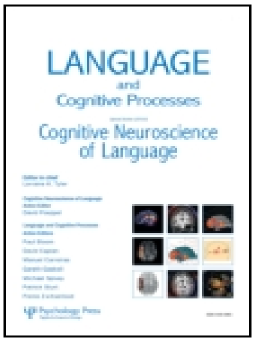

Language and Cognitive Processes

ISSN: 0169-0965 (Print) 1464-0732 (Online) Journal homepage: www.tandfonline.com/journals/plcp20

Hemispheric asymmetry in processing low- and high-pass filtered Cantonese speech in tonal and non-tonal language speakers

Ka Wing Chan & Janet H. Hsiao

To cite this article: Ka Wing Chan & Janet H. Hsiao (2013) Hemispheric asymmetry in processing low- and high-pass filtered Cantonese speech in tonal and non-tonal language speakers, Language and Cognitive Processes, 28:8, 1224-1243, DOI: 10.1080/01690965.2012.702915

To link to this article: https://doi.org/10.1080/01690965.2012.702915

LANGUAGE AND COGNITIVE PROCESSES, 2013
Vol. 28, No. 8, 1224–1243, http://dx.doi.org/10.1080/01690965.2012.702915

Routledge
Taylor & Francis Group

Hemispheric asymmetry in processing low- and high-pass filtered Cantonese speech in tonal and non-tonal language speakers

Ka Wing Chan and Janet H. Hsiao

Department of Psychology, The University of Hong Kong, Hong Kong

In auditory perception, a right hemisphere (RH)/left ear advantage(LEA) for low-pass filtered stimuli and a left hemisphere (LH)/right ear advantage(REA) for high-pass filtered stimuli have been reported. Here we investigated how tonal language experience modulates this hemispheric asymmetry. We recruited Cantonese, Mandarin (tonal languages), and English (non-tonal language) speakers, and asked them to recognise dichotically presented Cantonese speech pairs in either high- or low-pass filtered conditions. The results showed that in perception accuracy, whereas English speakers demonstrated the typical RH/LEA for low-pass filtered stimuli and LH/REA for high-pass filtered stimuli, for both high- and low-pass filtered stimuli, Cantonese speakers had similarly high accuracy in the two ears, and Mandarin speakers had higher right ear accuracy. In addition, Cantonese speakers had a preference to report the stimulus presented to the right ear; Mandarin speakers showed a similar, insignificant trend of preference, whereas English speakers showed no preference. This result is consistent with the hypothesis of language-experience-dependent specialisation of the LH in auditory perception, in contrast to an experience-independent general auditory or linguistic mechanism. While English speakers showed the typical hemispheric asymmetry in auditory perception, the automaticity of LH language processing pathways in Cantonese speakers resulted in no accuracy difference between the two ears, and a right ear preference regardless of the frequency condition. In contrast, although Mandarin speakers did not understand Cantonese, they generalised their tonal language experience to Cantonese speech perception and had a REA even in the perception of low-pass filtered Cantonese speech.

Keywords: Hemispheric asymmetry; Speech perception; Lexical tones; DFF theory.

Dichotic listening and hemispheric asymmetry in auditory perception

In the human auditory pathways, each cerebral hemisphere plays a dominant role in processing the input from the contralateral ear. Previous anatomical studies reported

---

Correspondence should be addressed to Janet H. Hsiao, Department of Psychology, University of Hong Kong, Pokfulam Road, Hong Kong. E-mail: jhsiao@hku.hk

We are grateful to the Research Grant Council of Hong Kong (project # HKU 744509H to J.H. Hsiao). We thank Dr. Antoni B. Chan and Dr. Yetta K. L. Wong for their help on acoustic analysis of the stimuli. We thank the editor and two anonymous reviewers for their helpful comments.

that the majority of the fibres from an ear were connected to the opposite hemisphere (Brodal, 1981; Kelly, 1981). Single-cell recordings on animals such as monkeys (Brugge & Merzenich, 1973) and cats (Phillips & Irvine, 1981) revealed greater responses in the auditory cortex after a contralateral stimulation compared with an ipsilateral simulation; Electroencephalography (EEG) studies showed larger evoked potentials in response to contralateral than ipsilateral auditory stimulation in both humans and non-human species (Celesia, 1976; Majkowski, Bochenek, Bochenek, Knapik-Fijalkowska, & Kopec, 1971; Rosenzweig, 1951; Tanguay, Taub, Doubleday, & Clarkson, 1977). Positron Emission Tomography (Lauter, Herscovitch, Formby, & Raichle, 1985) and MEG studies (Makela et al., 1993) also converged to a similar conclusion.

This contralateral projection in the auditory pathways suggests that contralateral auditory inputs may be more efficiently perceived and processed than ipsilateral ones. It has been shown that the processing advantage of the contralateral pathways becomes most apparent when the two ears are presented with different auditory materials simultaneously, as compared with when auditory materials are presented to one ear alone. This technique has been referred to as the dichotic listening technique (Broadbent, 1958). In a typical dichotic listening paradigm, in each trial, different stimuli are presented simultaneously to the two ears and initiate an information processing competition. Performance of the participants in terms of identification accuracy and ear preference is assessed and used as a measure of functional asymmetry between the two hemispheres.

Some researchers have reported functional asymmetries between the two hemispheres according to a distinction between speech (language) and music. For example, it has been shown that the left hemisphere (LH) plays a dominant role in language tasks such as speech production (McKeever, Seitz, Krutsch, & Van Eys, 1995) and language comprehension (Beeman & Chiarello, 1998). Auditory inputs that are language-relevant have been shown to be preferentially processed in the LH (Meyer & Yates, 1955), especially when they follow grammar rules (Vandenberghe, Nobre, & Price, 2002). In addition, recent Magnetoencephalography (MEG) studies showed that the dominance of the LH in speech processing could also be observed at a pre-attentive processing level in the magnetic mismatch negativity (MMNm; e.g., Alho et al., 1998; Koyama et al., 2000; Sittiprapaporn, Chindaduangratn, Tervaniemi, & Khotchabhakdi, 2003). In contrast, melodic and prosodic information is better processed in the RH than the LH (Bever & Chiarello, 1974; Kimura, 1964; Milner, 1962). Consistent with this functional asymmetry, dichotic listening studies also typically showed a RH/LEA in melodic pattern perception, such as brief melodies (Kimura, 1964) and sonar signals (Chaney & Webster, 1965); and a LH/right ear advantage (REA) in the recognition of linguistic materials, such as digits (Broadbent & Gregory, 1964; Bryden, 1963; Kimura, 1961) and vowel syllables (Shankweiler & Studdert-Kennedy, 1967). For example, in a study conducted by Bartholomeus (1974), participants were asked to report digits they heard in a series of digits sang by a singer in different notes. A REA was reported when the participants were told to name the digits, while a LEA was found if they had to recognise the melodies.

In contrast to this functional distinction between music and speech, Ivry and Robertson (1998) proposed the Double Filtering by Frequency (DFF) theory to account for the functional asymmetries of the two hemispheres in perception. The theory states that, after a sensory input is transformed into a sensory representation, the sensory representation undergoes two frequency-filtering stages. The first stage involves a selective filtering of task-relevant frequency range, whereas at the second stage, the LH amplifies high frequency information, and the RH amplifies low-frequency information. In other words, according to the DFF theory, hemispheric processing asymmetry is brought about due to differential frequency filtering in the two hemispheres. Processing in the RH and LH are characterised as low-pass filtering and high-pass filtering operations, respectively. Within a task-relevant frequency range, the RH biases information towards the relatively low frequency range, and the LH biases information towards to the high frequency range (Ivry & Lebby, 1993; see also Sergent, 1982).

In speech perception, it has been shown that prosodic cues such as fluctuation in pitch, rhythm, and stress are primarily conveyed in the low frequency portions of the signal (i.e., low-pass filtered speech), whereas semantics (linguistic content) are preserved in the high frequency part (i.e., high-pass filtered speech; see Ivry & Robertson, 1998). According to the DFF theory, the LH specialisation for the perception of speech content (e.g., Broadbent & Gregory, 1964; Shankweiler & Studdert-Kennedy, 1967; Vandenberghe et al., 2002) is due to its superiority in discriminating speech sounds at a relatively high frequency range. In contrast, the processing of prosody or intonation of speech has been shown to be mainly mediated by the RH due to its superiority in processing low frequency information (e.g., Blumstein & Cooper, 1974; Gandour et al., 2004; Shipley-Brown, Dingwall, Berlin, Yeni-Komshian, & Gordon-Salant, 1988).

