NEUROBIOLOGY OF LANGUAGE

EDITED BY GREGORY HICKOK
AND STEVEN L. SMALL

NEUROBIOLOGY OF LANGUAGE

Edited by

GREGORY HICKOK
Department of Cognitive Sciences, University of California, Irvine, CA, USA

STEVEN L. SMALL
Department of Neurology, University of California, Irvine, CA, USA

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Academic Press is an imprint of Elsevier

Academic Press is an imprint of Elsevier
32 Jamestown Road, London NW1 7BY, UK
525 B Street, Suite 1800, San Diego, CA 92101-4495, USA
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK

Notices
Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

ISBN: 978-0-12-407794-2

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

For Information on all Academic Press publications
visit our website at http://store.elsevier.com/

Typeset by MPS Limited, Chennai, India
www.adi-mps.com

Printed and bound in USA

Publisher: Mica Haley
Acquisition Editor: Mica Haley
Editorial Project Manager: Kathy Padilla
Production Project Manager: Julia Haynes
Designer: Maria Inês Cruz

CHAPTER

87

Processing Tone Languages

Jackson T. Gandour and Ananthanarayan Krishnan

Department of Speech Language Hearing Sciences, Purdue University, West Lafayette, IN, USA

87.1 INTRODUCTION

Speech perception is important because it provides multiple windows along the auditory pathway into the cerebral cortex regarding how continuous, acoustic signals are transformed into representations on which computations are based at different levels of the brain. Pitch is one of the most important information-bearing components of speech. Tone languages offer advantages for investigating neural mechanisms underlying pitch at different levels of processing because of their phonemic status at the word level (Yip, 2002).

With respect to tonal processing in the brain, almost all experiments performed since 2000 have focused on speech perception or recognition using techniques of functional brain imaging (positron emission tomography [PET]; functional magnetic resonance imaging [fMRI]) and neurophysiology (electroencephalography [EEG]; magnetoencephalography [MEG]). This review focuses primarily on the articles published within that time frame that address four topics related to lexical tone. We evaluate the effects of the phonological status of pitch information on pitch processing in the brain. These experiments tease apart sublexical tonal processing from other cognitive processes involved in speech perception, especially lexical semantic processing. Experimental findings reveal patterns of cortical activation that may vary as a function of acoustic features associated with types of phonological units (i.e., tone versus subsyllabic and segmental units, e.g., consonants and vowels). Because pitch is multidimensional, it is important that we evaluate the effects of pitch features in addition to tonal categories. Those experiments using methods with high temporal resolution reveal the role played by pitch features at early, preattentive stages of processing. There are other suprasegmental units besides tone. The question arises whether common or distinct neural substrates underlie the processing of different suprasegmental units (e.g., intonation, rhythm). Experimental findings to date support the view that speech prosody perception involves a dynamic interplay among widely distributed regions not only within a single hemisphere but also between the two hemispheres, and even different levels of the brain (e.g., midbrain). Moreover, it becomes clear that the time window is pivotal for revealing how hemispheric laterality patterns may reflect higher-level and lower-level stages of auditory processing.

This review on tonal processing in the brain extends previous surveys that have covered dichotic listening (Gandour, 2007; Wang, Behne, Jongman, & Sereno, 2004; Wang, Jongman, & Sereno, 2001), tonal breakdown in production and perception after brain damage (Gandour, 1987, 1994, 1998a, 1998b; Wong, 2002), brain mapping of speech prosody (Gandour, 2006a, 2006b; Zatorre & Gandour, 2008), meta-analysis of lesion literature of linguistic and emotional prosody perception (Witteman, van Ijzendoorn, van de Velde, van Heuven, & Schiller, 2011), and communication disorders in speakers of tone languages (Wong, Perrachione, Gunasekera, & Chandrasekaran, 2009).

87.2 TONE LANGUAGES OF EAST AND SOUTHEAST ASIA

This review focuses exclusively on *lexical tone* languages, that is, those in which the pitch of a word can change the meaning of a word. They are distinguished from *pitch accent* languages (e.g., Japanese), which have a smaller number of contrasting tones, narrower word distribution, and co-occurring syllable structure constraints (Yip, 2002, pp. 1–4). Mandarin Chinese (Beijing), hereafter referred to as Mandarin, has four contrastive tones: *ma*[1] "mother," *ma*[2] "hemp," *ma*[3] "horse," and *ma*[4] "scold." Tones 1 to 4 are high-level (M1), high-rising (M2),

Neurobiology of Language. DOI: http://dx.doi.org/10.1016/B978-0-12-407794-2.00087-0

low-falling−rising (M3), and high-falling (M4) (Xu, 1997). Cantonese (Hong Kong) has six contrastive tones: *ji*[1] "cure," *ji*[2] "chair," *ji*[3] "opinion," *ji*[4] "son," *ji*[5] "ear," and *ji*[6] "two." Tones 1 to 6 are high-level (C1), high-rising (C2), mid-level (C3), low-falling (C4), low-rising (C5), and low-level (C6) (Zee, 1999). Thai (Bangkok) has five contrastive tones: $khaa^M$ "stuck," $khaa^L$ "galangal," $khaa^F$ "kill," $khaa^H$ "trade," and $khaa^R$ "leg". Tones 1 to 5 are mid-level (T1), low-falling (T2), high-falling (T3), high-rising (T4), and low-rising (T5) (Tingsabadh & Abramson, 1999). Voice fundamental frequency (f_0) contours provide the dominant cue for tone recognition (Gandour, 1994).

87.3 LEXICAL VERSUS SUBLEXICAL UNITS

With technological advances in functional brain imaging and auditory neurophysiology at the turn of the century, the aim of the research agenda was to establish that the processing of pitch information in the brain could vary depending on its functional status (linguistic versus nonlinguistic). At that time, it was already well-known that nonlinguistic pitch perception was mediated by neural mechanisms in the right hemisphere (RH) (Zatorre, Belin, & Penhune, 2002, review).

Almost all functional imaging studies of lexical tones have been performed on Thai and Mandarin. Subjects were required to make active judgments (same−different, word recognition) involving later stages of cognitive processing (working memory, decision-making). In discrimination judgments of Thai tones embedded in real words, Thai natives activated the left inferior frontal gyrus (IFG), but Mandarin-speaking Chinese and English did not (1: Gandour et al., 2000; Gandour, Wong, & Hutchins, 1998).[1] This leftward asymmetry in the Thai group is not restricted to a phonemic contrast in tone. Vowel length (/bat^{low}/ "card," /$baat^{low}$/ "monetary unit") is phonemic in Thai. When asked to discriminate pitch and timing patterns in Thai pseudowords and nonlinguistic hums (4: Gandour et al., 2002), Thai natives, but not Chinese, similarly activated the left IFG. Chinese natives, however, activated the left IFG when presented with Mandarin tones (3: Klein, Zatorre, Milner, & Zhao, 2001); in contrast, homologous regions in the RH were activated by English (2: Hsieh, Gandour, Wong, & Hutchins, 2001). To isolate processing of lexical tone, Chinese and English listeners were presented with Mandarin tones embedded in actual Mandarin words and in English pseudowords (5: Wong, Parsons, Martinez, & Diehl, 2004). When Chinese listeners were asked to discriminate Mandarin tones embedded in Mandarin words, the left anterior insula was the most active; when embedded in English pseudowords, the right anterior insula was the most active. English listeners activated the right insula and IFG regardless of whether the pitch patterns were embedded in Mandarin or English words. This finding is strengthened by an experiment in which English-speaking adults were trained to use Mandarin tones (M1, M2, M4) to signal lexical meaning on English pseudosyllables (7: Wong, Perrachione, & Parrish, 2007). Good English learners of Mandarin tones showed increased activity in the left posterior superior temporal gyrus (STG); poor learners showed increased activity in the right STG and IFG. Thus, pitch processing engages the left hemisphere (LH) when the pitch patterns signal lexical meaning; otherwise, they are lateralized to the RH.

