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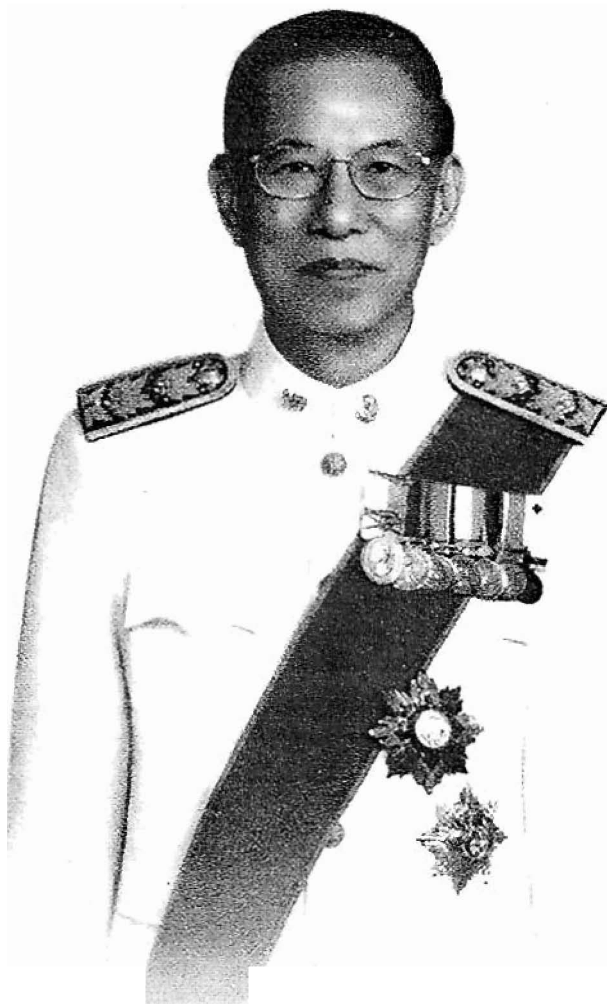

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Contents

Neuroplasticity in the preattentive processing of linguistic pitch: Evidence from cross-language and cross-domain studies

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Abstract

The mismatch negativity (MMN), a cortical event-related potential (ERP) hypothesized to be an objective index of auditory discrimination, is known to be modulated by long-term auditory experiences (e.g. language, music). Experience-dependent plasticity in the preattentive processing of linguistically relevant stimuli, as reflected by the mismatch negativity (MMN), has been assumed to reflect the influence of long-term stored categorical representations for native speakers. However, emerging cross-language and cross-domain research examining linguistic pitch processing have questioned the influence of categories on experience-dependent neural modulation. These data shed light on the possibility that neuroplasticity, as reflected by the MMN, may result from more faithful neural encoding of acoustic dimensions as a result of long-term experience. Such findings are consistent with neurobiological studies on animals that have demonstrated increased neural valence to behaviorally-relevant acoustic features. Furthermore, a proposal focusing on the acoustic rather than a phonetic basis for experience-dependent neuroplasticity has the potential to explain recent findings that long-term experience in the domain of music can influence preattentive processing of linguistically relevant stimuli. This review summarizes recent cross-language and cross-domain studies using the MMN, and relates their findings to current knowledge regarding the neurobiological basis for experience-dependent plasticity.

Introduction

The mismatch negativity (MMN) is an automatic, change-detection, fronto-centrally distributed cortical potential elicited using a passive oddball paradigm. To obtain the auditory MMN, the brain's response to a frequently presented standard is subtracted from the response to a rarely presented deviant. The difference waveform shows a large sustained negativity (between 125- 300 ms), that reflects the extent to which the brain detects a change in the incoming auditory stimulus stream (Näätänen, 2001; Näätanen, