	165	16	13	+3	56%
3	M	114	44	37	+7	54%
4	F	162	57	52	+5	52%
5	F	130	37	34	+3	52%
6	F	143	22	20	+2	52%
7	M	114	40	39	+1	51%
8	F	160	42	41	+1	50%
9	F	126	34	36	-2	49%
10	F	103	41	42	-1	49%
11	F	139	33	37	-4	47%
12	M	166	30	34	-4	47%
13	M	112	38	45	-7	46%
14	M	152	40	46	-6	46%
15	F	164	14	17	-3	46%
16	M	120	42	51	-9	45%
17	F	104	39	51	-12	44%
18	F	168	17	24	-7	42%
19	M	164	22	34	-12	39%
20	M	108	34	64	-30	34%
Mean		**139**	**34**	**37**	**-3**	**48%**
(SD)		(24)	(11)	(13)	(9)	(6)

a.Total number of stimuli excluding both-ear errors; b.Left ear errors; c.Right ear errors; d.Left minus right ear errors; e.Percentage of errors made on the left ear.

Table 6. American listeners' (n=20) mean errors for the left and right ears for the four individual tones, with SD in parentheses.

	Left ear errors	Right ear errors
Tone 1	5 (4)	7 (4)
Tone 2	9 (4)	10 (4)
Tone 3	8 (6)	7 (6)
Tone 4	12 (4)	12 (6)

3.4 Both-ear errors

Among the both-ear errors not included in the analyses above, two types of errors were further examined, i.e., those of "inversion" and "intrusion" (cf. Van Lancker and Fromkin, 1973). "Inversion" refers to two correctly identified stimuli with reversed ear locations; "intrusion" refers to errors in which one stimulus was correctly identified but located at the wrong ear. For example, if the left ear response was correct, but marked as the right ear response, this would be considered a left ear intrusion on the right ear.

Chinese and American listeners' inversion and intrusion errors are shown in Table 7. For the Chinese listeners, out of 52 both-ear errors, fifteen were inversion errors, fourteen were left ear intrusion errors, and eleven were right ear intrusion errors. Although the mean number of intrusions was greater for the left ear than for the right, a paired samples t-test revealed no significant difference [t (19) = 1.1, p>.284]. For the American listeners, there are 53 both-ear errors, including sixteen inversion errors, twelve left-ear intrusion errors, and twelve right-ear intrusion errors. A paired samples t-test showed that there was no significant difference between the number of left and right ear intrusions [t(19) = 1.76, p>.094].

Table 7. Chinese (n=20) and American (n=20) listeners' mean number of inversion errors (two correctly identified stimuli with reversed ear location), and intrusion errors (left to right = left ear response correct, but marked as the right ear response; right to left = right ear response correct, but marked as the left ear response), with SD in parentheses.

	Inversion	Intrusion	
		Left to right	Right to left
Chinese	15 (8)	14 (14)	11 (12)
American	16 (6)	12 (6)	12 (8)

3.5 Listeners' self-evaluation

After the dichotic test, both the Chinese and American listeners were asked, (1) if the stimuli were language-like or not; (2) which ear could better identify the tones; and (3) which tones were the easiest or the most difficult (Table 8). First, it is interesting to note that, although none of the American listeners had any previous experience with Chinese or any tone language, they all still considered the stimuli language-like. Second, in agreement with the behavioral data, more Chinese listeners considered their right ear better at identifying the tones. By contrast, American listeners overwhelmingly claimed that their left ear was the better ear for identifying the tones, although no significant LEA was revealed. Lastly, listeners' impression of tone difficulty was also highly consistent with the behavioral data (cf. Tables 4 and 6). That is, Tone 3 is most difficult for the Chinese listeners, whereas Tone 4 is most difficult for the American listeners. In general, it seems that listeners' self-evaluation authentically reflected their actual performance.

Table 8. Chinese (n=20) and American (n=20) listeners' evaluation of the dichotic task. The number in each cell represents number of occurrence.

	Language[a]	Better ear[b]				Easiest tone				Most difficult tone			
		L	R	Ø	N	1	2	3	4	1	2	3	4
Chinese	17	6	9	4	1	4	2	0	11	3	2	12	0
American	20	10	3	5	2	8	0	12	0	4	7	2	7

a.Language-like stimuli; b.Left ear (L), Right ear (R), No difference (Ø), Not known (N).

