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Dichotic Perception of Mandarin Tones by Chinese and American Listeners

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The dichotic perception of Mandarin tones by native and nonnative listeners was examined in order to investigate the lateralization of lexical tone. Twenty American listeners with no tone language background and 20 Chinese listeners were asked to identify dichotically presented tone pairs by identifying which tone they heard in each ear. For the Chinese listeners, 57% of the total errors occurred via the left ear, indicating a significant right ear advantage. 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 Mandarin speakers, whereas they are bilaterally processed by American English speakers with no prior tone experience. The results also suggest that the left hemisphere superiority for native Mandarin tone processing is similar to native processing of other tone languages. © 2001 Academic Press

Key Words: dichotic perception; Mandarin tones; hemispheric lateralization.

INTRODUCTION

Functions of the brain are generally believed to be distributed in such a way that the left hemisphere is dominant for ''analytic'' processing and the right hemisphere for ''holistic'' processing (Bever, 1975; Bever & 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 is better at phonemic processing, such as real words and synthesized syllables (Kimura, 1961; Shankweiler & Studdert-Kennedy, 1967; Studdert-Kennedy & Shankweiler, 1970), whereas the right hemisphere is better at melodic and prosodic processing, such as music, pitch contours, and prosody associated with affective meaning (Kimura, 1964; Curry, 1967; Bryden, 1982). It should also be noted from these studies that the lateralization of the brain is a tendency, in that ''dominant'' does not necessarily exclude activity in the other hemisphere.

While fundamental frequency (F0)-based stimuli have generally been found to be lateralized to the right hemisphere (e.g., Goodglass & Calderon, 1977, for musical

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notes; Blumstein & Cooper, 1974, for intonation contours; Mazzucchi, Parma, & Cattelani, 1981, for synthesized tones), the processing of lexical tones poses an interesting question. On the one hand, tones are used to make phonemic contrasts, assumed to be a function of the left hemisphere; on the other hand, they are a modulation of F0, generally found to be the domain of the right hemisphere (Ryalls & Reinvang, 1986). Therefore, lexical tone is a useful medium for studying hemispheric specialization.

Dichotic Perception of Lexical Tone

One research paradigm used to investigate possible functional lateralization is that of dichotic listening, which involves the simultaneous presentation of a pair of different stimuli to the right and left ear. Since the right ear is primarily connected to the left hemisphere and the left ear to the right hemisphere through contralateral pathways, a right ear advantage (REA) is often 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 & Murray, 1985), and vowels (Dwyer, Blumstein, & Ryalls, 1982).

Initial research on the dichotic perception of lexical tone 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 changes (Thai words differing only in tone, i.e., tone-words), linguistic stimuli without pitch changes (Thai words with the same tone, contrasting only in initial consonants, i.e., consonant-words), and pitch changes alone (hums of the Thai tones). Van Lancker and Fromkin (1973) found that the Thai speakers showed a significant REA for both tone-words and consonant-words, but no ear preference for hums. In contrast, the English speakers only showed an REA for the consonant-words. The authors concluded that the perception of tone 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 yielded no significant ear effects, because they were not linguistically relevant. For the English listeners, whose native language does not have tone distinctions, tones as well as hums were not processed as language and were thus not lateralized predominantly in the left hemisphere. Taken together, this study suggests that a left hemisphere advantage occurred when pitch differences were processed linguistically.

In a follow-up study with both musically trained and untrained native 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 advantage 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; that is, that 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. Her study consists of two dichotic listening experiments with Norwegian speakers, both containing eight pairs of words differing only in tone. In the first experiment, listeners were asked to point to the drawing representing the word they heard, but they were unaware of the dichotic nature of the stimuli. The results showed that 21 of 32 listeners reported the word presented to the right ear more frequently than that presented to the left ear. The second experiment was conducted in a similar fashion, except that listeners were told that they would receive a different stimulus in each ear and were told to concentrate on one ear at a time. The results revealed that, consistent with the first experiment, there was a general tendency for words presented to the right ear to be reported more correctly than for those presented to the left ear. The authors thus concluded that this study indicated left hemisphere lateralization of the ability to perceive the tonal distinctions in Norwegian.