In contrast to the DFF theory, Zatorre, Belin, and Penhune (2002) proposed that the hemispheric asymmetry in processing speech and music/tonal pattern stimuli (see also Zatorre, Evans, Meyer, & Gjedde., 1992) is due to differences in temporal and spectral resolution of the two hemispheres: the auditory area in the LH has better temporal resolution, which is crucial for speech processing, whereas that in the RH has better spectral resolution, which is important for processing music/tonal patterns. This proposal is consistent with the argument that the LH specialisation of speech processing is due to its superiority in rapid temporal processing/acoustic transitions of auditory signals (e.g., Belin et al., 1998; Schwartz & Tallal, 1980; Tallal, Miller, & Fitch, 1993). In addition, Poeppel (2003) proposed the asymmetric sampling in time (AST) hypothesis, which posits that speech input is processed bilaterally symmetric at an early perceptual stage, and the asymmetry emerges at a later perceptual stage due to an AST: the auditory area of the LH preferentially extracts information from short (20–40 ms) temporal integration windows, whereas that in the RH preferentially extracts information from long (150–250 ms) integration windows.

Although different theories have been proposed to account for the hemispheric asymmetry in speech and music perception (i.e., Ivry & Robertson, 1998; Poeppel, 2003; Zatorre et al., 2002), they all suggest that the LH specialisation in speech processing may not be because speech stimuli are linguistically relevant but because only the neural computation supported by the left auditory area is capable of performing the processing required in speech recognition. According to the dual-stream model of speech processing (see, e.g., Hickok & Poeppel, 2004, 2007; Scott & Wise, 2004), the locus of this asymmetry is likely to be in the superior temporal cortex in the ventral stream of speech processing. This leads to a speculation that the REA/LH lateralisation in speech processing may also be observed in non-linguistic auditory perception tasks that require rapid temporal/high frequency processing. Although this hypothesis has been supported by some studies (e.g., Nicholls, Schier, Stough, & Box, 1999), others have failed to show the effect (e.g., Best & Avery, 1999; Cutting, 1974). For example, Shtyrov et al. (2000) examined MMNm in an MEG study and showed a RH dominance in processing auditory signals with slow acoustic transitions; nevertheless, a LH advantage in processing auditory signals with rapid acoustic transitions was only observed in speech stimuli but not in non-speech sounds with similarly rapid acoustic transitions. Thus, there is a controversy over whether the LH specialisation for speech processing is due to a general auditory mechanism or a linguistic specific mechanism. An alternative view is the LH specialisation may be experience-dependent. For instance, Best and Avery (1999) found that native Zulu (a southern African language) speakers showed a LH advantage in processing click consonants (which are phonologically contrastive sounds akin to stop consonants) regardless of whether they were presented in isolation or in syllables. In contrast, the LH advantage was not observed in the English speakers, who perceived the clicks as non-speech noises instead. In addition, Gandour et al. (2004) showed that experience with lexical tones in tonal languages could modulate the lateralisation of speech prosody perception. We elaborate on this point below.

Cantonese and Mandarin tone systems

Human languages can be broadly classified into two categories, namely tonal and non-tonal languages. In tonal languages, a sequence of phonemes with a tone constitutes a syllable in the pronunciation, and tonal differences (or perceived pitch changes) are used to provide contrasts in lexical meaning in addition to differences in the phonemic structure. Thus, tones in tonal languages are also called lexical tones. In contrast, pronunciations in non-tonal languages concern only the phonemic structure, and tone information does not discriminate word meanings.

Cantonese is a major dialect of Chinese spoken by over 64 million people in South China, Hong Kong, Macau, and many other overseas Chinese communities (Grimes, 1992). It is a tonal language with a complex tone system. There are nine tones in Cantonese, six of which are *non-entering tones* (with a longer duration), and three are *entering tones* (with a shorter duration). Within each category, the tones can be further differentiated in terms of their pitch level and pitch contours (Gandour, 1978). Together these subcategories make up the nine tones (pitch level followed by pitch contour: upper level, upper rising, upper going, lower level, lower rising, lower going, upper entering, middle entering, and lower entering; see Figure 1; Lee, Meng, Lau, Lo, & Ching, 1999). In contrast, Mandarin has a simpler tone system. There are only four tones: high level, mid-rising, low-falling-rising, and high falling (see Figure 2; Cao & Sarmah, 2007).

Previous findings concerning hemispheric asymmetries in processing lexical tones among different language users have been inconsistent. For example, Van Lancker, and Fromkin (1973) compared performance of native tonal language speakers, Thai speakers, with non-tonal language English speakers on dichotic perception of (1) Thai tone-words: words differing only in tones, (2) Thai consonant-words: words that differ

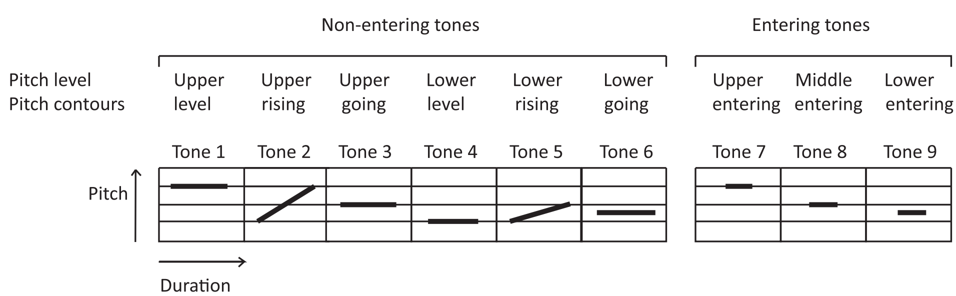

Figure 1. The Cantonese nine-tone system.

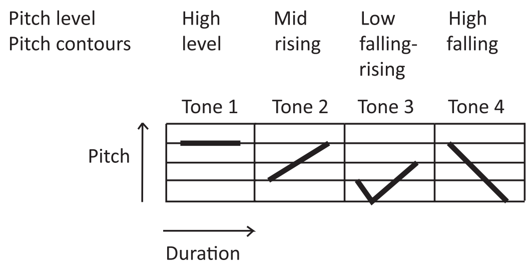

Figure 2. The Mandarin four-tone system.

in initial consonants but have the same tones, and (3) hums of Thai tones, which contain only pitch change information. They found Thai speakers showed a REA, in terms of perception accuracy, in processing tone-words and consonant-words but not hums, whereas English speakers showed a REA in consonant-words but no ear advantage in tone-words or hums. Assuming that a stimulus was only linguistically processed when a REA/LH was observed, the researchers concluded that hums were not linguistically processed.

Baudoin-Chial (1986) adopted a similar approach and attempted to generalise findings in Van Lancker and Fromkin (1973) to another tonal language, the Mandarin Chinese. However, they failed to observe laterality effects among Mandarin Chinese speakers in any of the three conditions; in contrast, French speakers showed REA for consonant words and LEA for tone-words, but no laterality effect for hums. Thus, they speculated that the effect might be language-dependent (see also Gandour et al., 2000).

In another study, Moen (1993) studied tonal language users, Norwegians, who were instructed to point to drawings representing the Norwegian tone-words they heard from dichotic listening tests. The Norwegian speakers reported stimuli presented to the right ear more frequently than that to the left ear. This finding supported the claim that tone information, as an integral part in the word pronunciation in tonal languages, was preferentially processed in the LH of tonal language users.

Wang, Jongman, and Sereno (2001) investigated dichotic perception of Mandarin tones by native Mandarin (tonal language) users and non-tonal language users, Americans, who were told to identify each tone of a tone pair (from either the same or different monosyllabic Mandarin words) they heard in each ear. The researchers reported a significant REA among native Mandarin users, but found no ear advantage among Americans. Thus, in contrast to some previous research findings (e.g., Baudoin-Chial, 1986), they argued that the LH lateralisation for native processing of tonal languages was language universal, rather than language dependent.

Differences in the experimental design, measures, and stimuli may explain inconsistencies in previous findings. In addition, previous research mostly used consonant-vowel syllables or monosyllabic words (e.g. Baudoin-Chial, 1986; Moen, 1993; Shankweiler & Studdert-Kennedy, 1967; Van Lancker & Fromkin, 1973; Wang et al., 2001), which only conveyed limited linguistic and prosodic information. Hence, in the present study, we use sentences instead of syllables or monosyllabic words in order to provide more linguistic and prosodic cues in a speech context. We aim to examine hemispheric asymmetry in processing low-pass filtered Cantonese speech and high-pass filtered Cantonese speech, in tonal (Cantonese and Mandarin) and non-tonal (English) language speakers. We recruit native Cantonese speakers and non-tonal language English speakers to examine whether the LH lateralisation for speech processing is due to an experience-independent general auditory processing mechanism. Since we are not able to tease apart the influence from a linguistic mechanism and an experience-dependent perceptual mechanism based only on Cantonese speakers' data, here we also recruit Mandarin speakers, who are tonal language speakers but have no knowledge of Cantonese, to examine whether the LH lateralisation for speech processing is because of an experience-independent linguistic mechanism. If hemispheric asymmetry in speech perception is due to an experience-independent general auditory processing mechanism, according to the DFF theory (Ivry & Robertson, 1998), we expect that all three groups of participants will show LH lateralisation for processing high-pass filtered Cantonese speech and RH lateralisation for processing low-pass filtered Cantonese speech. In contrast, if it is due to an experience-independent linguistic mechanism, since low-pass filtered speech carries considerable amount of lexical tone information, which is regarded as an inseparable part of pronunciation in Cantonese, we expect that Cantonese speakers will have a REA/LH lateralisation in processing either low- or high-pass filtered Cantonese speech, whereas Mandarin speakers will have a similar lateralisation pattern to English speakers that is governed by a general auditory processing mechanism since they do not understand Cantonese; alternatively, if it is language-experience-dependent, we expect that Mandarin speakers may have a similar lateralisation pattern to Cantonese speakers that differs from English speakers' due to the Mandarin speakers' tonal language experience.