4 Discussion

The results of the present study reveal that, for the Chinese listeners, errors made on the left ear exceeded those on the right ear, demonstrating a significant left hemisphere advantage for the processing of Mandarin tones by native listeners. In contrast, for the American English listeners without any experience with a tone language, no ear advantage was found. These results are in agreement with previous dichotic listening studies for other tone languages (e.g., Van Lancker and Fromkin, 1973; Moen, 1993), and with aphasia studies (e.g., Naeser and Chan, 1980; Gandour and Dardarananda, 1983; Ryalls and Reinvang, 1986) in that tones are predominantly lateralized in the left hemisphere when they are part of the listeners' linguistic system.

4.1 Chinese listeners

The degree of laterality for the Mandarin listeners, a 57% POE, is highly comparable to that for the Thai listeners in the Van Lancker and Fromkin (1973) study in which 57.3% of the errors occurred in the left ear. Moreover, this right ear advantage for processing tone occurred in most listeners. In the current study, fifteen out of twenty Mandarin listeners exhibited an REA (corresponding to 75% of the sample), which was similar to Van Lancker and Fromkin's (1973) sixteen out of twenty-one (76%). To a lesser degree, in Moen's (1993) study on Norwegian, the right ear was reported more correctly than the left ear by twenty-one out of thirty-two listeners (66%) in the first task, and by twelve out of twenty-three listeners (52%) in the second task.

Results from the present study, as well as from previous research, demonstrate that, for native listeners, the perception of tonal contrasts in tone languages like Chinese, Thai, and Norwegian, is to a large extent a property of the left hemisphere. To account for differences in lateralization between the perception of linguistic tones and other pitch-related contrasts, Van Lancker (1980) proposed a hypothetical scale of hemispheric specialization of pitch contrasts from the most linguistic use of pitch associated with the left hemisphere, to the least linguistic use of pitch associated with right hemisphere specialization. Hence, the most highly structured level of pitch pattern, phonological tone, falls at one end of the scale, while emotional and personal patterning of pitch phenomena are at the other end of the scale. In between these two extremes are pitch contrasts at the lexical and syntactic levels, such as stress and intonation.

An alternative hypothesis (Packard, 1986) assumed that the hemispheric lateralization of a prosodic feature is determined by whether the feature is specified in the lexicon. The basic hypothesis is that phonological aspects of the lexicon, which consist of that phonological information that is not predictable from context, are under the control of the left hemisphere. Since in tone languages, the phonological value of the tone in a word is not predictable from context, that information must be specified in the lexicon, and thus lateralized to the left hemisphere. In contrast to this are other pitch-related events such as stress and intonation, in which the pitch contours are invariant for all words in the language, and therefore are not specified in the lexicon. Packard suggested that it may be for this reason that stress and intonation contours have not generally been found to be left-lateralized.

Both of these hypotheses can accommodate the present findings on Chinese listeners' processing of tones. That is, Mandarin tones are highly structured phonologically and are specified in the lexicon, and are therefore processed in the left hemisphere.

Despite the present finding of left hemisphere superiority in the processing of Mandarin tones, some participation of the right hemisphere is also possible. After all, five out of the twenty Chinese listeners revealed, to a different degree, an LEA. Moreover, among the fifteen right-ear dominant listeners, the degree of REA varied to a large extent. In the literature, it has also been claimed that, even though the left hemisphere plays a dominant role in the linguistic realm, the right hemisphere is also involved in the processing of language (Carrol, 1994). For example, Chiarello (1991) has reported the joint functioning of both cerebral hemispheres in the interpretation of word meaning. Likewise, in a study using functional magnetic resonance imaging, listeners showed bilateral lower frontal activation in a verb generation task (Berry, Manelfe, Mueller, Franconi, Boulanouar, Demonet, Chollet, Rascol, and Clanet, 1996). Moreover, Ryalls and Reinvang (1986) found some disruptions in tone production in both left and right hemisphere damaged individuals. Therefore, it might be speculated that, in accordance with the processing of language in general, although linguistic tones are processed predominantly in the left hemisphere, the right hemisphere may also be involved.