To isolate sublexical tonal processing, hybrid stimuli were created by superimposing Thai tones onto Mandarin syllables (*tonal chimeras*) and Mandarin tones onto the same syllables (Mandarin words) (6: Xu, Gandour, Talavage, et al., 2006). The tonal chimeras were nonwords in both Mandarin and Thai. In a comparison of native versus nonnative tones, overlapping activity between Mandarin and Thai listeners was identified in the left planum temporale (PT). In this area, a double dissociation between language experience and neural representation of pitch occurred such that stronger activity was elicited in response to native as compared with non-native tones. This neural activity arguably reflects sublexical, phonological processing and is consistent with the view that neural responses to acoustic stimuli can be modulated by their linguistic function (Griffiths & Warren, 2002). Converging evidence that the left PT plays a role in tonal processing comes from an fMRI study in which Chinese listened *attentively* to normal and pitch-flattened sentences (8: Xu, Zhang, Shu, Wang, & Li, 2013). Pitch-flattened sentences elicited greater activation in the left PT compared with normal sentences. Moreover, this activation began to increase and reach its peak earlier than activations in other areas responsible for lexical semantic processing (right PT activation for passive listening to pitch-flattened German sentences; Meyer, Alter, Friederici, Lohmann, & von Cramon, 2002; Meyer, Steinhauer, Alter, Friederici, & von Cramon, 2004). The time course of activation suggests that access to lexical meaning in pitch-flattened sentences is accomplished by the recovery of long-term tonal representations.

[1]The *number:* notation preceding a citation indicates its location in Table 87.1.

TABLE 87.1 Selected References on the Neurobiology of Tonal Processing (2000–2013)

Study	Year	Stimuli	Tasks	Methods	Conclusions
LEXICAL VS. SUBLEXICAL UNITS					
1: Gandour	2000	THA: word, hum; onset consonant, tone	Same–different	PET	Activity in left IFG (frontal operculum) varies depending on linguistic status of pitch
2: Hsieh	2001	MAN: word sequences, hum; onset, rime, tone	Same–different	PET	Leftward asymmetry in inferior frontal cortex for pitch processing depends on its language functions
3: Klein	2001	MAN: word, silence; tone	Same–different	PET	Hemispheric specialization for pitch varies as a function of its linguistic relevance
4: Gandour	2002	THA: pseudowords, hum; tone, vowel length	Same–different	fMRI	Thai group shows more activity in left inferior frontal cortex than Mandarin for processing tone and vowel length in nonlexical contexts
5: Wong	2004	ENG: pseudosyllable; MAN: tones m1, m2, m4	Same–different	PET	Activity in anterior insula indexes whether stimulus is a word (LH) or nonword (RH) in the Mandarin group, but not English group
6: Xu	2006	MAN: word; tonal chimera: MAN syllable + Thai tones	Same–different	fMRI	Double dissociation in the left PT reflects stronger activity to native (Mandarin or Thai) than nonnative tones
7: Wong	2007	ENG, MAN: pseudowords with m1, m2, m4	Same–different	fMRI	Good English learners of Mandarin tones show increased activity in the left posterior STG; poor learners, in the right STG and IFG
8: Xu	2013	MAN: normal, pitch-flattened sentences	Active listening	fMRI	Pitch-flattened sentences elicit greater activity than normal in the left PT, reflecting its role in automatic tonal decoding
TONAL VS. SEGMENTAL UNITS					
9: Gandour	2003	MAN: word	Same–different	fMRI	Activity is greater for rimes versus onsets and tones in left posterior middle frontal gyrus, tones versus onsets and rimes in posterior IFG bilaterally
10: Li	2003	MAN: word	Auditory probe	fMRI	Tone extraction relative to the syllable elicits activity in dorsal frontoparietal areas of the LH
11: Liang	2004	MAN: word	Identification tone, vowel	Aphasia	Differential breakdown of vowels (spared) and tones (impaired) in spoken word production of Chinese aphasic supports a dissociation of tonal and segmental processing
12: Schirmer	2005	CAN: word	Passive oddball	N400	Tonal and segmental information play comparable roles for word processing in Cantonese
13: Luo	2006	MAN: word	Passive oddball	MMN	Opposite laterality for onsets (LH) and tones (RH) indicates acoustic basis for hemispheric dominance at early stage of processing
14: Liu	2006	MAN: word	Naming	fMRI	Tones elicit more activity than vowels in the right IFG in spoken word production
15: Li	2010	MAN: word	Auditory probe	fMRI	RH asymmetry in frontoparietal areas for tones versus onsets or rimes supports role of RH in speech prosody processing
16: Zhao	2011	MAN: word	Passive oddball	N400	Rimes, tones, and syllables equally modulate the amplitude and time course of N400
17: Malins	2012	MAN: word	Match picture	N400	Tonal and phonemic (onsets, rimes) information, not syllabic, constrain spoken word recognition
18: Hu	2012	MAN: word	Semantic congruity	N400	N400 and LPC support functional dissociation of vowel and tone processing in spoken word recognition

(*Continued*)

TABLE 87.1 (Continued)

Study	Year	Stimuli	Tasks	Methods	Conclusions
TONAL FEATURES					
19: Chandrasekaran	2007	MAN: m1/m3, m2/m3	Passive oddball	MMN	Language experience (M > E) influences early, preattentive cortical processing of pitch
20: Chandrasekaran	2007	MAN: m1/2, m1/3	Passive oddball	MMN	Language-dependent weighting of specific, perceptual features of tone may influence its early cortical processing
21: Chandrasekaran	2007	MAN: m1/2, m1/3, m2/3	Passive oddball	MMN, MDS	Effects of language experience vary depending on specific pitch dimensions (height, contour)
22: Kaan	2007	THA: word; t1/t2, t1/t4	Passive oddball	MMN	English and Mandarin listeners, respectively, are sensitive to pitch height and pitch contour of Thai tones
23: Tsang	2011	CAN: c6/1, c6/3, c1/2, c6/2	Passive oddball	MMN, P3a	Change in pitch contour (P3a) and height (MMN) indicate that both tonal attributes are important to tonal processing
TONAL PROCESSING IN THE BRAINSTEM					
24: Swaminathan	2008	MAN: nonspeech; m1, m2, m3, m4	Passive listening	FFR	Pitch representation in the brainstem is sensitive to specific features across speech/nonspeech contexts
25: Krishnan	2009	MAN: nonspeech; m2, m2 inverted, m2 linear, m2 trilinear	Passive listening	FFR	Brainstem pitch encoding is sensitive to time-varying perceptually salient features of pitch patterns
26: Krishnan	2009	MAN: nonspeech; m1, m2, m3, m4	Passive listening	FFR	Degree of acceleration is a critical variable that influences pitch extraction in the brainstem
27: Krishnan	2010	MAN: click trains; m2	Passive listening	FFR	Mandarin listeners' pitch encoding advantage extends to higher acceleration rates beyond the speech domain
28: Krishnan	2011	MAN: m2, m2i; [œ]	Passive listening	FFR	Functional ear (a)symmetries in the brainstem vary depending upon the linguistic status of pitch contours
CATEGORICAL PERCEPTION OF TONE					
29: Xi	2010	MAN: m2, m4	Passive oddball	MMN	Acoustic and phonological information is processed in parallel within the MMN time window
30: Zhang	2011	MAN: m2, m4	Passive oddball	fMRI	Across-category deviants elicit stronger activity in the mid portion of the left middle temporal gyrus; within-category deviants in the right Heshchl's gyrus and STG
31: Zheng	2012	MAN,CAN: m1, m2 and c1, c2	Active detection of deviants	P300	Cantonese (not Mandarin) show strong categorical perception effect in P300 amp that may reflect differences in tonal inventories between the two tone languages
TONE VS. OTHER SUPRASEGMENTAL UNITS					
32: Gandour	2004	MAN: pseudosentences; tone, sentence meaning (statement, question)	Same−different	fMRI	Speech prosody perception is mediated primarily by the RH, but is left-lateralized to task-dependent regions when language processing is required beyond the auditory analysis of the complex sound
33: Tong	2005	MAN: sentence focus (initial, final); intonation (statement, question)	Same−different	fMRI	Speech prosody perception involves a dynamic interplay among widely distributed regions not only within a single hemisphere but also between the two hemispheres