METHODS

Participants

A total of thirty-nine adult students at the University of Hong Kong were recruited for the study; however, three of them were excluded from the analyses, because one English speaker participant was currently taking a Mandarin course, one Mandarin speaker participant failed to complete the entire experiment due to a computer failure, and one Mandarin participant had a much lower overall accuracy (35.7%) compared to the rest of the participants (the group mean was 64.5% and the standard deviation was 13.9%; thus, the Mandarin participant's accuracy was lower than the mean minus two standard deviations, and was identified as an outlier), which may be due to misunderstanding of the instructions. The thirty-six valid participants were categorised into Cantonese, Mandarin, and English groups, according to their first language and their knowledge of different tonal languages.

The Cantonese group was composed of twelve native Cantonese speakers (seven males, five females) with an average age of 22.4 ($SD = 0.39$). The Mandarin group was made up of 12 native Mandarin users (3 males, 9 females); they only stayed in Hong Kong for less than a year and had no knowledge of Cantonese[1]; their average age was 20.9 ($SD = 0.33$). Note that although Cantonese and Mandarin are both tonal languages, they have very different tones and pronunciations, and are also different in some aspects of grammar and syntax; thus, a Mandarin speaker typically is not able to

[1] All of the Mandarin participants grew up in non-Cantonese speaking areas of China and had never learned Cantonese. In addition, we confirmed with the Mandarin participants after the experiment that they did not understand any of the speech materials. Note also that the two official languages used in Hong Kong are English and Cantonese; in addition, Mandarin has started to become prevalent since the 1997 handover due to an increasing number of immigrants from Mainland China and an increase in Mandarin language education. Thus, foreigners who know either English or Mandarin do not need to learn to use Cantonese in daily life.

understand any Cantonese. The remaining 12 participants (4 males, 8 females) constituted the English group, who were native English speakers (i.e., non-tonal language users) and had no prior knowledge of any tonal languages. They also only stayed in Hong Kong for less than a year. They had an average age of 24.1 ($SD = 0.51$). The language of instruction at University of Hong Kong is English.

None of the participants had any known history of speech and hearing impairments, and they were all classified as right-handed according to Edinburgh Handedness Inventory (Oldfield, 1971). All the participants gave informed written consent and received some honorarium for their participation. The research was approved by the ethics review board of the University of Hong Kong.

Stimuli

The materials contained 48 speech stimuli of commonly-used Cantonese sentences, ranged from 3 to 11 characters long. They were adopted from a CD recording of an elementary Cantonese self-learning reference guide by Kwan (2004); the speech stimuli were produced by a female native speaker of Cantonese.[2] A dichotic listening design was used; in each trial two different stimuli were played to the two ears simultaneously. The stimulus pairs for the dichotic listening design were selected by matching sentence duration. In total there were 24 stimulus pairs, and each stimulus was presented only once to the participants. The volume of the speech was adjusted and standardised with an audio-editing software, *Goldwave Portable* Version 5.55.

Following the DFF theory (Ivry & Robertson, 1998), we assumed that the task relevant frequency range (i.e., the first stage of the DFF) for human auditory processing tasks was the human audible range of frequencies, and conducted high- and low-pass filtering within this range accordingly (i.e., the second stage of the DFF). The human audible range of frequencies lies approximately between 20 and 20,000 Hz (e.g., Cutnell & Johnson, 1998). This hearing range of frequencies can be divided into 10 standard octave bands (An octave is an interval between one musical pitch to another with doubled frequency): 31, 63, 125, 250, 500, 1,000, 2,000, 4,000, 8,000, and 16,000 Hz. To prepare low-pass filtered speech, frequencies above an upper cut-off value 250 Hz (fourth octave) in the original speech were attenuated, whereas for high-pass filtered speech, frequencies below a lower cut-off 1,000 Hz (sixth octave) were attenuated, using second-order cascade filters provided in Goldwave version 5.55 with the parameter "steepness" set to 5 (The value specifies how sharply the filter cuts off frequencies outside the cut-off value; the larger the value is, the sharper the filter is); the resulting filter had a smooth transition rather than a sharp cut-off (consistent with the DFF implementation in Ivry & Robertson, 1998). Fourth and sixth octaves were adopted instead of the middle fifth octave (about 510 Hz), as in Blumstein and Cooper (1974), in order to increase the contrast between the two filtered speech.[3]

[2] All the stimuli were from the same female speaker. We used ProsodyPro, a Praat script for prosody analysis developed by Xu (2005–2011), to estimate the fundamental frequency (F0) of each sentence in our stimuli. The results showed that the average F0 of the sentences was 248.28 (ranging from 199.98Hz to 297.67Hz).

[3] We chose our cut-off frequencies based on the DFF theory instead of F0 characteristics of the speech stimuli because we aimed to examine whether the participants' behaviour was consistent with the DFF theory, which applies to auditory stimuli in general but not just to speech signals. Also, although the low-pass cut-off value 250 Hz was close to the estimated F0 of the sentences, our low-pass filter had a smooth cut-off transition from 200 to 450 Hz rather than a sharp cut-off, and thus it did not completely filter out F0; the low-pass filtered sentences sounded like human humming sounds and preserved intonation information.

The high-pass filtered stimuli preserved most of the content of the speech, whereas the low-pass filtered stimuli preserved intonation of the sentences, in resemblance to humming speech. Among the 24 stimulus pairs, 12 pairs were randomly selected to be presented in the low frequency condition, and the other 12 pairs were presented in the high frequency condition. There was no significant difference in mean duration between low- and high-pass filtered stimuli.[4,5]

Design

The design consisted of one between-subject variable: language group (Cantonese vs. Mandarin vs. English), and two within-subject variables: frequency (high vs. low) and ear (left vs. right). The dependent variables were *Ear Perception Accuracy* (defined by proportion of correct responses made in judging the stimulus from one ear)[6] and *Ear Bias* (defined by choice preference between the left and right ears).

During the experiment, in each trial a pair of Cantonese speech stimuli was presented to the participants' left and right ear, respectively, using the dichotic listening technique as the target stimulus. After the target stimulus presentation, participants were given four sentence choices and asked to judge which sentence choice best matched the preceding target stimulus they heard. Among the four available choices, two were possible correct options (left and right ear targets, respectively), and the other two were altered sentences, with one altered from the left ear target and the other altered from the right ear target, respectively. The presentation order of the four sentence choices was randomised. To create altered speech as options for each trial, pronunciations (including tones) of some of the characters in the target sentences were slightly changed, such that the resulting sentences would sound grammatically correct but meaningless. On average 38.5% of characters were changed in an altered sentence; the choice of characters for the pronunciation change was random and evenly distributed throughout a sentence.

During the experiment, participants were not informed about the dichotic listening design. Nevertheless, it was very difficult for participants to follow both sentences played in the two ears at the same time. Thus, through this choice design, we were able to measure both ear perception accuracy (i.e., proportion of correct responses made in judging the stimulus from one ear) and ear bias (i.e., choice preference between the left and right ears). We measured right ear perception accuracy as the number of trials in which the right ear target was selected divided by the number of trials in which either the right ear target or the altered speech that resembled the right ear target was

[4]All of the Mandarin participants reported that neither the high frequency nor the low frequency Cantonese sentences sounded intelligible to them after the experiment.

[5]To test the intelligibility of the high- and low-pass filtered speech to the Cantonese speakers, we asked three native Cantonese speakers (who did not participate in the experiment and were not familiar with the stimuli) to repeat the sentences one by one under a non-dichotic listening condition. Two of them got 100% accuracy in reporting the high-pass filtered sentences, whereas the third got one sentence partially incorrectly reported. However, none of them could accurately report any of the low-pass filtered sentences.