To summarize the findings of the dichotic perception of lexical tone, (1) for native speakers of languages with tonal distinctions such as Thai and Norwegian, tone is predominantly processed in the left hemisphere; (2) however, lateralization of tone was not found for Mandarin Chinese listeners, suggesting language-dependent hemispheric processing of tone; and (3) for native speakers of languages without tonal distinctions, such as American English and French, lexical tone is either not lateralized or lateralized in the right hemisphere.

The Current Study

Baudoin-Chial (1986) failed to show an REA for Mandarin tones when they were presented dichotically, suggesting language-dependent hemispheric processing of tone. These data are inconsistent with the studies on Thai and Norwegian tonal contrasts discussed above. Moreover, evidence from studies of aphasic speakers also indicates that for Mandarin aphasics (Naeser & Chan, 1980; Packard, 1986), as well as for Thai aphasics (Gandour & Dardarananda, 1983; Gandour, Petty, & Dardarananda, 1988) and Norwegian aphasics (Ryalls & Reinvang, 1986), damage to the left hemisphere (rather than to the right hemisphere) impairs both tone production and perception, clearly demonstrating a left hemisphere dominance for lexical tone processing. Furthermore, the Baudoin-Chial findings are also in conflict with other studies examining processing of Chinese words (e.g., Cai, 1992; Ip & Hoosain, 1993). In these dichotic listening studies, tone was not examined as a separate variable. Nevertheless, these dichotic studies show that Mandarin words (varying in both segmental and tone information) show a significant REA, suggesting that segmental plus tone information is processed predominantly in the left hemisphere for Chinese listeners.

These findings cast some doubt on the generalizability of Baudoin-Chial's (1986) results for Mandarin Chinese tone. As was also recognized by Baudoin-Chial herself, other factors, such as a ceiling effect, might account for the absence of an REA for tone. 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 $\times$ 12 tone pairs $\times$ 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 reexamination, including additional stimuli and under conditions which 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 Mandarin tones 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 tone is similar to that of other tone languages.

METHOD

Stimuli were presented dichotically to both Chinese and American listeners. To remedy possible ceiling effects present in previous studies, the following manipulations were introduced to increase task difficulty for the Chinese listeners. First, following a commonly used technique to induce errors (e.g., Weiss & House, 1973; Cullen, Thompson, Hughes, Berlin, & Samson, 1974; Schouten, van Dalen, & Klein, 1985; Shipley-Brown, Dingwall, Berlin, Yeni-Komshian, & Gordon-Salant, 1988), the dichotic stimuli were embedded in white noise. Second, trials were presented in rapid succession with a short (2-s) interstimulus interval (ISI). In addition, the total number of stimuli was increased by including four different types of 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.

Participants

Twenty adult native listeners of Mandarin Chinese (11 females, 9 males), and 20 adult native listeners of American English (11 females, 9 males) from the Cornell University population participated in the experiment.[1] 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, & Pugh, 1995; Weekes, Zaidel, & Zaidel, 1995).

The Chinese listeners were all native speakers of Mandarin. Ten of these Mandarin participants were also familiar with another dialect of Chinese which is also tonal. The listeners all had some previous exposure to English, with 8 years of class instruction in China, and less than 6 years of residence in

[1] Twenty-two Chinese and 24 American listeners were originally recruited. However, 1 Chinese listener could only hear the sounds from one ear, and 1 Chinese listener claimed to be a ''corrected right-handed'' person. Also, 1 American listener confused ''Left'' and ''Right'' on the answer sheets, and 3 American listeners failed the pretest, which required them to correctly identify the monaurally presented test stimuli (at least 75% correct identification). They were therefore eliminated from the analyses.

TABLE 1
The 16 Target Stimuli (4 Syllables × 4 Tones)

Character[a]	Pinyin	Tone	English gloss[b]
帆	*fan1*	1	sail
烦	*fan2*	2	annoy
反	*fan3*	3	reverse
饭	*fan 4*	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 in the instruction sheet.
[b] The most common meaning is used here.

the United States. In addition, 3 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.

Stimuli

The stimuli were 16 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.

The stimuli were produced 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 16 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,* and *guo4* produced by the speaker are shown in Fig. 1, illustrating the four Mandarin tones.

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 20 repetitions of each word, the tone quadruplets (for each syllable) were selected such that their durational difference was under 10%, the approximate JND (just noticeable 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 16 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 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, −3, −6, and −10 dB. A S/N ratio of −10 dB was found to generate an error rate of 35% (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 number of errors (31%) was generated, as tested with two native English pilot listeners. The pilot study used a relatively short ISI of 2 s for the Chinese listeners.

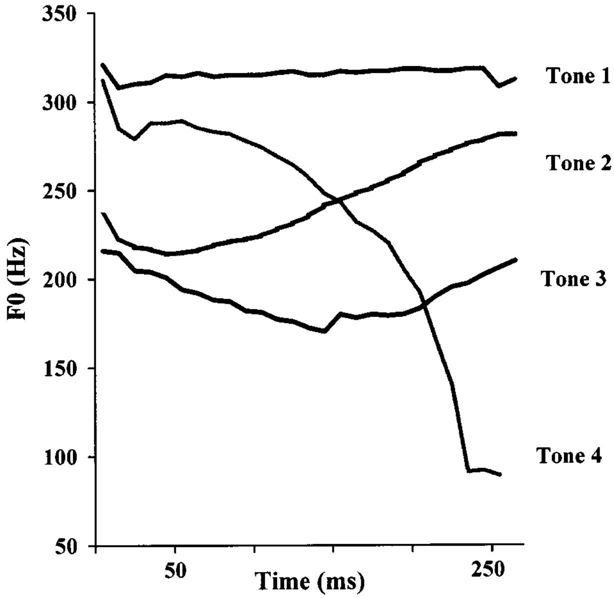

FIG. 1 F0 contours for the four Mandarin tones, each combined with the syllable *guo.*

For the American listeners, the ISI had to be increased to 4 s 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 software (Mertus, 1989). A total of 48 dichotic pairs (12 pairs $\times$ 4 syllables) were generated with all possible pairings for each of the four syllables, with the exception of 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.

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 participated in a pretest with the 16 target stimuli presented binaurally without noise 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 min) before the pretest, to familiarize them with the four Mandarin tones. They were presented binaurally with the 16 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 in the pretest were retained in the dichotic test (3 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 the four numerical tone marks) were counterbalanced across blocks to avoid order bias. In addition, to eliminate channel effects, the headphones were reversed after two blocks. Headphone channels were counterbalanced across listeners.

The instructions and answer sheets were presented in Chinese to the Chinese listeners and in English to the American listeners. The test lasted approximately 30 min for the Chinese listeners, while the test and training lasted approximately 60 min for the American listeners. To avoid fatigue, the American listeners took a short break between the training and the dichotic test.

Data Analysis

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

However, since this measurement fails to take into account overall performance, direct comparisons across listeners, tests, and experimental conditions are more difficult (Repp, 1977). An alternative index that has been proposed is percentage of errors (POE) (Studdert-Kennedy & Shankweiler, 1970; Harshman & Krashen, 1972). This measure has been widely adopted (e.g., Van Lancker & Fromkin, 1973; Blumstein & Cooper, 1974; Blumstein, Goodglass, & Tartter, 1975; Wexler & Halwes, 1983), as it has a lower correlation with overall performance (Harshman & Krashen, 1972). Repp (1977) has further pointed out that POE is a particularly precise measure when the percentage of 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_L is percentage errors in the left ear and P_R is percentage errors in the right ear. A POE value of 60%, therefore, means that the left ear makes 60% of the total errors. The index ranges from 0% (perfect LEA), to 50% (no advantage for either ear), to 100% (perfect REA), thus indicating the degree of laterality.