(*Continued*)

TABLE 87.1 (Continued)

Study	Year	Stimuli	Tasks	Methods	Conclusions
34: Gandour	2007	MAN, English: sentence focus (initial, final); intonation (statement, question)	Same−different	fMRI	Phonetic discrimination of functionally equivalent prosodic contrasts in Mandarin and English by unequal Chinese/English bilinguals reveals essentially a unitary neural system that can adapt to stimulus-specific and task-specific demands for processing a lower-proficiency second language
35: Fournier	2010	RD: rd1, rd2; statement, question	Active listening	MMNm	Lateralization of pitch processing is condition-dependent (tone, LH; intonation, RH) in the Roermond Dutch tone dialect group only, suggesting that language experience determines how processes should be distributed between hemispheres according to the functions available in the grammar
36: Zhang	2010	French: CV sequences; intonation, rhythm	Passive oddball	fMRI	Both rhythm and intonation activated a common area in the right mid portion of the STG for Mandarin listeners, whereas intonation elicited additional activation in the right anterior STS

Key to Table 87.1
List of abbreviations:

BRAIN	
MMN	Mismatch negativity, index of automatic auditory change detection
MMNm	Magnetic mismatch negativity
N400	ERP component associated with later-going lexical semantic processing
P300	ERP component indexes ease of updating memory of stimulus context in response to changes in stimulus attributes
P3a	ERP component associated with automatic switching of attention induced by unexpected change in stimulus event
METHODS	
ERP	Event-related potentials
FFR	Frequency following response generated from the auditory brainstem
fMRI	Functional magnetic resonance imaging
MDS	Multidimensional scaling
MEG	Magnetoencephalography
PET	Positron emission tomography
LANGUAGES	
CAN	Cantonese
ENG	English
MAN	Mandarin
RD	Roermond Dutch
THA	Thai
LEXICAL TONES	
c1	Cantonese Tone 1, high level
c2	Cantonese Tone 2, high rising
c3	Cantonese Tone 3, mid level
c4	Cantonese Tone 4, low falling
c5	Cantonese Tone 5, low rising
c6	Cantonese Tone 6, low level

(*Continued*)

TABLE 87.1 (Continued)

Key to Table 87.1
List of abbreviations:

m1	Mandarin Tone 1, high level
m2	Mandarin Tone 2, high rising, curvilinear
m2i	Mandarin Tone 2 inverted
m2l	Mandarin Tone 2 linear
m2tl	Mandarin Tone 2 trilinear
m2up	Mandarin Tone 2 transposed up 2 semitones
m3	Mandarin Tone 3, low falling–rising
m4	Mandarin Tone 4, high falling
rd1	Roermond Dutch Accent 1, falling
rd2	Roermond Dutch Accent 2, falling–rising
t1	Thai Tone 1, mid level
t2	Thai Tone 2, low falling
t3	Thai Tone 3, high falling
t4	Thai Tone 4, high rising
t5	Thai Tone 5, low rising

87.4 TONAL VERSUS SEGMENTAL UNITS

Linguistic theory informs us that the onset and rime of a syllable contain segmental units. They differ in their duration and the order in which their information unfolds in time over the duration of a syllable. Rimes and tones, however, overlap substantially in the order in which their information unfolds in time. Tones are suprasegmental; they are mapped onto (morpho) syllables.

Depending on task demands, tones elicit effects that differ from those of segments. The time course and amplitude of N400 (a negative component associated with lexical semantic processing that peaks approximately 400 ms after the auditory stimulus) were the same for consonant, rime, and tone violations in Cantonese (12: Schirmer, Tang, Penney, Gunter, & Chen, 2005). Their findings were replicated in Mandarin, but syllable violations elicited an earlier and stronger N400 than tone (17: Malins & Joanisse, 2012; cf. 16: Zhao, Guo, Zhou, & Shu, 2011). This separation of tone from its carrier syllable was also reported in an auditory verbal recognition paradigm in which subjects selectively attended to either the syllable or the tone (10: Li et al., 2003). In a spoken word recognition paradigm, tones elicited larger late positive event-related potential (ERP) component than vowels (19: Hu, Gao, Ma, & Yao, 2012). In a left brain-damaged Chinese aphasic, vowels were spared and tones were severely impaired (11: Liang & van Heuven, 2004). These findings together support a functional dissociation of tonal and segmental information.

It is well-known that hemispheric specialization may be driven by differences in acoustic features associated with segments. The question is whether hemispheric specialization for tone can be dissociated from segments. Tones induce greater activation in the right posterior middle frontal gyrus (MFG) for English speakers when compared with consonants or rimes (9: Gandour et al., 2003). This area has been implicated in pitch perception (Zatorre et al., 2002). Their increased activation is presumably due to their lack of experience with Chinese tones. Using a tone identification task, the right IFG was found to be activated in English learners of Mandarin tone only *after* training (Wang, Sereno, Jongman, & Hirsch, 2003). This finding demonstrates early cortical effects of learning a second language that involve recruitment of cortical regions implicated in tonal processing. Focusing on hemispheric specialization for tone production (14: Liu et al., 2006), Mandarin tones elicited more activity in the right IFG than vowels. This rightward preference for tonal processing converges more broadly with the role of the RH in mediating speech prosody (Friederici & Alter, 2004; Glasser & Rilling, 2008; Wildgruber, Ackermann, Kreifelts, & Ethofer, 2006).

As measured by the mismatch negativity (MMN), a fronto-centrally distributed cortical ERP that indexes a change in auditory detection, it is well-known that language experience may influence the automatic, involuntary processing of consonants and vowels (Naatanen, 2001, review). Therefore, one would expect language experience to modulate the automatic cortical processing of lexical tones. Tones evoked stronger MMN in the RH relative to the LH, whereas consonants produced the opposite pattern (13: Luo et al., 2006). An fMRI study showed that Mandarin tones, relative to consonants or rimes, elicited increased activation in right frontoparietal areas (15: Li et al., 2010). Taken together, these data suggest the balance of hemispheric specialization may be modulated by distinct acoustic features associated with tonal as compared with segmental units.

87.5 TONAL FEATURES

The notion that a phonetic segment can be decomposed into a set of features is universally accepted among linguists. Tone, a suprasegmental unit, has also been characterized as being made up of features (Wang, 1967; Yip, 2002, pp. 39−64). Their ontological status in tone perception is well-established (Gandour, 1983; Gandour & Harshman, 1978) and confirmed in more recent studies of tone perception (Huang & Johnson, 2011; Khouw & Ciocca, 2007) and tone learning (Chandrasekaran, Sampath, & Wong, 2010; Francis, Ciocca, Ma, & Fenn, 2008). The brain, however, is a neurophysiological apparatus. Features, however, are not to be confused with neural mechanisms.

How they are implemented in the brain depends on the anatomical level to which they are being applied and their functional status in a particular language. Using nonspeech homologues of Mandarin tones (19: Chandrasekaran, Krishnan, & Gandour, 2007a), native Chinese exhibited larger MMN responses than English in response to a deviant representing a natural *curvilinear* rising pitch contour representative of M2, but not in response to a *linear* rising ramp that is a crude approximation of M2 that does not occur in natural speech. This finding demonstrates that experience-dependent plasticity is sensitive to the shape of pitch contours. To further probe the stimulus attributes that trigger these language-dependent effects (20: Chandrasekaran, Krishnan, & Gandour, 2007b), two passive oddball conditions were presented to Mandarin and English listeners. One contained two tones that are acoustically dissimilar to one another (M1/M3); the other contained two tones that are acoustically similar (M2/M3). MMN responses of Chinese listeners were larger than those of English for the high dissimilarity condition only (M1/M3). An explanation based on tonal categories does not tell us why MMN amplitude is reduced for one condition but not the other. All three stimuli exhibited pitch contours exemplary of their tonal category. Language group differences may be attributed to the relative saliency of perceptual features. To test the hypothesis of separate neural processing of pitch dimensions, another oddball condition (M1/M2) was added. A multidimensional scaling analysis of pairwise dissimilarities of MMN responses to Mandarin tones revealed that Chinese listeners, relative to English, are more sensitive to pitch contour than pitch height (21: Chandrasekaran, Gandour, & Krishnan, 2007). Thus, MMN may serve as a neural index of the relative saliency of underlying features of pitch that are differentially weighted by language experience.