[6]Previous research has adopted different measures in assessing ear laterality effects under a dichotic listening condition. The choice of measures mainly depended on experimental settings and response requirements. In the current dichotic listening study, large-sized verbal materials, sentences, were used, which were acoustically heterogeneous; the waveforms played to the two ears showed little correspondence and did not tend to fuse (cf. Repp, 1977), and hence it was difficult for participants to report both since usually they could only attend to one of them. Thus, the laterality index used in some previous studies (e.g., in Blumstein & Cooper, 1974; Blumstein, Goodglass, & Tartter, 1975; Van Lancker & Fromkin, 1973; Wexler & Halwes, 1983), in which participants had to report stimuli presented to both ears (Repp, 1977), was not applicable here.

selected (the same applied to the calculation of left ear perception accuracy); right ear bias was calculated as the proportion of trials the participant chose the right ear target or the one altered from the right ear target, regardless of correctness. The experiment program was constructed and run using E-prime 2.0.

Procedures

Participants were asked to fill in the handedness questionnaire before they proceeded to the listening test. Throughout the test, they wore a pair of headphones (model YO-MT505). There were four practice trials to make sure participants understood the test instructions and got familiar with the test environment.

In each trial, after a stimulus pair was presented to the two ears dichotically as the target stimulus, four binaurally presented sentences were delivered in succession, one separated from another by a 2-second interval. The sentences were numbered, and the participants had to judge which sentence best matched the preceding target stimulus by pressing keys "1," "2," "3," or "4" on the keyboard. After the participant made his/her answer, the next trial would start after the participant pressed a key to continue.

During the experiment, each stimulus pair was only played once, and the order of presentation was randomised. In order to eliminate any channel effect, and to make the overall difficulty level equalised for the two ears, the headphones were reversed in half of the participants for counterbalancing. The output volume of the two channels of the headphones was calibrated such that equal intensity was maintained in the two ears.

RESULTS

Ear perception accuracy

The mean ear perception accuracies in all of the three language groups were significantly above the chance level (50%) [Cantonese group: 75.0%, $t(11) = 7.605$, $p < .001$; Mandarin group: 58.7%, $p < .05$; English group: 59.7, $p < .05$]. Repeated measures ANOVA was used to analyse the ear perception accuracy data. There were two within-subject variables: frequency condition (high vs. low), ear (left vs. right), and a between-subject variable: language group (Cantonese, Mandarin, or English). An overall comparison between the three language groups showed main effects of language group [$F(2, 33) = 6.857$, $MSE = 0.058$, $p < .01$], frequency condition [$F(1, 33) = 7.775$, $MSE = 0.054$, $p < .01$], and ear [$F(1, 33) = 7.031$, $MSE = 0.058$, $p < .05$]. There were also a significant interaction between language group and frequency condition [$F(2, 33) = 5.116$, $MSE = 0.054$, $p < .05$], a significant interaction between language group and ear [$F(2, 33) = 4.070$, $MSE = 0.058$, $p < .05$], and a tendency of a three-way interaction between language group, frequency, and ear [$F(2, 33) = 2.786$, $MSE = 0.116$, $p = .076$]. In order to examine our hypotheses regarding how tonal language experience modulates hemispheric asymmetry in auditory perception, and to better understand the interactions between these variables, we conducted pair comparisons between the three participant groups: the comparison between English and Mandarin speakers allowed us to examine the tonal-language-experience-dependent modulation on the asymmetry effect at a pre-linguistic/basic processing level, since neither group understood Cantonese speech; the comparison between Mandarin and Cantonese speakers and between English and Cantonese speakers allowed us to examine the experience-independent linguistic mechanism modulation on the asymmetry effect. The analyses are as follows.

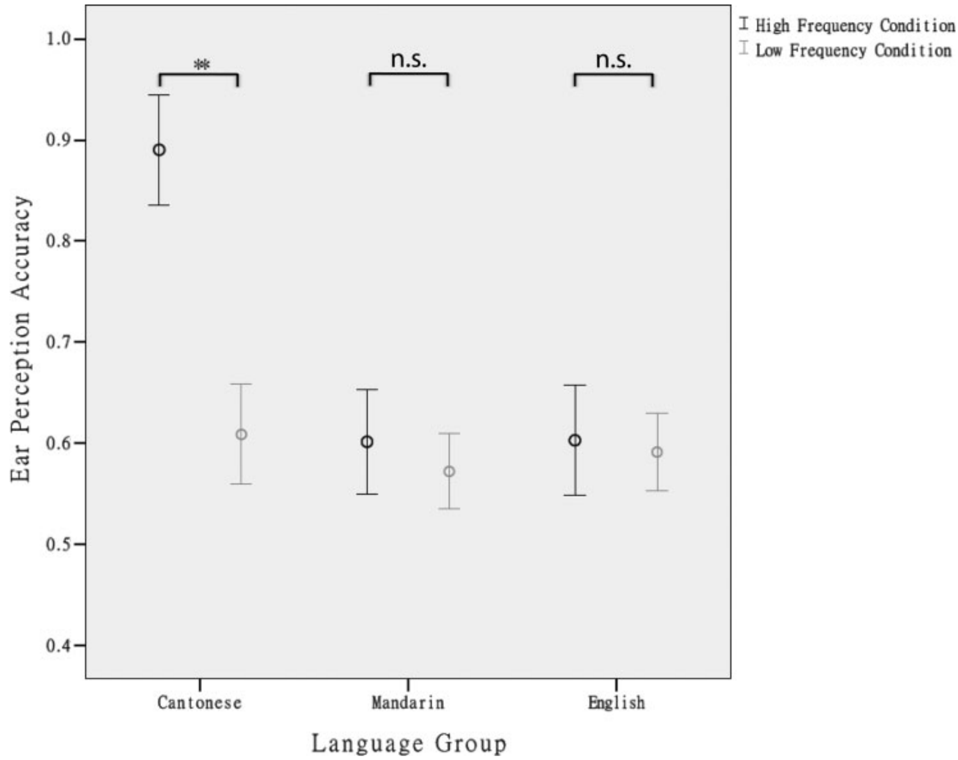

Figure 3. Ear perception accuracy of Cantonese, Mandarin and English participants in the high and low frequency conditions (**$p < .01$). Accuracy values shown here are calculated by collapsing across the two ears (averaging the accuracy values of the two ears). Error bars show standard errors.

A comparison between the Cantonese and English groups revealed main effects of language group [$F(1, 22) = 9.885$, $MSE = 0.056$, $p < .01$] and frequency condition [$F(1, 22) = 8.346$, $MSE = 0.062$, $p < .01$]. There was an interaction effect between language group and frequency condition [$F(1, 22) = 7.077$, $MSE = 0.062$, $p < .05$; Figure 3]: Cantonese participants had better accuracy in the high frequency condition than the low frequency condition [$F(1, 11) = 12.230$, $MSE = 0.078$, $p < .01$]; this effect was not significant in the English group [$F(1, 11) = .035$, n.s.]. In addition, there was a three-way interaction between language group, frequency condition, and ear [$F(1, 22) = 7.201$, $MSE = 0.030$, $p < .05$]. To examine this three-way interaction further, we analysed the data in the two groups separately. The results showed that in the English group, there was a significant frequency by ear interaction [$F(1, 11) = 5.705$, $MSE = 0.037$, $p < .05$]; consistent with the DFF theory, the right ear (LH) had higher accuracy in the high frequency condition, whereas the left ear (RH) had higher accuracy in the low frequency condition (Figure 4c). In contrast, this interaction between frequency and ear was not significant in the Cantonese group [$F(1, 11) = 1.686$, n.s.; Figure 4a]. As shown in Figure 4a, the Cantonese group had similar accuracy in the left and right ears in both high and low frequency conditions. This result demonstrated a modulation effect of either tonal language experience or linguistic mechanism, or both, on hemispheric asymmetry in auditory perception.

A comparison between Cantonese and Mandarin groups revealed main effects of language group [$F(1, 22) = 11.228$, $MSE = 0.057$, $p < .01$], frequency condition [$F(1, 22) = 10.111$, $MSE = 0.057$, $p < .01$], and ear [$F(1, 22) = 11.816$, $MSE = 0.052$, $p < .01$]. In addition, there were interaction effects between language group and frequency

