Neural specializations for pitch in tonal languages

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Abstract

Tonal languages provide a window for tracing the hierarchical transformation of the pitch of a sound from early sensory to later cognitive stages of processing in the human brain. Hemispheric laterality of pitch is driven by multiple dichotomies or scalar features that apply during real-time intervals at cortical and subcortical levels. Using functional neuroimaging, we show that pitch processing recruits the hemispheres differentially as a function of its phonological relevance to the listener. Mismatch negativity, a neural index of early, cortical processing, shows that pitch processing is shaped by the relative saliency of tonal features. Frequency following response, a neural index of brainstem pitch encoding, shows that enhancement of pitch features is sensitive to rapidly-changing segments of tonal contours, and that ear asymmetries can be modulated by functional changes in pitch based on linguistic status. We conclude that nascent representations of acoustic-phonetic features emerge early along the auditory pathway.

Index Terms: perception; pitch; lexical tone; intonation; cerebral cortex; brainstem; auditory electrophysiology; functional brain imaging; experience-dependent plasticity; hemispheric specialization; cue-specific; domain-specific; Mandarin; Cantonese; Thai

1. Introduction

Pitch is one of the most important information-bearing components of speech. Tone languages of Asia provide a window to investigate neural mechanisms underlying pitch at different levels of processing because of its phonemic status at the syllable level [1]. Dynamic variations in voice fundamental frequency (F0) contours provide the dominant acoustic cue for tone recognition [2].

Mandarin Chinese, Cantonese, and Thai are tone languages. They are of special interest to speech prosody perception and the brain because of differences in their number of tonal phonemes and types of tonal shapes as well as tonal relationships governed by rule. Mandarin has four contrastive tones: high level^1, rising^2, low falling-rising^3, falling^4 [3]; Thai, five: mid level^1, low falling^2, high falling^3, high rising^4, low rising^5 [4]; and Cantonese, six: high level^1, high rising^2, mid level^3, low rising^4, low level^5, low falling^6 [5].

Speech perception provides multiple windows on how continuous, acoustic signals are transformed into representations upon which computations are based at different levels of biological abstraction. The brain is driven by neurophysiology and, as such, our heuristic research strategy for investigating the neurobiology of tone perception focuses on how representations and computations are implemented in real time at different stages of processing [6, 7]. In the case of pitch, computations applied to representations appear to be driven by experience-dependent sensitivity to specific features or dimensions that are relevant to one's domain of pitch expertise (e.g., language, music), albeit not necessarily limited to that domain.

The conventional wisdom is that "processing operations conducted in the relay nuclei of the brainstem and thalamus are general to all sounds, and speech-specific operations probably do not begin until the signal reaches the cerebral cortex" [8]. Though we concur that speech-specific operations are likely circumscribed to the cortex, the auditory signal may still be subject to language-dependent effects at subcortical stages of processing [9]. By focusing on specific pitch-relevant properties of the auditory signal, we observe that the emergence of acoustic-phonetic *features* relevant to speech perception begins no later than 5-7 ms from the time the auditory signal enters the ear.

From a theoretical perspective, we present evidence to show that simple dichotomies, either cognitive domains (e.g., language, music) or acoustic cues (e.g., temporal, spectral), are inadequate as the sole explanatory model for patterns of neural specialization at different levels of the brain [10]. The evidence reviewed herein demonstrates that neural specializations for pitch in tonal languages are driven by both low-level acoustic features and higher-order, linguistic knowledge.

2. Tonal features in speech perception

Multidimensional scaling analysis of paired dissimilarity ratings of pitch stimuli reveal that a common set of features (e.g., height, direction, slope) underlie the perceptual space across languages, but that they are differentially weighted depending upon the number and type of pitch patterns and their phonological relationship to one another in one's native language [11, cf. 12, 13]. Given this behavioral evidence that weighting of pitch cues varies as a function of language experience, it seems reasonable to expect that experience-dependent processing of pitch information related to tonal features would also be reflected at different levels of the brain.

3. Tonal processing in the cerebral cortex

3.1. Functional neuroimaging

Functional neuroimaging methods (positron emission tomography, PET; functional magnetic resonance imaging, fMRI) make it possible to observe in vivo how changes in behavioral and cognitive task demands lead to changes in brain activity as reflected by properties of blood flow. They enable us to map areas at the level of gyri and sulci in the cerebral cortex.

The perception of non-linguistic pitch is associated with activation in the right hemisphere (RH) [14]. Pitch processing engages the left hemisphere (LH) only when the pitch patterns are phonologically significant to the listener. In judging Thai tones in real words [15], native Thais, but neither Chinese nor English, showed LH activation in the inferior frontal gyrus (IFG). When asked to discriminate tone and vowel length patterns in Thai pseudowords and their hummed homologues

[16], Thais, but not Chinese, activated the left IFG. Left frontal areas are similarly activated by native Chinese when presented with Mandarin tones in real words; homologous regions in the RH are activated by English [17]. In contrast, when Mandarin tones are superimposed on English words, it is the right insula and IFG that are activated regardless of language background [18]. Thus, pitch processing engages the LH only when the pitch patterns are phonologically significant to the listener; otherwise, they are lateralized to the RH. Moreover, LH mechanisms mediate processing of linguistic information irrespective of acoustic cues or type of phonological unit.

Neural activity may be related to *prelexical* phonological processing of tones [19]. Thai and Mandarin natives were presented with (i) hybrid stimuli consisting of Thai tones superimposed onto Mandarin syllables (tonal chimeras) and (ii) Mandarin tones onto the same syllables (Mandarin words). Overlapping activity between language groups was identified in the left planum temporale. In this area, a double dissociation between language experience and neural representation of pitch revealed that activity was stronger in response to native than nonnative tones. This finding supports the view that relatively early stages of acoustic-phonetic processing can be modulated by stimulus features that are phonologically relevant in particular languages [20, 21].

Differential patterns of cortical activation, however, are not driven by language affiliation alone. They may also be driven by differences in acoustic features associated with specific types of phonological units. In a phonological recognition task, Mandarin tones, relative to either consonants or rhymes, showed increased activation in frontal-parietal areas of the RH [22]. This rightward asymmetry of tone converges with the role of the RH in mediating speech prosody [23-25].

Superior regions of the temporal lobe are known to be responsible for initial stages of auditory analysis, whereas the middle temporal gyrus (MTG) has been implicated in phonological processing [21]. In response to an acoustic continuum from Mandarin high rising to falling tone [26], brain areas activated by acoustic variation within tonal categories were located in the superior temporal gyrus (STG) bilaterally, with the strongest activation in the middle STG of the RH. In contrast, brain areas activated by phonological variation across tonal categories were located in the middle MTG of the LH. These findings are consistent with a functional pathway linking areas in the bilateral dorsal STG to areas in the left MTG that are engaged in higher-level phonological processing [27, 28].

3.2. Auditory evoked potentials

Electrophysiological recordings make it possible to observe the time course of events or processes in the brain. The mismatch negativity (MMN) response is an event-related potential evoked from an auditory passive oddball paradigm [29].

MMN data support an acoustic basis for hemispheric specialization of pitch at early cortical stages of processing. Lexical tones elicit a stronger MMN response from native speakers of Mandarin in the RH than in the LH, whereas consonants evoke the opposite asymmetry [30]. Consonants are characterized by rapidly-changing temporal variation; tones, slowly-changing spectral variation. These hemispheric asymmetries suggest that early cortical processing of linguistic pitch is driven primarily by acoustic features before being mapped onto a semantic representation at later stages. MMNs also yield RH dominance across levels of prosodic representation (tone, intonation) [31].

MMN data also serve as index of automatic, preattentive encoding of features of pitch that are differentially weighted by language experience. Using Mandarin tonal pairs, one acoustically similar (high rising vs. low falling-rising), the other dissimilar (high level vs. low falling-rising), the MMN amplitude of native Chinese listeners was larger than that of English for the dissimilar pair only [32]. This finding is difficult to reconcile in terms of tonal categories because all pitch contours were prototypical of Mandarin lexical tones. Indeed, a multidimensional scaling analysis of MMN responses revealed that Chinese are more sensitive to the pitch contour feature, relative to pitch height, than English [33]. Using an exemplary, nonspeech homologue of the Mandarin high rising tone and its linear approximation, MMN responses were larger for Chinese listeners than English to the natural, curvilinear pitch contour only [34]. These findings collectively suggest that experience-dependent neural plasticity in early cortical processing of linguistic pitch is sensitive to naturally-occurring pitch features, but not specific to speech per se.

The notion that pitch features are driving early tonal processing is further supported in Cantonese [35]. MMN and P3a (involuntary attention-switching response after MMN in the passive oddball paradigm) were elicited from two tonal pairs, one that differed in pitch height (height-large vs. height-small), and the other in pitch contour (contour-early vs. contour late). Pitch height exerted a strong effect on the peak amplitude and latency of MMN, whereas pitch contour did not. But the mere presence of a change in pitch contour, early or late, did influence P3a. This may reflect the salience of the turning point in signaling contour tones [36]. It appears that language-dependent enhancement of neural mechanisms for processing perceptually salient pitch features depend upon the prosodic needs of a particular language.

At later stages of cortical processing, the influence of pitch height and slope features is further demonstrated in a categorical perception experiment of rising pitch contours that occur in both Cantonese and Mandarin [37]. The P300, an index of task demands, is a voluntary, attention-switching response evoked in an active oddball paradigm [38]. As reflected by the P300, Cantonese listeners discriminated the tonal stimuli better than Mandarin. Cantonese listeners may make finer distinctions in F0 height and slope because of differences in cue-weighting within their tonal spaces [39, 40].

4. Tonal processing in the brainstem

The human frequency following response (FFR) reflects sustained phase-locked activity in a population of neural elements within the brainstem, and is characterized by a periodic waveform that follows the individual cycles of the stimulus waveform [41, 42]. FFRs give us a window on pitch processing at a subcortical level of the brain.

4.1. Within domain – language

Comparisons between native speakers of tone (Mandarin) and non-tone (English) languages show that native experience with lexical tones, embedded in either a speech or nonspeech context, enhances pitch encoding at the level of the brainstem [43, 44]. Its role in shaping tone perception is supported by a strong correlation observed between neural and behavioral measures of pitch [45].

Analysis of 40-ms segments within all four Mandarin tones further reveals that native Chinese exhibit more robust pitch representation of those segments containing rapidly-changing pitch movements [46]. These dynamic pitch features of high perceptual saliency are important in discriminating tone language (Mandarin, Thai) from non-tone language (English) listeners [47]. The absence of a difference between Mandarin and Thai suggests that the pitch encoding advantage transfers between languages with similar prosodic systems. These pitch features are also more resistant to degraded listening conditions in Chinese listeners [48]. Enhancement of voice pitch encoding is maintained even at increasingly higher acceleration rates that fall outside the boundary of natural speech [49]. This finding suggests that neuroplasticity for pitch encoding in the brainstem is not necessarily limited to the domain in which pitch contours are behaviorally relevant.

Language-dependent pitch encoding mechanisms in the brainstem are especially sensitive to the *curvilinear* shape of pitch contours that occur in natural speech [50, 51]. We fail to observe any language-dependent effects no matter how close a linear pitch pattern approximates a native lexical tone. A nonnative curvilinear pitch pattern similarly fails to elicit a language-dependent effect.