In Cantonese (23: Tsang, Jia, Huang, & Chen, 2011), MMN and P3a (an automatic attention shift induced by the detection of deviant features in the passive oddball paradigm) were elicited from two Cantonese tonal pairs: one differing in pitch height (height-large, C6/C1; height-small, C6/C3) and the other differing in pitch contour (contour-early, C1/C2; contour late, C6/C2). The size and latency of MMN were sensitive to the size of pitch level change, whereas the latency of P3a captured the presence of pitch contour change. Their findings confirm that pitch contour and pitch height are important tonal features in early lexical tone processing. Most importantly, MMN and P3a are revealed to be independent neural components that are differentially sensitive to pitch height and contour, respectively. In another study (22: Kaan, Wayland, Bao, & Barkley, 2007), two oddball conditions were presented to Mandarin and English listeners to assess the effects of perceptual training of Thai tones as a function of language background. One condition contained two tones that are acoustically dissimilar (T1/T4), mid versus high-rising; the other contained two tones that are acoustically similar (T1/T2), mid versus low-falling. After training, the high-rising deviant (T4) elicited a larger MMN amplitude for English listeners in contrast to a later MMN latency for Mandarin listeners. Their findings suggest that English listeners are more sensitive to early differences in pitch height, whereas Mandarin Chinese are more sensitive to later rapid changes in pitch contour.

87.6 TONAL PROCESSING AT THE LEVEL OF THE AUDITORY BRAINSTEM

Pitch processing may also be subject to experience-dependent effects at the level of the brainstem before the auditory signal reaches the cerebral cortex. Electrophysiological responses to tonal features may emerge no later than 5 to 8 ms from the time the auditory signal enters the ear (Krishnan & Gandour, 2009, review). The frequency following response (FFR) reflects sustained phase-locked activity in a population of neural units within the brainstem and is characterized by a periodic waveform that follows the individual cycles of the stimulus waveform (Chandrasekaran & Kraus, 2010; Krishnan, 2007, tutorials). Experience-dependent pitch encoding mechanisms in the brainstem are especially sensitive to the *curvilinear* shape of pitch contours that occur in speech and nonspeech contexts (24: Swaminathan, Krishnan, & Gandour, 2008). Linear approximations of Mandarin tones (M2, M4) fail to elicit a language-dependent effect (25: Krishnan, Gandour, Bidelman, & Swaminathan, 2009; Xu, Krishnan, & Gandour, 2006).

Neural mechanisms in the brainstem show enhanced language-dependent pitch encoding in response to particular time-varying acoustic properties within tonal *subsections*. Using nonspeech homologues of Mandarin tones (26: Krishnan, Swaminathan, & Gandour, 2009), pitch strength (magnitude of the normalized autocorrelation peak) of 40-ms subsections revealed that Chinese listeners, relative to English, exhibit more robust pitch representation of those subsections containing rapid changes in pitch. This heightened sensitivity to rapid changes in pitch by Chinese listeners was maintained even in severely degraded stimuli (Krishnan, Gandour, & Bidelman, 2010a). This experience-dependent enhancement of pitch encoding may transfer to other tone languages. Pitch strength of tonal subsections containing moderate rises in pitch were most important in distinguishing tonal (Mandarin, Thai) from nontonal language (English) groups (Krishnan, Gandour, & Bidelman, 2010b). Neuroplasticity for pitch processing in the brainstem is not necessarily limited to the domain in which the pitch contours are perceptually relevant. Mandarin listeners had an advantage over English not only in response to a click-train homologue of M2 but also in response to scaled variants with increasingly higher acceleration rates that fall proximal to or outside the boundary of natural speech (27: Krishnan, Gandour, Smalt, & Bidelman, 2010). Moreover, changes to the acoustic periodicity of a stimulus directly influence brainstem encoding and its corresponding perceptual responses to pitch (Krishnan, Bidelman, & Gandour, 2010). Neural pitch strength in the brainstem and perceptual pitch salience, as reflected by f_0 difference limen estimates, improved systematically with increasing temporal regularity of the M2 stimulus. This strong correlation between neural and behavioral measures supports the view that pitch encoding at a subcortical sensory level of processing plays an important role in shaping tone perception.

Hemispheric asymmetries in the cerebral cortex are predictable based on low-level, spectrotemporal features of stimuli, but they can also be modulated by their linguistic function (Meyer, 2008; Poeppel, Idsardi, & van Wassenhove, 2008; Wildgruber et al., 2006; Zatorre & Gandour, 2008, reviews). It is also well-known that there are fixed, structural asymmetries in the auditory pathway. Whether *ear asymmetries* at the level of the brainstem can be modulated by functional changes in pitch is an open question. Using two synthetic speech stimuli (native M2; nonnative flipped variant of M2), magnitude of the f_0 component in the FFR (amplitude of the spectral component at f_0) was obtained from a perceptually salient portion of M2 that exhibits rapidly changing pitch (28: Krishnan, Gandour, Ananthakrishnan, Bidelman, & Smalt, 2011). The native tone (M2) evoked a comparatively larger degree of rightward ear asymmetry in pitch encoding than the non-native pitch pattern. In response to left-ear and right-ear stimulation, the FFR evoked by M2 was larger than its flipped variant with right ear stimulation only. On an absolute scale, asymmetry favoring left ear stimulation was evoked by the non-native pitch contour. These differences in ear asymmetry may reflect an emerging functional separation of periodicity and spectral representations at the midbrain level.

87.7 CATEGORICAL PERCEPTION OF TONE

Categorical perception is believed to reflect fundamental aspects of the processing of speech sounds (Harnad, 1987, review). It refers to the phenomenon whereby a specific step along a continuous sensory dimension may signal the boundary between separate categories. The bulk of research has focused on consonants and vowels (tones; Francis, Ciocca, & Ng, 2003; Peng et al., 2010; Xu, Gandour, & Francis, 2006). An ERP study of the categorical perception of Mandarin tones provides a window to the interplay between phonetic and phonological processing (29: Xi, Zhang, Shu, Zhang, & Li, 2010). Xi et al. created an 11-step f_0 continuum with M2 (high-rising) and M4 (high-falling) as the endpoint stimuli in both speech and nonspeech conditions. Using a passive oddball paradigm, both within-category and across-category deviants elicited larger MMNs in the RH sites; however, at the same time, larger MMNs were elicited by across-category than by within-category deviants in the LH. Given their low spatial resolution and methodological constraints that limit unambiguous interpretation of hemispheric dominance of ERPs based on scalp topographical maps, it was necessary to use a method with high spatial resolution to clearly identify cortical activation in different brain regions. In a companion fMRI study (30: Zhang et al., 2011), brain areas activated by acoustic variation within tonal categories were located in the dorsal and posterior-lateral STG bilaterally, especially the right middle STG. In contrast, brain areas activated by phonological variation across tonal categories, as compared with within-category acoustic variation, were located in the left middle temporal gyrus (MTG). These findings are consistent with the view that the dorsal STG and lateral mSTS/MTG are responsible for acoustic analysis and phonological processing, respectively. Superior regions of the temporal lobe are known to be responsible for initial stages of auditory analysis, whereas the superior temporal sulcus (STS) and MTG have been implicated in higher-level phonological processing (Hickok & Poeppel, 2004, 2007; Liebenthal, Binder, Spitzer, Possing, & Medler, 2005; Liebenthal et al., 2010). A cross-language ERP study focused on the influence of language experience (Mandarin, Cantonese) on categorical perception of a three-step f_0 continuum consisting of rising pitch contours common to both tone languages (31: Zheng, Minett, Peng, & Wang, 2012). Deviant responses were measured by the P300 amplitude, a voluntary attention-switching response elicited by an *active* oddball paradigm (Polich, 2007). As reflected by P300 amplitude, Cantonese listeners discriminated the tonal stimuli better than Mandarin. Zheng et al. speculate that Cantonese listeners make finer distinctions in f_0 height and slope because the Cantonese tonal space (six contrasts) is more dense that that of Mandarin (four contrasts).

87.8 TONE VERSUS OTHER SUPRASEGMENTAL UNITS

There are other suprasegmental units of speech besides tone (Lehiste, 1996). In comparison with tone, we are especially interested in those units that may also be signaled by variations in pitch (e.g., stress, intonation, sentence focus). In tone languages, pitch variations can be used to signal differences in the meaning of sentences as well as words. In an fMRI study of Mandarin tone and intonation (32: Gandour et al., 2004), Chinese listeners exhibited greater activity than English in the left ventral aspects of the inferior parietal lobule regardless of the level of prosodic representation. Both language groups, however, showed activity within the right STS and MFG (Ren, Yang, & Li, 2009). This right-sided preference may reflect shared mechanisms underlying early processing of complex pitch patterns irrespective of language experience (Zatorre, Mondor, & Evans, 1999). The LH activity in the inferior parietal lobule is likely to reflect higher-level, language-dependent phonological processing (Jacquemot, Pallier, LeBihan, Dehaene, & Dupoux, 2003).

In tone languages, pitch variations can be used to signal differences in the meaning of sentences as well as words. The MEG study of tone and intonation in Roermond Dutch provides an account of a tonal dialect that unambiguously encodes both contrasts phonologically (35: Fournier, Gussenhoven, Jensen, & Hagoort, 2010). That is, Roermond has two lexical tones that are phonetically distinct in statements and questions. When asked to listen *attentively* to oddball sequences, native Roermond listeners showed a stronger MMNm (150−250 ms) over the left temporal cortex for tone and a predominantly RH response for intonation. Non-native listeners showed a stronger response over the left temporal cortex irrespective of prosodic unit. Using a *passive* oddball paradigm, the MMN (120−240 ms) yielded RH dominance in Mandarin for both word-level (tone) and sentence-level (intonation) prosodic functions (Ren et al., 2009). These conflicting findings between Roermond Dutch and Mandarin are likely due to task demands (attentive versus preattentive) rather than the lack of a prosodic function in their phonological system.

Mandarin and English differ structurally in their use of prosody at the word level. However, both languages exploit prosody at the sentence level to distinguish focus and discourse meaning. A cross-language fMRI study of the perception of Mandarin sentence focus and intonation demonstrated that Mandarin listeners exhibited greater activity in the left supramarginal gyrus and posterior MTG than English across conditions (33: Tong et al., 2005). This leftward specialization is consistent with the notion of a dorsal processing stream that emanates from auditory cortex, projects to the inferior parietal lobule, and ultimately projects to frontal lobe regions, and with a ventral processing stream that projects to the posterior MTG (Hickok & Poeppel, 2007). Rightward preferences were observed in the middle portion of the MFG for both language groups, implicating more general attention and working memory processes associated with pitch perception. Because both sentence-level phenomena occur in Mandarin and English, it is also possible to compare the processing of the same prosodic contrasts in late-onset Chinese/English bilinguals' first (Mandarin) and second languages (English). Any differences in neural activity associated with auditory processing of the same prosodic contrast in the bilinguals' native language and second language may serve as an index of whether the neural substrates are shared or segregated for the two languages. Chinese/English bilinguals displayed overlapping activation between Mandarin and English stimuli in frontal, parietal, and temporal areas regardless of language (34: Gandour et al., 2007). The sentence focus task, however, elicited greater activation for English stimuli than Mandarin in the bilateral anterior insula and MFG. This is presumably attributable to differences in the way sentence focus is signaled phonetically in the two languages (Xu, 2006). Increased computational demands for the lower-proficiency language lead to greater activation in frontal areas implicated in attention (Shaywitz et al., 2001) and working memory (Smith & Jonides, 1999).

Another suprasegmental feature of speech is rhythm (pattern of timing variations over phrases). Both rhythm and intonation (pattern of pitch variations over phrases) span a number of segments over a relatively long time interval and, therefore, are expected to be preferentially processed in the RH (Poeppel, 2003). The question is whether overlapping or distinct regions of the RH are involved in the processing of rhythm and intonation. Using a passive listening task, a common area in the right middle portion of the STG was activated by Mandarin listeners for both rhythm and intonation conditions (36: Zhang, Shu, Zhou, Wang, & Li, 2010). Compared with rhythm, intonation elicited additional activation in the right anterior STS. This isolation of a particular brain region in the processing of intonation suggests that it is responsive to specific acoustic features associated with dynamic variations in pitch (Humphries, Love, Swinney, & Hickok, 2005; Lattner, Meyer, & Friederici, 2005).

87.9 CONCLUSION

Language experience shapes processing of pitch information at both cortical and subcortical levels. Tones play a role comparable with that of segments in word processing. Whereas both engage the LH in attention-modulated, task-dependent processing, tones show a distinctive rightward asymmetry relative to segments, especially at early stages of processing. Pitch is a multidimensional perceptual attribute that affords us an opportunity to investigate pitch features. Tonal processing reveals experience-dependent sensitivity to specific features that are linguistically relevant at the level of the cerebral cortex and the brainstem. Specific cortical regions may index whether variation in pitch contour falls within or between tonal category boundaries. Neural representations of pitch information are already extracted by early preattentive sensory level processing in both the brainstem and auditory cortex. Neural substrates of tone and other units of speech prosody that are manifested by variations in pitch share widely distributed cortical regions in common. However, when compared directly with a unit of speech prosody based primarily on timing variations (e.g., rhythm), segregated brain regions appear that are responsive to acoustic features associated with dynamic variations in pitch.

The importance of pitch features in gaining a fuller understanding of tonal processing in the brain cannot be overemphasized. We argue that it is necessary to develop a neural response specific to pitch features and, moreover, one that is capable of indexing dynamic variations in pitch that are ecologically representative of those that occur in natural speech (Krishnan, Bidelman, Smalt, Ananthakrishnan, & Gandour, 2012; Krishnan, Gandour, Ananthakrishnan, & Vijayaraghavan, 2014). With respect to speech perception, each pitch feature is defined by an auditory pattern that triggers its detection (Poeppel et al., 2008, pp. 1082−1082, review). Their precise definition, however, varies depending on the level of brain structure, time window, and functional representation in speech perception.

We hasten to acknowledge that the fundamental elements of linguistic theory are not easily reduced to or matched up with the fundamental biological units identified by neuroscience (Poeppel & Embick, 2006). The challenge is to formulate hypotheses about linguistic computations that underlie *real-time* tonal processing at different levels of biological structure in the brain.

Acknowledgment

Research was supported by the National Institutes of Health 5R01DC008549 (A.K.).

References

Chandrasekaran, B., Gandour, J. T., & Krishnan, A. (2007). Neuroplasticity in the processing of pitch dimensions: A multidimensional scaling analysis of the mismatch negativity. *Restorative Neurology and Neuroscience*, *25*(3−4), 195−210.

Chandrasekaran, B., & Kraus, N. (2010). The scalp-recorded brainstem response to speech: Neural origins and plasticity. *Psychophysiology*, *47*(2), 236−246. Available from: http://dx.doi.org/10.1111/j.1469-8986.2009.00928.x.

Chandrasekaran, B., Krishnan, A., & Gandour, J. T. (2007a). Experience-dependent neural plasticity is sensitive to shape of pitch contours. *Neuroreport*, *18*(18), 1963−1967. Available from: http://dx.doi.org/10.1097/WNR.0b013e3282f213c5.

Chandrasekaran, B., Krishnan, A., & Gandour, J. T. (2007b). Mismatch negativity to pitch contours is influenced by language experience. *Brain Research*, *1128*(1), 148−156. Available from: http://dx.doi.org/10.1016/j.brainres.2006.10.064.

Chandrasekaran, B., Sampath, P. D., & Wong, P. C. (2010). Individual variability in cue-weighting and lexical tone learning. *Journal of the Acoustical Society of America*, *128*(1), 456−465. Available from: http://dx.doi.org/10.1121/1.3445785.

Fournier, R., Gussenhoven, C., Jensen, O., & Hagoort, P. (2010). Lateralization of tonal and intonational pitch processing: An MEG study. *Brain Research*, *1328*, 79−88. Available from: http://dx.doi.org/10.1016/j.brainres.2010.02.053.

Francis, A. L., Ciocca, V., Ma, L., & Fenn, K. (2008). Perceptual learning of Cantonese lexical tones by tone and non-tone language speakers. *Journal of Phonetics*, *36*(2), 268−294. Available from: http://dx.doi.org/10.1016/j.wocn.2007.06.005.

Francis, A. L., Ciocca, V., & Ng, B. K. (2003). On the (non)categorical perception of lexical tones. *Perception and Psychophysics*, *65*(7), 1029–1044.

Friederici, A. D., & Alter, K. (2004). Lateralization of auditory language functions: A dynamic dual pathway model. *Brain and Language*, *89*(2), 267–276. Available from: http://dx.doi.org/10.1016/S0093-934X(03)00351-1.

Gandour, J. T. (1983). Tone perception in far Eastern languages. *Journal of Phonetics*, *11*, 149–175.

Gandour, J. T. (1987). Tone production in aphasia. In J. Ryalls (Ed.), *Phonetic approaches to speech production in aphasia and related disorders* (pp. 45–57). Boston, MA: College-Hill.

Gandour, J. T. (1994). Phonetics of tone. In R. Asher, & J. Simpson (Eds.), *The encyclopedia of language & linguistics* (Vol. 6, pp. 3116–3123). New York, NY: Pergamon Press.

Gandour, J. T. (1998a). Aphasia in tone languages. In P. Coppens, A. Basso, & Y. Lebrun (Eds.), *Aphasia in atypical populations* (pp. 117–141). Hillsdale, NJ: Lawrence Erlbaum.

Gandour, J. T. (1998b). Phonetics and phonology. In B. Stemmer, & H. A. Whitaker (Eds.), *Handbook of neurolinguistics* (pp. 207–219). San Diego, CA: Academic Press.

Gandour, J. T. (2006a). Brain mapping of Chinese speech prosody. In P. Li, L. H. Tan, E. Bates, & O. J. L. Tzeng (Eds.), *Handbook of East Asian psycholinguistics* (Vol. 1, pp. 308–319). Cambridge, UK: Cambridge University Press (Chinese).

Gandour, J. T. (2006b). Tone: Neurophonetics. In K. Brown (Ed.), *Encyclopedia of language and linguistics* (Vol. 12, 2nd ed.). Oxford, UK: Elsevier.

Gandour, J. T. (2007). Neural circuitry underlying the perception of linguistic prosody. In C. Gussenhoven, & T. Raid (Eds.), *Tones and tunes: Experimental studies in word and sentence prosody* (Vol. 2, pp. 3–25). Berlin: Mouton de Gruyter.

Gandour, J. T., & Harshman, R. A. (1978). Crosslanguage differences in tone perception: A multidimensional scaling investigation. *Language and Speech*, *21*(1), 1–33.

Gandour, J. T., Tong, Y., Talavage, T., Wong, D., Dzemidzic, M., Xu, Y., et al. (2007). Neural basis of first and second language processing of sentence-level linguistic prosody. *Human Brain Mapping*, *28*(2), 94–108. Available from: http://dx.doi.org/10.1002/hbm.20255.

Gandour, J. T., Tong, Y., Wong, D., Talavage, T., Dzemidzic, M., Xu, Y., et al. (2004). Hemispheric roles in the perception of speech prosody. *NeuroImage*, *23*(1), 344–357. Available from: http://dx.doi.org/10.1016/j.neuroimage.2004.06.004.

Gandour, J. T., 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.

Gandour, J. T., Wong, D., & Hutchins, G. (1998). Pitch processing in the human brain is influenced by language experience. *Neuroreport*, *9*(9), 2115–2119.

Gandour, J. T., Wong, D., Lowe, M., Dzemidzic, M., Satthamnuwong, N., Tong, Y., et al. (2002). A cross-linguistic fMRI study of spectral and temporal cues underlying phonological processing. *Journal of Cognitive Neuroscience*, *14*(7), 1076–1087. Available from: http://dx.doi.org/10.1162/089892902320474526.

Gandour, J. T., Xu, Y., Wong, D., Dzemidzic, M., Lowe, M., Li, X., et al. (2003). Neural correlates of segmental and tonal information in speech perception. *Human Brain Mapping*, *20*(4), 185–200. Available from: http://dx.doi.org/10.1002/hbm.10137.

Glasser, M. F., & Rilling, J. K. (2008). DTI tractography of the human brain's language pathways. *Cerebral Cortex*, *18*(11), 2471–2482. Available from: http://dx.doi.org/10.1093/cercor/bhn011.

Griffiths, T. D., & Warren, J. D. (2002). The planum temporale as a computational hub. *Trends in Neurosciences*, *25*(7), 348–353.

Harnad, S. R. (Ed.), (1987). *Categorical perception: The groundwork of cognition* New York, NY: Cambridge University Press.

Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition*, *92*(1–2), 67–99.

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience*, *8*(5), 393–402. Available from: http://dx.doi.org/10.1038/nrn2113.

Hsieh, L., Gandour, J. T., Wong, D., & Hutchins, G. D. (2001). Functional heterogeneity of inferior frontal gyrus is shaped by linguistic experience. *Brain and Language*, *76*(3), 227–252. Available from: http://dx.doi.org/10.1006/brln.2000.2382.

Hu, J. H., Gao, S., Ma, W. Y., & Yao, D. Z. (2012). Dissociation of tone and vowel processing in Mandarin idioms. *Psychophysiology*, *49*(9), 1179–1190. Available from: http://dx.doi.org/10.1111/j.1469-8986.2012.01406.x.

Huang, T., & Johnson, K. (2011). Language specificity in speech perception: Perception of Mandarin tones by native and nonnative listeners. *Phonetica*, *67*, 243–267.

Humphries, C., Love, T., Swinney, D., & Hickok, G. (2005). Response of anterior temporal cortex to syntactic and prosodic manipulations during sentence processing. *Human Brain Mapping*, *26*(2), 128–138. Available from: http://dx.doi.org/10.1002/hbm.20148.

Jacquemot, C., Pallier, C., LeBihan, D., Dehaene, S., & Dupoux, E. (2003). Phonological grammar shapes the auditory cortex: A functional magnetic resonance imaging study. *Journal of Neuroscience*, *23*(29), 9541–9546.

Kaan, E., Wayland, R., Bao, M., & Barkley, C. M. (2007). Effects of native language and training on lexical tone perception: An event-related potential study. *Brain Research*, *1148*, 113–122. Available from: http://dx.doi.org/10.1016/j.brainres.2007.02.019.

Khouw, E., & Ciocca, V. (2007). Perceptual correlates of Cantonese tones. *Journal of Phonetics*, *35*(1), 104–117. Available from: http://dx.doi.org/10.1016/j.wocn.2005.10.003.

Klein, D., Zatorre, R. J., Milner, B., & Zhao, V. (2001). A cross-linguistic PET study of tone perception in Mandarin Chinese and English speakers. *NeuroImage*, *13*(4), 646–653. Available from: http://dx.doi.org/10.1006/nimg.2000.0738.

Krishnan, A. (2007). Human frequency following response. In R. F. Burkard, M. Don, & J. J. Eggermont (Eds.), *Auditory evoked potentials: Basic principles and clinical application* (pp. 313–335). Baltimore, MD: Lippincott Williams & Wilkins.