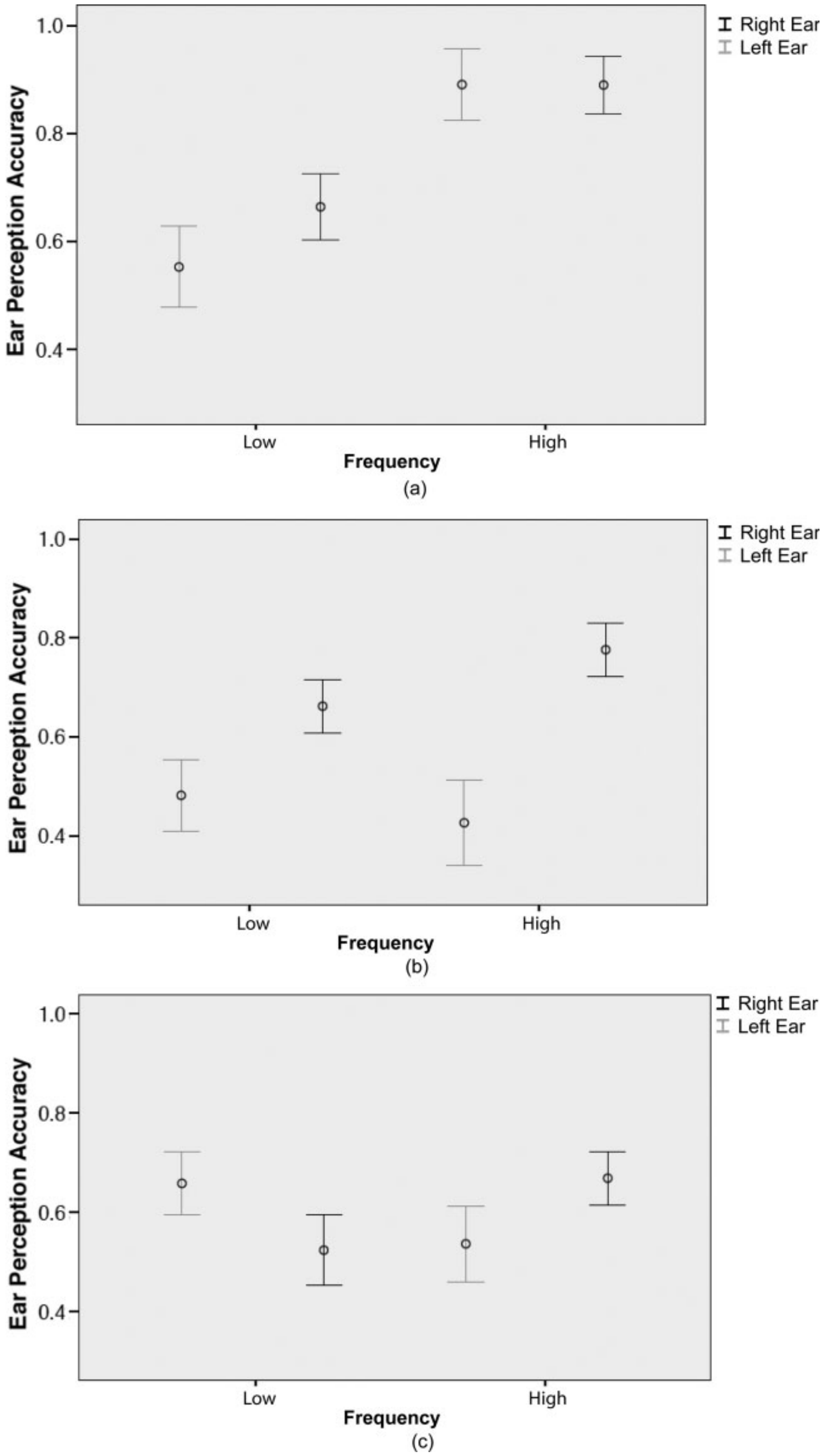

Figure 4. Ear perception accuracy of (a) Cantonese, (b) Mandarin, and (c) English participants in different ear and frequency conditions. The interaction between ear and frequency conditions was significant in the English group, consistent with the DFF theory; in contrast, this interaction was not significant in the other two groups who had tonal language experience. Error bars show standard errors.

condition [$F(1, 22) = 6.658$, $MSE = 0.057$, $p < .05$] and between language group and ear [$F(1, 22) = 5.065$, $MSE = 0.052$, $p < .05$]. As shown in Figure 4a (see also Figure 3), there was a significant frequency effect in the Cantonese group: a higher ear perception accuracy in the high frequency condition compared with the low frequency condition [$F(1, 11) = 12.230$, $MSE = 0.078$, $p < .01$]; this frequency effect was not significant in the Mandarin group (Figure 4b). Also, Mandarin participants had higher accuracy in the right ear compared with the left ear [$F(1, 11) = 14.701$, $MSE = 0.057$, $p < .01$], whereas Cantonese participants did not have this effect; they had high accuracy in both left and right ears (Figure 5). These effects suggested the modulation of linguistic mechanism on the hemispheric asymmetry: although both groups were tonal language speakers, only Cantonese speakers understood the meaning of the speech stimuli.

A comparison between the Mandarin and the English groups showed a main effect of ear [$F(1, 22) = 6.581$, $MSE = 0.064$, $p < .05$]. There was an interaction between ear and language group [$F(1, 22) = 6.690$, $MSE = 0.064$, $p < .05$; Figure 5]: Mandarin participants had higher right ear accuracy than the left ear [$F(1, 11) = 14.701$, $MSE = 0.057$, $p < .01$], whereas the English group did not have this effect. In addition, consistent with the DFF theory, there was an interaction between ear and frequency condition [$F(1, 22) = 5.554$, $MSE = 0.051$, $p < .05$]. However, when we examined the data in the

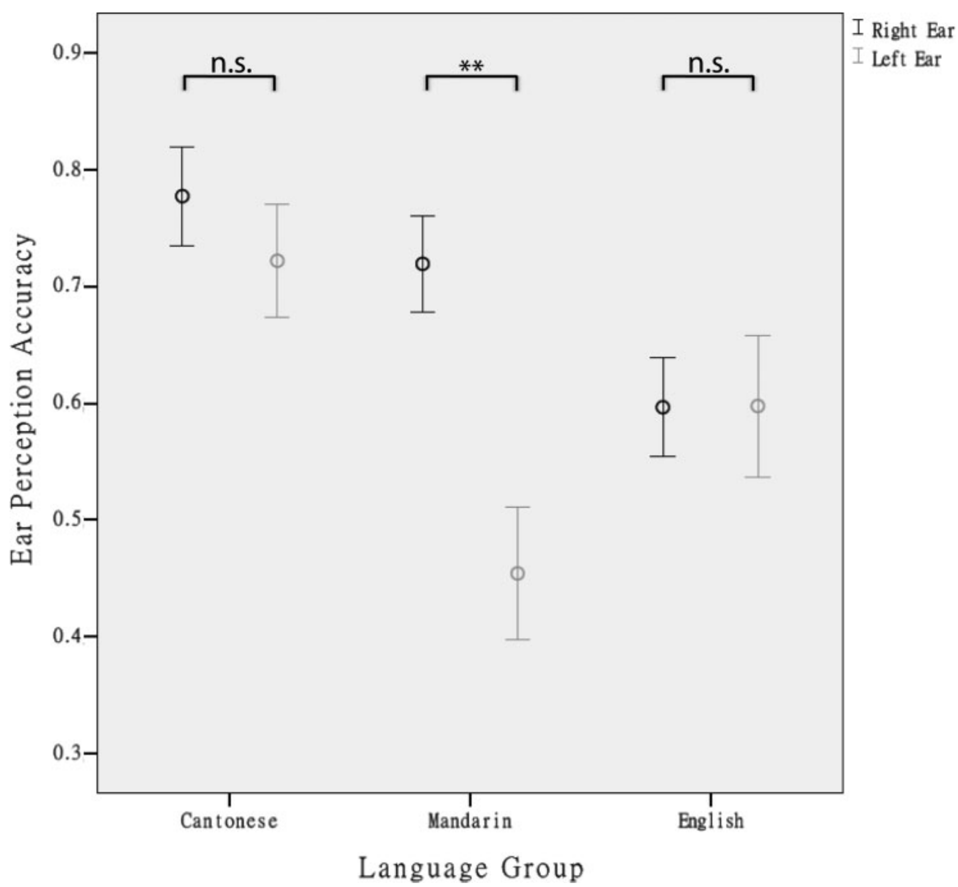

Figure 5. Right and left ear perception accuracy of Cantonese, Mandarin, and English participants (**$p < .01$). Accuracy values shown here are calculated by collapsing across the two frequency conditions (averaging the accuracy values in the two frequency conditions). Error bars show standard errors.

two groups separately, this interaction was significant only in the English group [$F(1, 11) = 5.705$, $MSE = 0.037$, $p < .05$; Figure 4c] but not in the Mandarin group [$F(1, 11) = 2.512$, n.s.; Figure 4b]. These effects suggested a language-experience-dependent modulation: while the English group's behaviour was consistent with the DFF theory, the Mandarin group's behaviour was not consistent with the DFF theory due to a generalisation effect from their tonal language (Mandarin) experience to the perception of Cantonese speech, although neither groups understood Cantonese speech.

Ear bias effect

Two-way ANOVA was used to analyse the right ear bias data, with frequency condition (high vs. low) being the within-subject variable, and language group (Cantonese, Mandarin, or English) being the between-subject variable. The results showed a tendency of a language group effect [$F(2, 33) = 2.866$, $MSE = 0.025$, $p = .071$]: the Cantonese group had the largest right ear bias whereas the English group had the smallest bias; this effect did not interact with frequency condition. Further analysis showed that the Cantonese group demonstrated significant right ear bias in both high [One sample t-test against the chance level 0.5, $t(11) = 3.708$, $p < .01$] and low [$t(11) = 3.045$, $p < .05$] frequency conditions; there was a tendency of right ear bias in the Mandarin group when we collapsed the data in the two frequency conditions [$t(11) = 1.974$, $p = .074$], although the bias did not reach significance when we examined the two frequency conditions separately. In contrast, the English group did not have a significant bias overall or in either condition (Figure 6).