Both-ear errors (i.e., neither tone is identified correctly) are analyzed and discussed separately. In calculating number of errors and POE, both-ear errors in a dichotic pair 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).

RESULTS

Overall Results

Overall, of a total of 384 stimuli (192 pairs), the error rate was 45% for the Chinese listeners and 46% for the American listeners. The similarity of error rates for the two groups of listeners suggests that the manipulation of S/N ratio and ISI was highly successful in matching error rates. Table 2 lists the number and distribution of correct and incorrect responses for the Chinese and American listeners.

The average POE for the Chinese listeners was 57%, whereas that for the American listeners was 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

TABLE 2
Number and Distribution of Correct and Incorrect Responses for the 192 Pairs of Stimuli for the Chinese and American Listeners

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

[a] LX, left ear wrong.
[b] RC, right ear correct.
[c] LC, left ear correct.
[d] RX, right ear wrong.

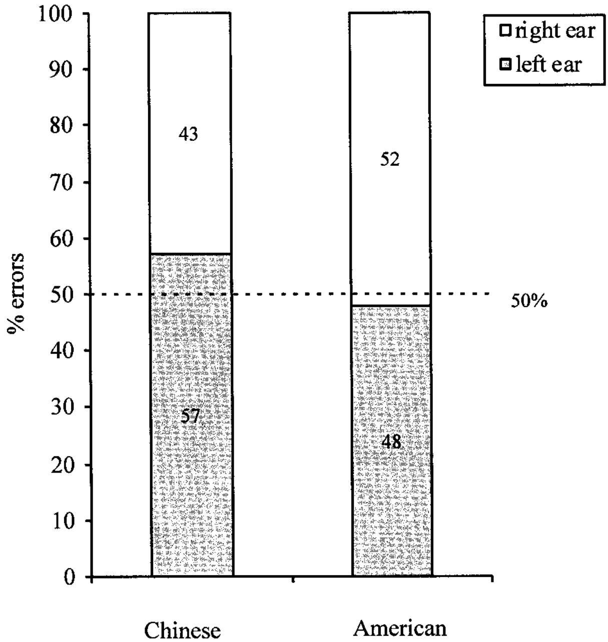

FIG. 2 Distribution of left ear errors and right ear errors (in %) by the Chinese ($n = 20$) and the American ($n = 20$) listeners.

the Chinese and 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 Fig. 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 difference between ears.

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, 15 of the 20 Chinese listeners exhibited an REA (with more errors on the left than on the right ear), and 5 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 for the Chinese listeners.

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 two-way repeated measures ANOVA was calculated, with Number of Errors as the dependent variable and Ear (right, left) 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 posthoc 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

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.

addition, the interaction of Ear and Tone was also significant [$F(3, 58) = 3.33$, $p < .019$]; as can be seen in Table 4, the magnitude of REA is greater for Tone 3 than for the other three tones.

American Listeners

Individual American listeners' performance in terms of number of errors and POE is listed in Table 5. For the Americans, no clear ear asymmetry was observed. Eight

TABLE 4
Chinese Listeners' ($n = 20$) Mean Number of Errors for the Left and Right Ears for the Four Individual Tones, with SD in Parentheses

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

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.

of the listeners revealed a slight tendency toward an REA, while 12 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 which is different from that observed for the Chinese listeners (cf. Table 4).

A two-way repeated measures ANOVA was conducted for the American listeners in which the within-subjects factors were Ear and Tone and the dependent variable

TABLE 6
American Listeners' ($n = 20$) Mean Number of Errors for the Left and Right Ears for the Four Individual Tones, with SD in Parentheses

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

was 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 [$F(3, 57) = 2.25$, $p > .065$]. However, a main effect of Tone was observed [$F(3, 57) = 9.18$, $p = .000$]. A posthoc 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, compared 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.