Krishnan, A., Bidelman, G. M., & Gandour, J. T. (2010). Neural representation of pitch salience in the human brainstem revealed by psychophysical and electrophysiological indices. *Hearing Research*, *268*(1–2), 60–66. Available from: http://dx.doi.org/10.1016/j.heares.2010.04.016.

Krishnan, A., Bidelman, G. M., Smalt, C. J., Ananthakrishnan, S., & Gandour, J. T. (2012). Relationship between brainstem, cortical and behavioral measures relevant to pitch salience in humans. *Neuropsychologia*, *50*(12), 2849–2859. Available from: http://dx.doi.org/10.1016/j.neuropsychologia.2012.08.013.

Krishnan, A., & Gandour, J. T. (2009). The role of the auditory brainstem in processing linguistically-relevant pitch patterns. *Brain and Language*, *110*(3), 135–148. Available from: http://dx.doi.org/10.1016/j.bandl.2009.03.005.

Krishnan, A., Gandour, J. T., Ananthakrishnan, S., Bidelman, G. M., & Smalt, C. J. (2011). Functional ear (a)symmetry in brainstem neural activity relevant to encoding of voice pitch: A precursor for hemispheric specialization? *Brain and Language*, *119*(3), 226–231. Available from: http://dx.doi.org/10.1016/j.bandl.2011.05.001.

Krishnan, A., Gandour, J. T., Ananthakrishnan, S., & Vijayaraghavan, V. (2014). Cortical pitch response components index stimulus onset/offset and dynamic features of pitch contours. *Neuropsychologia*, *59C*, 1–12. Available from: http://dx.doi.org/10.1016/j.neuropsychologia.2014.04.006.

Krishnan, A., Gandour, J. T., & Bidelman, G. M. (2010a). Brainstem pitch representation in native speakers of Mandarin is less susceptible to degradation of stimulus temporal regularity. *Brain Research*, *1313*, 124–133. Available from: http://dx.doi.org/10.1016/j.brainres.2009.11.061.

Krishnan, A., Gandour, J. T., & Bidelman, G. M. (2010b). The effects of tone language experience on pitch processing in the brainstem. *Journal of Neurolinguistics*, *23*(1), 81–95. Available from: http://dx.doi.org/10.1016/j.jneuroling.2009.09.001.

Krishnan, A., Gandour, J. T., Bidelman, G. M., & Swaminathan, J. (2009). Experience-dependent neural representation of dynamic pitch in the brainstem. *Neuroreport*, *20*(4), 408–413. Available from: http://dx.doi.org/10.1097/WNR.0b013e3283263000.

Krishnan, A., Gandour, J. T., Smalt, C. J., & Bidelman, G. M. (2010). Language-dependent pitch encoding advantage in the brainstem is not limited to acceleration rates that occur in natural speech. *Brain and Language*, *114*(3), 193–198. Available from: http://dx.doi.org/10.1016/j.bandl.2010.05.004.

Krishnan, A., Swaminathan, J., & Gandour, J. T. (2009). Experience-dependent enhancement of linguistic pitch representation in the brainstem is not specific to a speech context. *Journal of Cognitive Neuroscience*, *21*(6), 1092–1105. Available from: http://dx.doi.org/10.1162/jocn.2009.21077.

Lattner, S., Meyer, M. E., & Friederici, A. D. (2005). Voice perception: Sex, pitch, and the right hemisphere. *Human Brain Mapping*, *24*(1), 11–20. Available from: http://dx.doi.org/10.1002/hbm.20065.

Lehiste, I. (1996). Suprasegmental features of speech. In N. J. Lass (Ed.), *Principles of experimental phonetics* (pp. 226–244). St. Louis, MO: Mosby.

Li, X., Gandour, J., Talavage, T., Wong, D., Dzemidzic, M., Lowe, M., et al. (2003). Selective attention to lexical tones recruits left dorsal frontoparietal network. *Neuroreport*, *14*(17), 2263–2266. Available from: http://dx.doi.org/10.1097/01.wnr.0000097045.56589.31.

Li, X., Gandour, J. T., Talavage, T., Wong, D., Hoffa, A., Lowe, M., et al. (2010). Hemispheric asymmetries in phonological processing of tones versus segmental units. *Neuroreport*, *21*(10), 690–694. Available from: http://dx.doi.org/10.1097/WNR.0b013e32833b0a10.

Liang, J., & van Heuven, V. J. (2004). Evidence for separate tonal and segmental tiers in the lexical specification of words: A case study of a brain-damaged Chinese speaker. *Brain and Language*, *91*(3), 282–293. Available from: http://dx.doi.org/10.1016/j.bandl.2004.03.006.

Liebenthal, E., Binder, J. R., Spitzer, S. M., Possing, E. T., & Medler, D. A. (2005). Neural substrates of phonemic perception. *Cerebral Cortex*, *15*(10), 1621–1631. Available from: http://dx.doi.org/10.1093/cercor/bhi040.

Liebenthal, E., Desai, R., Ellingson, M. M., Ramachandran, B., Desai, A., & Binder, J. R. (2010). Specialization along the left superior temporal sulcus for auditory categorization. *Cerebral Cortex*, *20*(12), 2958–2970. Available from: http://dx.doi.org/10.1093/cercor/bhq045.

Liu, L., Peng, D., Ding, G., Jin, Z., Zhang, L., Li, K., et al. (2006). Dissociation in the neural basis underlying Chinese tone and vowel production. *NeuroImage*, *29*(2), 515–523.

Luo, H., Ni, J. T., Li, Z. H., Li, X. O., Zhang, D. R., Zeng, F. G., et al. (2006). Opposite patterns of hemisphere dominance for early auditory processing of lexical tones and consonants. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(51), 19558–19563.

Malins, J. G., & Joanisse, M. F. (2012). Setting the tone: An ERP investigation of the influences of phonological similarity on spoken word recognition in Mandarin Chinese. *Neuropsychologia*, *50*(8), 2032–2043. Available from: http://dx.doi.org/10.1016/j.neuropsychologia.2012.05.002.

Meyer, M. (2008). Functions of the left and right posterior temporal lobes during segmental and suprasegmental speech perception. *Zeitshcrift fur Neuropsycholgie*, *19*(2), 101–115.

Meyer, M., Alter, K., Friederici, A. D., Lohmann, G., & von Cramon, D. Y. (2002). FMRI reveals brain regions mediating slow prosodic modulations in spoken sentences. *Human Brain Mapping*, *17*(2), 73–88.

Meyer, M., Steinhauer, K., Alter, K., Friederici, A. D., & von Cramon, D. Y. (2004). Brain activity varies with modulation of dynamic pitch variance in sentence melody. *Brain and Language*, *89*(2), 277–289. Available from: http://dx.doi.org/10.1016/S0093-934X(03)00350-X.

Naatanen, R. (2001). The perception of speech sounds by the human brain as reflected by the mismatch negativity (MMN) and its magnetic equivalent (MMNm). *Psychophysiology*, *38*(1), 1–21.

Peng, G., Zheng, H.-Y., Gong, T., Yang, R.-X., Kong, J.-P., & Wang, W. S.-Y. (2010). The influence of language experience on categorical perception of pitch contours. *Journal of Phonetics*, *38*, 616–624.

Poeppel, D. (2003). The analysis of speech in different temporal integration windows: Cerebral lateralization as "asymmetric sampling in time". *Speech Communication*, *41*(1), 245–255.

Poeppel, D., & Embick, D. (2006). Defining the relation between linguistics and neuroscience. In A. Cutler (Ed.), *Twenty-first century psycholinguistics. Four cornerstones* (pp. 103–118). Mahwah, NJ: Lawrence Erlbaum.

Poeppel, D., Idsardi, W. J., & van Wassenhove, V. (2008). Speech perception at the interface of neurobiology and linguistics. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *363*(1493), 1071–1086. Available from: http://dx.doi.org/10.1098/rstb.2007.2160.

Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. Available from: http://dx.doi.org/10.1016/j.clinph.2007.04.019.

Ren, G. Q., Yang, Y., & Li, X. (2009). Early cortical processing of linguistic pitch patterns as revealed by the mismatch negativity. *Neuroscience*, *162*(1), 87–95. Available from: http://dx.doi.org/10.1016/j.neuroscience.2009.04.021.

Schirmer, A., Tang, S. L., Penney, T. B., Gunter, T. C., & Chen, H. C. (2005). Brain responses to segmentally and tonally induced semantic violations in Cantonese. *Journal of Cognitive Neuroscience*, *17*(1), 1–12.

Shaywitz, B. A., Shaywitz, S. E., Pugh, K. R., Fulbright, R. K., Skudlarski, P., Mencl, W. E., et al. (2001). The functional neural architecture of components of attention in language-processing tasks. *NeuroImage*, *13*(4), 601–612.

Smith, E. E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science*, *283*(5408), 1657–1661.

Swaminathan, J., Krishnan, A., & Gandour, J. T. (2008). Pitch encoding in speech and nonspeech contexts in the human auditory brainstem. *Neuroreport*, *19*(11), 1163–1167. Available from: http://dx.doi.org/10.1097/WNR.0b013e3283088d31.

Tingsabadh, K., & Abramson, A. S. (1999). Thai. In I.P.A. (Ed.), *Handbook of the international phonetic association* (pp. 147–149). Cambridge, UK: Cambridge University Press.

Tong, Y., Gandour, J. T., Talavage, T., Wong, D., Dzemidzic, M., Xu, Y., et al. (2005). Neural circuitry underlying sentence-level linguistic prosody. *NeuroImage*, *28*(2), 417–428. Available from: http://dx.doi.org/10.1016/j.neuroimage.2005.06.002.

Tsang, Y. K., Jia, S., Huang, J., & Chen, H. C. (2011). ERP correlates of pre-attentive processing of Cantonese lexical tones: The effects of pitch contour and pitch height. *Neuroscience Letters*, *487*(3), 268–272. Available from: http://dx.doi.org/10.1016/j.neulet.2010.10.035.

Wang, W. S.-Y. (1967). Phonological features of tone. *International Journal of American Linguistics*, *33*(2), 93–105.

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

Wang, Y., Jongman, A., & Sereno, J. A. (2001). Dichotic perception of Mandarin tones by Chinese and American listeners. *Brain and Language*, *78*(3), 332−348.

Wang, Y., Sereno, J. A., Jongman, A., & Hirsch, J. (2003). fMRI evidence for cortical modification during learning of Mandarin lexical tone. *Journal of Cognitive Neuroscience*, *15*(7), 1019−1027.

Wildgruber, D., Ackermann, H., Kreifelts, B., & Ethofer, T. (2006). Cerebral processing of linguistic and emotional prosody: fMRI studies. *Progress in Brain Research*, *156*, 249−268. Available from: http://dx.doi.org/10.1016/S0079-6123(06)56013-3.

Witteman, J., van Ijzendoorn, M. H., van de Velde, D., van Heuven, V. J., & Schiller, N. O. (2011). The nature of hemispheric specialization for linguistic and emotional prosodic perception: A meta-analysis of the lesion literature. *Neuropsychologia*, *49*(13), 3722−3738. Available from: http://dx.doi.org/10.1016/j.neuropsychologia.2011.09.028.

Wong, P. C. (2002). Hemispheric specialization of linguistic pitch patterns. *Brain Research Bulletin*, *59*(2), 83−95.

Wong, P. C., Parsons, L. M., Martinez, M., & Diehl, R. L. (2004). The role of the insular cortex in pitch pattern perception: The effect of linguistic contexts. *Journal of Neuroscience*, *24*(41), 9153−9160.

Wong, P. C., Perrachione, T. K., Gunasekera, G., & Chandrasekaran, B. (2009). Communication disorders in speakers of tone languages: Etiological bases and clinical considerations. *Seminars in Speech and Language*, *30*(3), 162−173. Available from: http://dx.doi.org/10.1055/s-0029-1225953.

Wong, P. C., Perrachione, T. K., & Parrish, T. B. (2007). Neural characteristics of successful and less successful speech and word learning in adults. *Human Brain Mapping*, *28*(10), 995−1006. Available from: http://dx.doi.org/10.1002/hbm.20330.

Xi, J., Zhang, L., Shu, H., Zhang, Y., & Li, P. (2010). Categorical perception of lexical tones in Chinese revealed by mismatch negativity. *Neuroscience*, *170*(1), 223−231. Available from: http:dx.doi.org/10.1016/j.neuroscience.2010.06.077.

Xu, G., Zhang, L., Shu, H., Wang, X., & Li, P. (2013). Access to lexical meaning in pitch-flattened Chinese sentences: An fMRI study. *Neuropsychologia*, *51*(3), 550−556. Available from: http://dx.doi.org/10.1016/j.neuropsychologia.2012.12.006.

Xu, Y. (1997). Contextual tonal variations in Mandarin. *Journal of Phonetics*, *25*, 61−83.

Xu, Y. (2006). Tone in connected discourse. In (2nd ed.K. Brown (Ed.), *Encyclopedia of language and linguistics* (Vol. 12Oxford, UK: Elsevier.

Xu, Y., Gandour, J., Talavage, T., Wong, D., Dzemidzic, M., Tong, Y., et al. (2006). Activation of the left planum temporale in pitch processing is shaped by language experience. *Human Brain Mapping*, *27*(2), 173−183.

Xu, Y., Gandour, J. T., & Francis, A. L. (2006). Effects of language experience and stimulus complexity on the categorical perception of pitch direction. *Journal of the Acoustical Society of America*, *120* (2), 1063−1074.

Xu, Y., Krishnan, A., & Gandour, J. T. (2006). Specificity of experience-dependent pitch representation in the brainstem. *Neuroreport*, *17*(15), 1601−1605. Available from: http://dx.doi.org/10.1097/01.wnr.0000236865.31705.3a.

Yip, M. (2002). *Tone*. New York, NY: Cambridge University Press.

Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: Music and speech. *Trends in Cognitive Sciences*, *6*(1), 37−46.

Zatorre, R. J., & Gandour, J. T. (2008). Neural specializations for speech and pitch: Moving beyond the dichotomies. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *363*(1493), 1087−1104. Available from: http://dx.doi.org/10.1098/rstb.2007.2161.

Zatorre, R. J., Mondor, T. A., & Evans, A. C. (1999). Auditory attention to space and frequency activates similar cerebral systems. *NeuroImage*, *10*(5), 544−554.

Zee, E. (1999). *Handbook of the international phonetic association*. Cambridge, UK: Cambridge University Press.

Zhang, L., Shu, H., Zhou, F., Wang, X., & Li, P. (2010). Common and distinct neural substrates for the perception of speech rhythm and intonation. *Human Brain Mapping*, *31*(7), 1106−1116. Available from: http://dx.doi.org/10.1002/hbm.20922.

Zhang, L., Xi, J., Xu, G., Shu, H., Wang, X., & Li, P. (2011). Cortical dynamics of acoustic and phonological processing in speech perception. *Public Library of Science One*, *6*(6), e20963 Retrieved from: http://www.ncbi.nlm.nih.gov/pubmed/21695133. Available from: doi:10.1371/journal.pone.0020963.

Zhao, J., Guo, J., Zhou, F., & Shu, H. (2011). Time course of Chinese monosyllabic spoken word recognition: Evidence from ERP analyses. *Neuropsychologia*, *49*(7), 1761−1770. Available from: http://dx.doi.org/10.1016/j.neuropsychologia.2011.02.054.

Zheng, H.-Y., Minett, J. W., Peng, G., & Wang, W. S.-Y. (2012). The impact of tone systems on the categorical perception of lexical tones: An event-related potentials study. *Language and Cognitive Processes*, *27*(2), 184−209. Available from: http://dx.doi.org/10.1080/01690965.2010.520493.