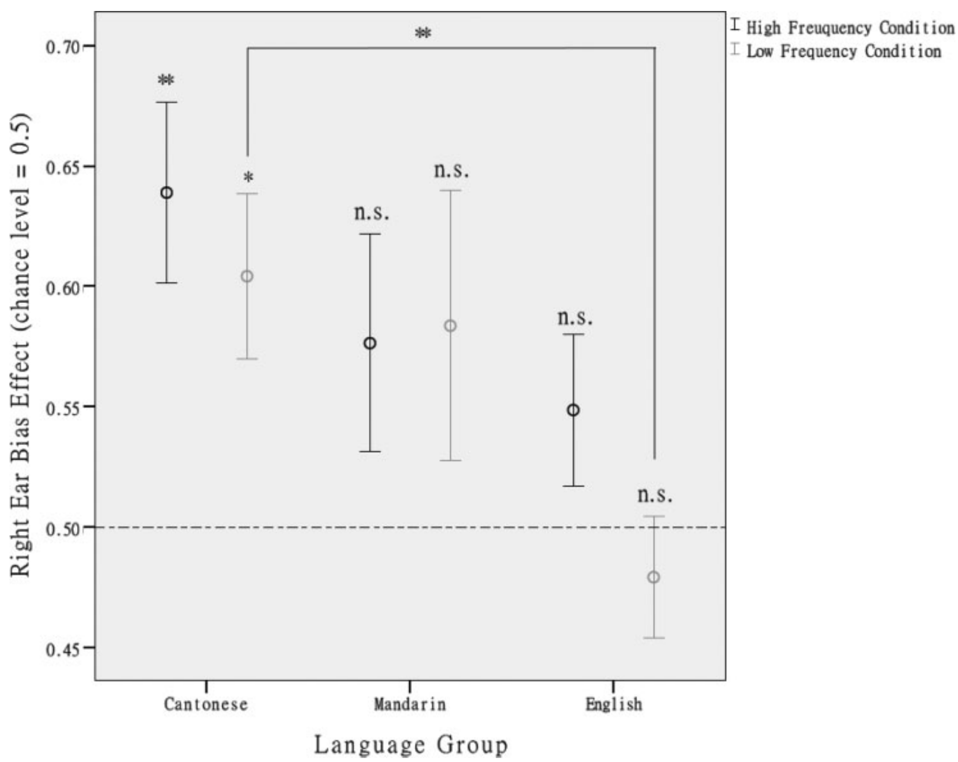

Figure 6. Right ear bias effect of Cantonese, Mandarin, and English participants in the high frequency conditions vs. low frequency conditions (the dash line indicates the 0.5 chance level; in comparison with the chance level: $*p < .05$, $**p < .01$). Error bars show standard errors.

We further compared ear bias between different pairs of language groups. There was a within-subject variable: frequency condition (high vs. low), and a between-subject variable: language group (Cantonese vs. Mandarin, Cantonese vs. English, or Mandarin vs. English). A comparison between the Cantonese and English groups revealed a main effect of language group [$F(1, 22) = 8.039$, $MSE = 0.017$, $p = .01$]: The Cantonese group had larger right ear bias compared with the English group; this effect did not interact with frequency condition. This result suggested that the right ear bias effect in the Cantonese group was due to their experience with Cantonese language. In addition, there was a tendency of a frequency effect [$F(1, 22) = 4.007$, $MSE = 0.008$, $p = .056$]: the right ear bias was stronger in the high frequency condition compared with the low frequency condition. Further analysis showed that the Cantonese group had significantly larger right ear bias than the English group in the low frequency condition [$t(22) = 2.934$, $p < .01$: Figure 6], but not in the high frequency condition [although there was an insignificant tendency: $t(22) = 1.844$, $p = .079$]. In addition, there was no significant difference in right ear bias between the low and high frequency conditions in the Cantonese group [$t(11) = 1.000$, n.s.], whereas in the English group there was a tendency of larger right ear bias in the high frequency condition than the low frequency condition [$t(11) = 1.820$, $p = .096$; Figure 6], consistent with the DFF theory.

The comparison between Cantonese and Mandarin participants showed neither main effects of frequency condition, language group, nor interaction effect between frequency condition and language group. This result suggested that although Mandarin participants did not understand Cantonese speech,[7] they had a similar ear bias effect to Cantonese participants because of their tonal language background; there was an insignificant tendency in their right ear bias effect.

The comparison between the Mandarin and English groups also revealed no significant main effects of frequency condition, language group, nor interaction effect between frequency condition and language group. Neither of the groups showed a significant bias in either the high or low frequency condition (Figure 6).

In summary, the ear bias data showed that the Cantonese group had larger right ear bias than the English group in the perception of Cantonese speech, especially in the low frequency condition, suggesting modulation effects of either tonal language experience or linguistic mechanism, or both. In contrast, although the Mandarin group did not understand Cantonese speech, they had a similar (an insignificant tendency) ear bias effect to the Cantonese group, suggesting an influence from their tonal language experience.

DISCUSSION

In the current study, we investigated the mechanism underlying the LH specialisation in speech processing by examining how tonal language experience modulates hemispheric asymmetry in auditory perception: we examined tonal language (Cantonese and Mandarin) speakers' and non-tonal language (English) speakers' behaviour in the perception of high-pass and low-pass filtered Cantonese speech through a dichotic listening design. According to the DFF theory (Ivry & Robertson, 1998), the LH has a bias towards high frequency information whereas the RH biases information towards the low frequency range (cf. Poeppel, 2003; Zatorre et al., 2002).

[7] See footnote (4).

Thus, if the LH specialisation for speech processing is due to an experience-independent general auditory processing mechanism, all three groups of participants would have a LH/REA for high-pass filtered stimuli and a RH/LEA for low-pass filtered stimuli. In contrast, if the LH lateralisation is due to an experience-independent linguistic mechanism, Cantonese speakers would have a LH/REA in processing both high- and low-pass filtered Cantonese speech, whereas the other two groups would not. If the LH lateralisation is language-experience-dependent, Mandarin speakers may have similar behaviour to Cantonese speakers that differed from English speakers' because of their tonal language experience.

Our data showed that, in the ear perception accuracy data, the English group demonstrated a significant interaction between hemisphere and frequency condition: a higher LH/right ear perception accuracy in perceiving high-pass filtered speech, and a higher RH/left ear perception accuracy in perceiving low-pass filtered speech. This differential hemispheric processing superiority observed is consistent with the DFF theory (Ivry & Robertson, 1998; see also Sergent, 1982): the RH and LH are more advantageous in processing low- and high-pass filtered information, respectively.

Compared with the English group, the Cantonese participants had higher perception accuracy in both ears (Figure 5). In addition, in contrast to the English group, the Cantonese group had similar accuracy in the left and right ears in both high and low frequency conditions (Figure 5). While the data in Figure 4a show no hemispheric lateralisation in processing either high- or low-passed filtered speech in the Cantonese speakers (cf. Baudoin-Chial, 1986), a comparison with the English group suggests that their Cantonese language experience eliminated the typical hemispheric asymmetry in perceiving high- and low-pass filtered auditory stimuli, which was observed in the novices, the English group. A possible explanation for this effect is that the Cantonese group's intensive processing of Cantonese speech on a day-to-day basis may have led to automaticity of LH language processing pathways (or automatic activation of memory traces for lexical items in the LH; see, e.g., Sittiprapaporn et al., 2003); regardless of whether the stimulus was low- or high-pass filtered speech, and whether the input was originally from the left or the right ear, their LH may always preferentially processed the Cantonese-language-related auditory information.[8] Thus, this effect may have demonstrated the modulation of the linguistic mechanism.

In addition, the Cantonese group showed significantly higher ear perception accuracy in the high frequency condition, as compared to the low frequency condition; this effect was not observed in either the Mandarin or English group. Since the matching task required short-term auditory memory, this advantage in matching high-pass filtered sentences in the Cantonese group may be because Cantonese participants could make use of the semantic information in the high-pass filtered speech to help them remember the sentences, since high-pass filtered speech was more intelligible to them than low-pass filtered speech.[9] In contrast, the Mandarin and English groups did not show this effect because they did not understand Cantonese (Figure 3).

As for the Mandarin group, they had higher right ear (LH) accuracy than the left ear (RH) in both the high and low frequency conditions (Figure 4b). The effect of higher right ear (LH) accuracy in the low frequency condition was not consistent with

[8] Kimura (1961) found that 93% of right-handers have their language processing lateralised to their LH, [0]whereas Branch, Milner, and Rasmussen (1964) estimated that 90% of right-handers have speech functions lateralised to the LH.