Both Ear Errors

Among the both ear errors, two types of errors were examined: those of ‘‘inversion’’ and ‘‘intrusion’’ (cf. Van Lancker & Fromkin, 1973). ‘‘Inversion’’ refers to two correctly identified stimuli with reversed ear locations, whereas ‘‘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, 15 of 52 both ear errors were inversion errors, 14 were left ear intrusion errors, and 11 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 [$t(19) = 1.1$, $p > .284$]. The American listeners had 53 both ear errors, including 16 inversion errors, 12 left ear intrusion errors, and 12 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 [$t(19) = 1.76$, $p > .094$].

Listeners’ Self-Evaluation

After the dichotic test, both the Chinese and American listeners were asked three questions: (1) if the stimuli were language-like or not; (2) which ear could better

TABLE 7

Chinese ($n = 20$) and American ($n = 20$) Listeners’ Mean Numbers 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.

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

TABLE 8
Chinese (n = 20) and American (n = 20) Listeners' Evaluations of the Dichotic Task

		Better ear[b]				Easiest tone				Most difficult tone			
	Language[a]	L	R	O	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

Note. The number in each cell represents the number of listeners.
[a] Language-like stimuli.
[b] Left ear (L), right ear (R), no difference (0), not known (N).

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. Last, listeners' impressions of tone difficulty were also highly consistent with the behavioral data (cf. Tables 4 and 6); Chinese listeners found Tone 3 to be most difficult, whereas American listeners found Tone 4 to be most difficult. In general, it seems that listeners' self-evaluation authentically reflected their actual performance.

DISCUSSION

The results of the present study reveal that, for the Chinese listeners, errors made with the left ear exceeded those with 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 & Fromkin, 1973; Moen, 1993) and with aphasia studies (e.g., Naeser & Chan, 1980; Gandour & Dardarananda, 1983; Ryalls & Reinvang, 1986) in that tones are predominantly lateralized in the left hemisphere when they are part of the listeners' linguistic system. Contrary to an earlier dichotic test with Chinese listeners (Baudoin-Chial, 1986), Mandarin tones do show a significant REA.

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, 15 of 20 Mandarin listeners exhibited an REA (corresponding to 75% of the sample), which was similar to Van Lancker and Fromkin's (1973) 16 of 21 (76%). To a lesser degree, in Moen's (1993) study on Norwegian, the right ear was reported more correctly than the left ear by 21 of 32 listeners (66%) in the first task and by 12 of 23 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 is to a large extent a property of the left hemisphere.

To account for differences in lateralization between the perception of lexical tone 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 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. Among the 15 listeners showing an REA, the degree of REA varied. Moreover, 5 of the 20 Chinese listeners revealed an LEA to different degrees. Even though the left hemisphere plays a dominant role in the linguistic realm, the right hemisphere is also involved in the processing of language. Chiarello (1991), for example, 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 frontal activation in a verb generation task (Berry, Manelfe, Mueller, Franconi, Boulanouar, Demonet, Chollet, Rascol, & 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 lexical tone is 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 (e.g., Stevens and Davis, 1938). Thus, Tone 3 could be more severely masked than the other tones when it was presented under masked conditions (recall that the S/N ratio for the dichotic stimuli for the Mandarin group was -10 dB). The lack of accuracy for Tone 3 might also be due to the normalization of duration. Research has shown that intrinsic duration differs for the four tones, with Tone 3 being longer than the other three tones (Lin, 1965), and that Mandarin listeners use duration as a cue in the perception of Tone 3 (Blicher, Diehl, & Cohen, 1990). As such, the Chinese listeners in the present study were likely to miss Tone 3 when they heard a dichotic tone pair with the same duration, as they might have expected it to be longer.

American Listeners

The present study found no ear advantage in the processing of Mandarin tones by American listeners, a result in agreement with Van Lancker and Fromkin's (1973) study showing no ear advantage for Americans in the dichotic listening of Thai tones. These data seem inconsistent with those of Baudoin-Chial (1986), whose study revealed a significant left ear effect for Mandarin tones in French listeners. However, it is unclear why a significant LEA was found in the overall data, since Baudoin-Chial's further analyses demonstrated that it was only the group of 7 females that revealed significant left-ear superiority, whereas the group of 21 males did not produce a significant ear advantage.