The present study also revealed that, for the Chinese listeners, regardless of ear, the number of Tone 3 errors was greater than that of the other three tones. It should be noted that, although the RMS amplitude was equalized for the four tones, Tone 3 might still be perceptually less salient than the other three tones given the low frequency of its F0 contour, especially in the middle part. This may be due to the fact that the perception of loudness is affected by the frequency of a sound - a sound with lower frequency requires a higher amplitude for it to be perceived as loud as a sound with higher frequency (Stevens and Davis, 1938). Thus, Tone 3 could be more severely masked as compared to the other tones when it was presented under masked conditions (recall the S/N ratio for the dichotic stimuli for the Mandarin group was -10 dB).

4.2 American listeners

The present study found very little ear advantage in the processing of Mandarin tones by the American listeners, a result in agreement with Van Lancker and Fromkin's (1973) study showing no ear advantage in the dichotic listening of Thai tones. These data seem inconsistent with Baudoin-Chial (1986) whose study revealed a significant left ear effect for Mandarin tones in French listeners. However, Baudoin-Chial's further analyses demonstrated that it was only the group of seven females that revealed significant left-ear superiority, whereas the group of twenty-one males did not produce a significant ear advantage[1]. Given these findings, it would appear that non-native listeners of tone languages process linguistic tones bilaterally.

Related to the two hypotheses (Van Lancker, 1980; Packard, 1986) discussed earlier, it seems that, unlike the Chinese listeners, the American listeners are unaware of the phonological function and the lexical specification of linguistic tone. They are more adept at other functions of pitch used in English, such as stress and intonation, and are thus less likely to process lexical tone predominantly in the left hemisphere.

Findings in the domain of first language acquisition have led to some interesting assumptions concerning the interaction of the hemispheric processing of tones and other pitch-related events. For instance, given the findings that the linguistic tone system is acquired before the segmental system (e.g., Li and Thompson, 1977), just as the acquisition of other pitch-related abilities such as intonation (e.g. Leopold, 1953; Kaplan, 1970), Ioup and Tansomboon (1987) hypothesized that children acquiring linguistic tone first perceive and process it as part of the prosodic system of language, using more holistic strategies. That is, they first process tones at a universal phonetic rather than

[1] As no specific data were provided in Baudoin-Chial (1986), it is not known why a significant LEA was found in the overall data; whereas in the detailed analysis, it was only shown by the seven female listeners.

language-specific phonemic level. Only when the phonetic quality of the tones becomes integrated into children's emerging lexicon, does the tone system become a left hemisphere function. In contrast, adults acquiring a second language seem to use a different processing system, relying on their existing linguistic framework via the left hemisphere for processing the new language system.

These assumptions might lend some support to the lack of localization of tones by the American listeners in this study. These naive listeners might have processed the Mandarin tones as language (they also claimed to have heard the stimuli as language. cf. Table 8); yet, due to the lack of experience with the functional use of lexical tones, they were presumably influenced by the pitch functions that were more familiar to them, e.g., the native intonation system, which has generally been found to be a right hemisphere property. As a consequence of this interaction, both of their hemispheres may have been involved in the processing of the Mandarin tones.

One of the interesting additional findings with the American listeners was that, for both ears, more errors were made on Tone 4 words than on Tone 1 and 3 words. This is consistent with the previous findings that Tone 4 is a difficult tone for American learners of Mandarin (Shen, 1989; Wang, Spence, Jongman, and Sereno, 1999).

5 Concluding remarks

Consistent with the previous studies on other tones languages, the present results indicate that Mandarin tones are predominantly processed in the left hemisphere by native speakers, suggesting that hemispheric processing of linguistic tones may be more language-universal than language-specific, as was claimed previously.

Moreover, the present finding of left hemisphere superiority in native listeners of Mandarin Chinese, as opposed to American listeners naive to a tone language, raises an interesting question: Will native American listeners' tone processing patterns be shifted toward the "native-like" direction as they gain more experience with Mandarin? Evidence along these lines will advance our understanding of the processing of language in general.

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