[9] See footnote (5).

the DFF theory. This phenomenon highlighted the modulation effect of tonal language experience: although the Mandarin participants did not have experience with Cantonese speech, they were able to generalise their tonal language (Mandarin) experience to processing Cantonese speech, and thus had better accuracy in the right ear (LH) in the perception of low-pass filtered Cantonese speech. This result was consistent with the language-experience-dependent hypothesis. Nevertheless, in contrast to the Cantonese group, who had similar perception accuracy in both the right and left ears, the Mandarin participants had a higher right ear perception accuracy compared to the left ear (Figure 5). This effect may be because the Mandarin participants did not have experience with Cantonese speech, and thus the language processing pathways for Cantonese auditory input, in particular from the left ear/RH to the LH, was not as efficient as those of the Cantonese participants; or they did not have memory traces of the lexical items in Cantonese in the LH to facilitate the processing (e.g., Sittiprapaporn et al., 2003). Consequently when Mandarin speakers selectively attended to left ear speech stimuli, the RH might still be dominant in processing the information, even though it was not specialised for auditory language perception. In other words, this behavioural difference between Mandarin and Cantonese participants may be because of Mandarin participants' unfamiliarity with Cantonese tones, or modulation from a linguistic mechanism in the Cantonese group. Thus, although the result was consistent with the language-experience-dependent hypothesis, it could not completely rule out the possibility of influence from a linguistic mechanism.

In addition, we also showed that in the ear bias data, the Cantonese group demonstrated a significant right ear bias effect regardless of the frequency condition: they had a preference to respond to the right ear targets in either the high-pass filtered or low-pass filtered condition. In contrast, the English participants had a significantly lower right ear bias than the Cantonese group, especially in the perception of low-pass filtered Cantonese speech, and also did not show a significant bias effect against the chance level (Figure 6). This effect can be accounted for by the novelty of the stimuli appeared to the English group and their lack of tonal language experience, and thus they showed no signs of bias (Note, however, that there was a tendency of larger right ear bias in the high frequency condition than the low frequency condition, consistent with the DFF theory). Using the English group as the control condition, the significantly higher right ear bias in the Cantonese group (Figure 6) suggests that either the linguistic mechanism and or tonal language experience of the Cantonese speakers modulates the typical hemispheric asymmetry in auditory perception posited by the DFF theory, resulting in a preference over using the LH to process both high-pass and low-pass filtered Cantonese speech. However, the data of the Cantonese group alone could not adequately differentiate between the two possibilities. When we examined the behaviour of the Mandarin group, who did not understand Cantonese speech, the right ear bias effect in the Mandarin group showed a similar trend to and did not significantly differ from the Cantonese group, although the bias was only marginally different from the chance level (Figure 6). This effect suggests that the familiarity with a tonal language other than Cantonese may be sufficient to show the right ear bias effect. This result thus is again consistent with the language-experience-dependent hypothesis on LH lateralisation of speech processing. The large variance observed in the Mandarin group's ear bias data might have reflected individual differences in the degree to which the Mandarin speakers were exposed to Cantonese during the months they spent in Hong Kong and/or generalisation ability.

Thus, the current study suggests that experience with lexical tones can modulate auditory processing of tonal language users at a pre-linguistic level. The Cantonese group tended to respond to low-pass filtered stimuli presented to the right ear (LH) more frequently as compared with the left ear (RH); this result was consistent with Moen's study (1993), who also found that tonal language users, Norwegians, responded to tone-words presented to the right ear more frequently than those to the left ear. Although the Mandarin group did not understand Cantonese speech, similar to Cantonese speakers, they had a tendency of right ear bias in the perception of Cantonese speech. In contrast, the English group, who had no tonal language experience, did not have any ear bias. In addition, the present study showed that the Cantonese group did not demonstrate a typical RH advantage in processing low-pass filtered speech (i.e., the DFF theory, Ivry & Robertson, 1998) that was observed in the English group because of the Cantonese group's experience with lexical tones. Another tonal language group, the Mandarin group, also did not show this RH advantage in processing low-pass filtered speech, even though they did not have experience with Cantonese speech; they showed a LH advantage instead. This phenomenon demonstrated a generalisation effect across different tonal languages. These results were thus consistent with the hypothesis about a language-experience-dependent mechanism instead of an experience-independent linguistic mechanism or an experience-independent general auditory processing mechanism in the LH lateralisation of speech stimuli (see, e.g., Best & Avery, 1999). Note, however, that our current results did not completely rule out the possibility of modulation from a linguistic mechanism, since the Mandarin and Cantonese groups differed in processing low-pass filtered Cantonese speech in terms of ear perception accuracy. This phenomenon suggests that a linguistic mechanism may also influence the lateralisation in processing speech stimuli. Future work will use high- and low-pass filtered Mandarin speech as the materials and see if a pattern symmetric to the current findings can be obtained. In addition, high- and low-pass filtered non-linguistic auditory stimuli can be used to examine whether similar modulation effects of tonal language experience can also be obtained in tonal language speakers compared with non-tonal language speakers. Another possible future work is to examine whether bilinguals (or multilinguals) who can communicate in both tonal and non-tonal languages will generalise their experience with lexical tones to the processing of non-tonal language speech, and show a LH/REA in both high and low frequency conditions; these bilinguals may be more sensitive to tone/intonation differences in processing non-tonal language speech, and this may influence their listening comprehension.

The discrepant results between the current study and some previous studies that examined hemispheric asymmetry in lexical tone perception may be due to the use of stimuli at different language processing levels. For example, in a dichotic listening task with monosyllabic Mandarin tone words, Wang, Behne, Jongman, and Sereno (2004) showed that Mandarin speakers had a LH/REA in perception accuracy in identifying which tone they heard in each ear, whereas non-tonal language, English speakers did not have any ear advantage. In addition, they showed that speakers of a different tonal language, Norwegian, also did not have any ear advantage. This result suggested that the LH lateralisation of Mandarin tone processing did not generalise to speakers of a different tonal language (see also Sittiprapaporn, Chindaduangratn, & Kotchabhakdi, 2004). In contrast to their results, here we showed that in perceiving low-pass filtered Cantonese speech (as opposed to tones of monosyllabic words), similar to Cantonese speakers, Mandarin speakers demonstrated a stronger REA compared with English speakers. This effect may be because in the present study, instead of using monosyllabic words, we used sentences, which conveyed more linguistic and prosodic information with regard to the context of speech. Although in the present study, the low-pass filtered Cantonese speech was intelligible to Cantonese speakers,[10] it may still convey information about intonation and semantics in the sentences to some extent. Alternatively, the difference between our results and Wang et al.'s (2004) results may also be due to a higher similarity between Cantonese and Mandarin tones compared with that between Cantonese and Norwegian tones.

In summary, here we showed that in the perception of high- and low-pass filtered Cantonese speech, the non-tonal language English speakers' behaviour was well predicted by the DFF theory: a LH/REA in the perception of high-pass filtered stimuli and a RH/LEA in the perception of low-pass filtered stimuli. In contrast, the Cantonese speakers demonstrated a preference to report stimuli presented to the right ear and no ear difference in perception accuracy regardless of frequency conditions, suggesting a modulation effect from linguistic and tonal language experience due to the automaticity of LH language processing pathways. As for the Mandarin participants, although they had no experience with Cantonese speech, they were able to generalise their experience with lexical tones in Mandarin to the perception of Cantonese speech, thus had higher right ear perception accuracy than the left ear even in the low frequency condition. Thus, our results were consistent with the hypothesis that the relevant language experience, e.g., experience with lexical tone processing in a tonal language, is sufficient to change the typical functional hemispheric asymmetry in auditory perception at a pre-linguistic/basic auditory processing level. In other words, the LH specialisation in speech processing is likely to be due to a language-experience-dependent mechanism, instead of an experience-independent linguistic mechanism or an experience-independent general auditory processing mechanism.

Manuscript received 7 May 2011
Revised manuscript received 15 May 2012
First published online 28 September 2012

REFERENCES

Alho, K., Connolly, J. F., Cheour, M., Lehtokoski, A., Huotilainen, M., Virtanen, J., et al. (1998). Hemispheric lateralization in preattentive processing of speech sounds. *Neuroscience Letters*, *258*, 9–12.

Bartholomeus, B. (1974). Effects of task requirements on ear superiority for sung speech. *Cortex*, *10*, 215–223.

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

Beeman, M. J., & Chiarello, C. (1998). Complementary right- and left-hemisphere language comprehension. *Current Directions in Psychological Science*, *7*, 2–8.

Belin, P., Zilbovicius, M., Crozier, S., Thivard, L., Fontaine, A., Masure, M. C., et al. (1998). Lateralization of speech and auditory temporal processing. *Journal of Cognitive Neuroscience*, *10*(4), 536–540.