It seemed that, unlike the Chinese listeners, the American listeners were unaware of the phonological function and the lexical specification of tone. Being more adept with more holistic functions of pitch used in English, such as intonation, they were 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 tone and other pitch-related events. For instance, given the findings that the lexical tone system, along with other pitch-related abilities such as intonation (e.g., Leopold, 1953; Kaplan, 1970), is acquired before the segmental system (e.g., Li & Thompson, 1977), Ioup and Tansomboon (1987) hypothesized that children acquiring lexical 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 language-specific phonemic level. Only when the phonetic quality of the tones becomes integrated into the children's emerging lexicon does the tone system become a left hemisphere function.

These assumptions might lend some support to the lack of lateralization of tone by the American listeners in this study. These listeners might have processed the Mandarin tones as language (they also claimed to have heard the stimuli as language, cf. Table 8). This might be the case, especially since the left hemisphere processing of prosodic features is not completely novel to them. For example, research has found a left hemisphere superiority for the processing of lexical stress (e.g., **hot**dog, hot **dog**) in English (Baum, Kelsch Daniloff, Daniloff, & Lewis, 1982; Emmorey, 1987). Still, due to the lack of experience with the linguistic use of lexical tone, the American listeners were presumably also influenced by the pitch functions that were more familiar to them, such as their native intonation system, which has generally been found to be a right hemisphere property. As a consequence of this coincidence, 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. This is consistent with previous findings that Tone 4 is a difficult tone for American learners of Mandarin (Shen, 1989; Wang, Spence, Jongman, & Sereno, 1999).

CONCLUDING REMARKS

The present results indicate that Mandarin tones are predominantly processed in the left hemisphere by native Mandarin speakers. These results are consistent with previous studies on other tone languages, suggesting that hemispheric processing of lexical tone may be more language-universal than language-dependent, as was claimed previously (Baudoin-Chial, 1986).

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 the interesting question whether native American listeners' tone processing patterns will shift in the ''native-like'' direction as they gain more experience with Mandarin. We have begun to explore this issue using functional magnetic resonance imaging (Wang, Sereno, Jongman, & Hirsch, 2000). Evidence along these lines will further advance our understanding of the processing of language in general.

REFERENCES

Baudoin-Chial, S. (1986). Hemispheric lateralization of Modern standard Chinese tone processing. *Journal of Neurolinguistics,* **2,** 189–199.

Baum, S., Kelsch Daniloff, J., Daniloff, R., & Lewis, J. (1982). Sentence comprehension by Broca's aphasics: effects of some suprasegmental variables. *Brain and Language,* **17,** 261–271.

Berry, I., Manelfe, C., Mueller, E., Franconi, J. M., Boulanouar, K., Demonet, J. F., Chollet, F., Rascol, O., & Clanet, M. (1996). Functional magnetic resonance of motor and verbal tasks. In L. Heuser & M. Oudkerk (Eds.), *Advances in MRI.* Berlin: Blackwell. Pp. 27–33.

Bever, T. G. (1975). Cerebral asymmetries in humans are due to the differentiation of two incompatible processes: Holistic and analytic. *Annals of the New York Academy of Sciences,* **163,** 251–262.

Bever, T. G., & Chiarello, R. J. (1974). Cerebral dominance in musicians and nonmusicians. *Science,* **185,** 137–139.

Blicher, D. L., Diehl, R. L., & Cohen, L. B. (1990). Effects of syllable duration on the perception of the Mandarin tone2/tone3 distinction: Evidence of auditory enhancement. *Journal of Phonetics,* **18,** 37–49.

Blumstein, S., & Cooper, W. (1974). Hemispheric processing of intonation contours. *Cortex,* **10,** 146–158.

Blumstein, S., Goodglass, H., & Tartter, V. (1975). The reliability of ear advantage in dichotic listening. *Brain and Language,* **2,** 226–236.

Broadbent, D. E., & Gregory, M. (1964). Accuracy of recognition for speech presented to the right and left ears. *Quarterly Journal of Experimental Psychology,* **16,** 359–360.