Having established that early processing of linguistic pitch may be implemented at the level of the auditory brainstem by an experience-dependent encoding scheme, we next ask whether *ear asymmetries* at the level of the rostral brainstem can be modulated by functional changes in pitch based on linguistic status rather than the fixed, structural asymmetries in the auditory pathway [52]. We hypothesized that enhanced pitch encoding in monaural stimulation of either ear will also be preferentially processed in the contralateral hemisphere, or both, depending on their linguistic status. We found that a native pitch contour, i.e., Mandarin lexical tone, exhibited a comparatively larger degree of rightward ear asymmetry in pitch encoding than a nonnative pitch contour. An absolute asymmetry favoring left ear stimulation was evoked by the nonnative pitch contour only; no ear asymmetry was detected in response to the lexical tone. This early shaping of the auditory signal at a pre-attentive, sensory stage of processing is compatible with the idea that nascent representations of acoustic-phonetic features relevant to linguistic aspects of speech prosody may contribute to the functional hemispheric specialization observed in the auditory cortex.

4.2. Across domains – music & language

A longstanding debate in the cognitive neurosciences is whether language and music are processed by distinct and separate neural substrates or alternatively, whether these two domains recruit similar and perhaps overlapping neural resources. Pitch is an important information-bearing component shared by both domains. Yet important differences are noted in how pitch is exploited in each domain. Thus, the question then is whether long-term experience with pitch patterns specific to one domain may differentially shape the neural processing of pitch within another domain. Indeed, brainstem pitch encoding of Mandarin tones by English-speaking musicians is more robust and accurate than nonmusicians [53]. Conversely, tone language experience facilitates music processing. FFRs elicited from Mandarin-speaking nonmusicians were stronger than those of English-speaking nonmusicians in response to a musical pitch interval [54]. Surprisingly, English-speaking musicians' FFRs were even superior to those of Chinese in just those subparts of a lexical tone that can be related to perceptually-salient notes along the musical scale [cf. 55]. These findings suggest that experience-dependent plasticity of brainstem responses is shaped by the relative saliency of acoustic dimensions underlying the pitch patterns associated with a particular domain.

Behavioral and neurophysiological transfer effects from music experience to language processing are well-established. Whether or not linguistic expertise (e.g., speaking a tone language) benefits music perception is an open question. We attempted to determine whether the previously observed superiority in Chinese listeners' subcortical representation of musical pitch [54] provides any benefit in music perception [56]. By measuring brainstem responses to prototypical and detuned musical chord sequences we found that listeners with extensive pitch experience (English musicians, Chinese nonmusicians) have enhanced subcortical representation for musical pitch when compared to inexperienced listeners (English nonmusicians). Yet, despite the relatively strong brainstem encoding of the Chinese, behavioral measures of pitch discrimination and chordal detuning sensitivity reveal that this neural improvement does not necessarily translate to perceptual benefits as it does in the musician group. Indeed, tone language speakers performed no better than English nonmusicians in discriminating musical pitch stimuli. No brain-behavior correlations were found for either tone language speakers or nonmusicians. These findings point to a dissociation between subcortical neurophysiological processing and behavioral measures of pitch perception in Chinese listeners. We infer that sensory-level enhancement of musical pitch information yields cognitive-level perceptual benefits only when that information is behaviorally relevant to the listener [cf. 57].

5. Conclusions

Tonal languages provide a valuable window for tracing the transformation of the pitch signal from early, pre-attentive sensory to later, attention-modulated tasks at cognitive stages of processing in the human brain. Instead of simple dichotomies, hemispheric laterality of pitch is seen to be driven by multiple dichotomies or scalar features that may apply at different real-time intervals at cortical or subcortical levels of the brain. A more complete account of tonal processing will require that we understand the interplay between general sensory-motor and cognitive processes in addition to those derived from linguistic knowledge. Experience-dependent effects at sensory levels of processing are compatible with an integrated, hierarchically organized auditory pathway to the brain. General-purpose processes are tuned differentially to perceptually-salient features of the auditory signal depending upon their linguistic status. Enhancements in brainstem neural activity relevant to encoding of voice pitch is comparable to neural mechanisms that are developed for processing behaviorally-relevant sounds in other non-primate and nonhuman primate animals [58]. Such findings point to language-dependent enhancement of neural mechanisms for differential processing of pitch features that are perceptually salient depending upon the prosodic needs of a particular language. .

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7. References

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