Best, C. T., & Avery, R. A. (1999). Left-hemisphere advantage for click consonants is determined by linguistic significance and experience. *Psychological Science*, *10*, 65–70.

Bever, T. G., & Chiarello, R. J. (1974). Cerebral dominance in musicians and nonmusicians. *Science*, *185*, 537–539.

Blumstein, S. E., & Cooper, W. E. (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.

Branch, C., Milner, B., & Rasmussen, T. (1964). Intracarotid sodium amytal for the lateralization of cerebral speech dominance. *Journal of Neurosurgery*, *21*, 399–405.

Broadbent, D. E. (1958). *Perception and communication*. New York: Pergamon Press.

[10] See footnote (5).

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

Brodal, A. (1981). *Neurological anatomy in relation to clinical medicine* (3rd ed). New York: Oxford University Press.

Brugge, J. F., & Merzenich, M. M. (1973). Response of neurons in auditory cortex of the macaque monkey to monaural and binaural stimulation. *Journal of Neurophysiology*, *36*, 1138–1158.

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

Cao, R., & Sarmah, P. (2007). A perception study on the third tone in Mandarin Chinese. *UTA Working Papers in Linguistics*, *2*, 50–66.

Celesia, G. G. (1976). Organization of auditory cortical areas in man. *Brain*, *99*, 403–414.

Chaney, R. B., & Webster, J. C. (1965). *Information in certain multidimensional acoustic signals* (p. 1330). San Diego, CA: U.S. Navy Electronics Laboratory Reports.

Cutnell, J. D., & Johnson, K. W. (1998). *Physics* (4th ed., p. 466.). New York: Wiley.

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

Gandour, J. (1978). The perception of tone. In V. A. Fromkin (Ed.), *Tone: A linguistic survey* (pp. 41–76). New York: Academic.

Gandour, J., Tong, Y., Wong, D., Talavage, T., Dzemidzic, M., Xu, Y., et al. (2004). Hemispheric roles in the perception of speech prosody. *Neuroimage*, *23*, 344–357.

Gandour, J., Wong, D., Hsieh, L., Weinzapfel, B., Van Lancker, D., & Hutchins, G. D. (2000). A crosslinguistic PET study of tone perception. *Journal of cognitive neuroscience*, *12*(1), 207–222.

Grimes, B. F. (1992). *Ethnologue: Languages of the world*. Dallas, TX: Summer Institute of Linguistics.

Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition*, *92*, 69–99.

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience*, *8*, 393–402.

Ivry, R., & Lebby, P. (1993). Hemispheric differences in auditory perception are similar those found in visual perception. *Psychological Science*, *4*, 41–45.

Ivry, R. B., & Robertson, L. C. (1998). *The two sides of perception*. Cambridge, MA: MIT Press.

Kelly, J. P. (1981). Hearing. In E. R. Kandel & J. H. Schwartz (Eds.), *Principles of neuroscience* (pp. 590–613). New York: Elsevier North Holland.

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*, 355–358.

Koyama, S., Gunji, A., Yabe, H., Oiwa, S., Akahane-Yamada, R., Kakigi, R., et al. (2000). Hemispheric lateralization in an analysis of speech sounds. Left hemisphere dominance replicated in Japanese subjects. *Cognitive Brain Research*, *10*(1-2), 119–124.

Kwan, L. Y. (2004). 跟我說廣東話：學習[廣東話]的最快捷徑. 三思堂文化 [Speak Cantonese with me The fastest way to learn Cantonese.]. Hong Kong.

Lauter, J. L., Herscovitch, P., Formby, C., & Raichle, M. E. (1985). Tonotopic organization in the human auditory cortex revealed by positron emission tomography. *Hearing Research*, *20*, 199–205.

Lee, T., Meng, H. M., Lau, W., Lo, W. K., & Ching, P. C. (1999). Microprosodic control in Cantonese text-to-speech synthesis. *Proceedings of the Sixth European Conference on Speech Communication and Technology*, *4*, 1855–1858.

Majkowski, J., Bochenek, Z., Bochenek, W., Knapik-Fijalkowska, D., & Kopec, J. (1971). Latency of averaged evoked potentials to contralateral and ipsilateral auditory stimulation in normal subjects. *Brain Research*, *25*, 416–419.

Makela, J. P., Ahonen, A., Hamalainen, M., Hari, R., Llmoniemi, R., Kajola, M., et al. (1993). Functional differences between auditory hemispheres revealed by whole-head neuromagnetic recordings. *Human Brain Mapping*, *1*, 48–56.

McKeever, W. F., Seitz, K. S., Krutsch, A. J., & Van Eys, P. L. (1995). On language laterality in normal dextrals and sinistrals: Results from the bilateral object naming latency task. *Neuropsychologia*, *33*, 1627–1635.

Meyer, V., & Yates, A. J. (1955). Intellectual changes following temporal lobectomy for psychomotor epilepsy. *Journal of Neurology, Neurosurgical and Psychiatry*, *18*, 44–52.

Milner, B. (1962). Some effects of temporal-lobe damage on auditory perception. *Canadian Journal of Psychology*, *15*, 156–165.

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

Nicholls, M. E., Schier, M., Stough, C. K., & Box, A. (1999). Psychophysical and electrophysiologic support for a left hemisphere temporal processing advantage. *Neuropsychiatry, Neuropsychology and Behavioral Neurology*, *12*, 11–16.

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

Phillips, D. P., & Irvine, D. R. F. (1981). Responses of single neurons in physiologically defined area A1 of cat cerebral cortex: Sensitivity of interaural intensity differences. *Hearing Research*, *4*, 299–307.

Poeppel, D. (2003). The analysis of speech in different temporal integration windows: Cerebral lateralization as asymmetric sampling in time. *Speech Communication*, *41*, 245–255.

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

Rosenzweig, M. R. (1951). Representations of the two ears in the auditory cortex. *American Journal of Physiology*, *167*, 147–158.

Schwartz, J., & Tallal, P. (1980). Rate of acoustic change may underlie hemispheric specialization for speech perception. *Science*, *207*, 1380–1381.

Scott, S. K., & Wise, R. J. S. (2004). The functional neuroanatomy of prelexical processing in speech perception. *Cognition*, *92*, 13–45.

Sergent, J. (1982). The cerebral balance of power: Confrontation or cooperation? *Journal of Experimental Psychology: Human Perception & Performance*, *8*, 253–272.

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.

Shipley-Brown, F., Dingwall, W. O., Berlin, C. I., Yeni-Komshian, G., & Gordon-Salant, S. (1988). Hemispheric processing of affective and linguistic intonation contours in normal subjects. *Brain & Language*, *33*, 16–26.

Shtyrov, Y., Kujala, T., Lyytinen, H., Kujala, J., Ilmoniemi, R. J., & Naatanen, R. (2000). Lateralization of speech processing in the brain as indicated by mismatch negativity and dichotic listening. *Brain & Cognition*, *43*, 392–398.

Sittiprapaporn, W., Chindaduangratn, C., & Kotchabhakdi, N. (2004). Brain electrical activity during the pre-attentive perception of speech sounds in tonal languages. *Songklanakarin Journal of Science and Technology*, *26*(4), 439–445.

Sittiprapaporn, W., Chindaduangratn, C., Tervaniemi, M., & Khotchabhakdi, N. (2003). Preattentive processing of lexical tone perception by the human brain as indexed by the mismatch negativity paradigm. *Annals New York Academy of Sciences*, *999*, 199–203.

Tallal, P., Miller, S., & Fitch, R. (1993). Neurobiological basis of speech: A case for the pre-eminence of temporal processing. *New York Academy of Sciences, Annals*, *682*, 27–47.

Tanguay, P., Taub, J., Doubleday, C., & Clarkson, D. (1977). An interhemispheric comparison of auditory evoked responses to consonant-vowel stimuli. *Neuropsychologia*, *15*, 123–131.

Vandenberghe, R., Nobre, A. C., & Price, C. J. (2002). The response of left temporal cortex to sentences. *Journal of Cognitive Neuroscience*, *14*, 550–560.

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

Wang, Y., Behne, D. M., Jongman, A., & Sereno, J. (2004). The role of linguistic experience in the hemispheric processing of lexical tone. *Applied Psycholinguistics*, *25*, 449–466.

Wang, Y., Jongman, A., & Sereno, J. (2001). Dichotic perception of Mandarin tones by Chinese and American listeners. *Brain and Language*, *78*, 332–348.

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

Xu, Y. (2005–2011). ProsodyPro.praat. Available from: http://www.phon.ucl.ac.uk/home/yi/ProsodyPro/.

Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: Music and speech. *Trends in Cognitive Sciences*, *6*, 37–46.

Zatorre, R. J., Evans, A. C., Meyer, E., & Gjedde, A. (1992). Lateralization of phonetic and pitch discrimination in speech processing. *Science*, *256*, 846–849.