Bryden, M. P. (1963). Ear preference in auditory perception. *Journal of Experimental Psychology,* **65,** 103–105.

Bryden, M. P. (1982). *Laterality: Functional asymmetry in the brain.* New York: Academic Press.

Bryden, M. P., & Murray, J. E. (1985). Toward a model of dichotic listening performance. *Brain and Cognition,* **4,** 241–257.

Bryden, M. P. (1988). An overview of the dichotic listening procedure and its relation to cerebral organization. In K. Hugdahl (Ed.), *Handbook of dichotic listening: Theory, methods and research.* Chichester: Wiley.

Cai, H. (1992). A study of ear advantage in the dichotic listening of Chinese single-character words. *Psychological Science,* **80,** 25–28.

Chiarello, C. (1991). Interaction of word meanings by the cerebral hemisphere: One is not enough. In P. J. Schwanenflugel (Ed.), *The psychology of word meaning.* Hillsdale: Erlbaum. Pp. 251–278.

Cullen, J. K., Jr., Thompson, C. L., Hughes, L. R., Berlin, C. I., & Samson, D. S. (1974). The effects of varied acoustic parameters on performance in dichotic speech perception tasks. *Brain and Language,* **1,** 307–322.

Curry, F. K. W. (1967). A comparison of left-handed and right-handed subjects on verbal and non-verbal dichotic listening tasks. *Cortex,* **3,** 343–352.

Cutting, J. E. (1974). Two left-hemisphere mechanisms in speech perception. *Perception and Psychophysics,* **16,** 601–612.

Dwyer, J., Blumstein, S. E., & Ryalls, J. (1982). The role of duration and rapid temporal processing on the lateral perception of consonants and vowels. *Brain and Language,* **17,** 272–286.

Emmorey, K. (1987). The neurological substrates for prosodic aspects of speech. *Brain and Language,* **30,** 305–320.

Gandour, J., & Dardarananda, R. (1983). Identification of tonal contrasts in Thai aphasic patients. *Brain and Language,* **18,** 98–114.

Gandour, J., Petty, S. H., & Dardarananda, R. (1988). Perception and production of tone in aphasia. *Brain and Language,* **35,** 201–240.

Goodglass, H., & Calderon, M. (1977). Parallel processing of verbal and musical stimuli in right and left hemispheres. *Neuropsychologia*, **15,** 397.

Harshman, R., & Krashen, S. (1972). An ''unbiased'' procedure for comparing degree of lateralization of dichotically presented stimuli. *UCLA Working Papers in Phonetics* **23.**

Ioup, G., & Tansomboon, A. (1987). The acquisition of tone: A maturational perspective. In G. Ioup & S. H. Weinberger (Eds.), *Inter-language phonology: The acquisition of a second language sound system.* Cambridge: Newburry House. Pp. 333–349.

Ip, K. F., & Hoosain, R. (1993). Dichotic listening of Chinese and English words. *Psychologia,* **36,** 140–143.

Kaplan, E. L. (1970). Intonation and child acquisition. *Papers in Research in Child Language Development,* **1,** 1–21.

Ke, C. (1992). Dichotic listening with Chinese and English tasks. *Journal of Psycholinguistic Research,* **21,** 463–471.

Kimura, D. (1961). Cerebral dominance and the perception of verbal stimuli. *Canadian Journal of Psychology,* **15,** 166–171.

Kimura, D. (1964). Left-right differences in the perception of melodies. *Quarterly Journal of Experimental Psychology,* **16,** 335–358.

Lehiste, I. (1970). *Suprasegmentals.* Cambridge: MIT Press.

Leopold, W. (1953). Patterning in children's language. *Language Learning,* **5,** 1–14.

Li, C. H., & Thompson, S. A. (1977). The acquisition of tone in Mandarin speaking children. *Journal of Child Language,* **4,** 185–199.

Lin, M. C. (1965). The pitch indicator and the pitch characteristics of tones in Standard Chinese. *Acta Acoustica* **2,** 8–15.

Mazzucchi, A., Parma, M., & Cattelani, R. (1981). Hemispheric dominance in the perception of tonal sequences in relation to sex, musical competence and handedness. *Cortex,* **17,** 291–302.

Mertus, J. (1989). *BLISS manual.* Providence: Brown Univ.

Minami, K. (1995). Sex differences and handedness in dichotic listening performance. *Psychologia,* **38,** 38–43.

Moen, I. (1993). Functional lateralization of the perception of Norwegian word tones—Evidence from a dichotic listening experiment. *Brain and Language,* **44,** 400–413.

Neaser, M. A., & Chan, S. W. C. (1980). Case study of a Chinese aphasic with the Boston diagnostic aphasia exam. *Neuropsychologia,* **18,** 389–410.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia,* **9,** 97–113.

Packard, J. L. (1986). Tone production deficits in nonfluent aphasic Chinese speech. *Brain and Language,* **29,** 212–223.

Repp, B. H. (1977). Measuring laterality effects in dichotic listening. *Journal of the Acoustical Society of America,* **62,** 720–737.

Ryalls, J., & Reinvang, I. (1986). Functional lateralization of linguistic tones: Acoustic evidence from Norwegian. *Language and Speech,* **29,** 389–398.

Schouten, M. E. H., van Dalen, T. E., & Klein, A. J. J. (1985). Ear advantage and second language proficiency. *Journal of Phonetics,* **13,** 53–60.

Shankweiler, D., & Studdert-Kennedy, M. (1967). Identification of consonants and vowels presented to left and right ears. *Quarterly Journal of Experimental Psychology,* **19,** 59–63.

Shaywitz, B. A., Shaywitz, W. E., & Pugh, K. R. (1995). Sex differences in the functional organization of the brain for language. *Nature,* **373,** 607–609.

Shen, X. S. (1989). Toward a register approach in teaching Mandarin tones. *Journal of Chinese Language Teachers Association,* **24,** 27–47.

Shipley-Brown, R., Dingwall, W. O., Berlin, C., Yeni-Komshian, G., & Gordon-Salant, S. (1988). Hemispheric processing of affective and linguistic intonation contours in normal subjects. *Brain and Language,* **33,** 15–26.

Stevens, S. S., & Davis, H. (1938). *Hearing: Its psychology and physiology.* New York: Wiley.

Studdert-Kennedy, M., & Shankweiler, D. (1970). Hemispheric specialization for speech perception. *Journal of the Acoustical Society of America,* **48,** 579–594.

Van Lancker, D. (1980). Cerebral lateralization of pitch cues in the linguistic signal. *Papers in Linguistics: International Journal of Human Communication,* **13,** 201–277.

Van Lancker, D., & Fromkin, V. A. (1973). Hemispheric specialization for pitch and ‘‘tone’’: Evidence from Thai. *Journal of Phonetics,* **1,** 101–109.

Van Lancker, D., & Fromkin, V. A. (1978). Cerebral dominance for pitch contrasts in tone language speakers and in musically untrained and trained English speakers. *Journal of Phonetics,* **6,** 19–23.

Wang, Y., Sereno, J. A., Jongman, A., & Hirsch, J. (2000). Cortical reorganization associated with the acquisition of Mandarin tones by American learners: An fMRI study. *Proceedings of the* 6*th* *International Conference on Spoken Language Processing,* **II,** 511–514.

Wang, Y., Spence, M. M., Jongman, A., & Sereno, J. A. (1999). Training American listeners to perceive Mandarin tones. *Journal of the Acoustical Society of America,* **106,** 3649–3658.

Weekes, N. Y., Zaidel, D. W., & Zaidel, E. (1995). Effects of sex and sex role attributions on the ear advantage in dichotic listening. *Neuropsychology,* **9,** 62–67.

Weiss, M. S., & House, A. S. (1973). Perception of dichotically presented vowels. *Journal of the Acoustical Society of America,* **53,** 51–58.

Wexler, B. E., & Halwes, T. (1983). Increasing the power of dichotic methods: The fused rhymed words test. *Neuropsychologia,* **21,** 59–66.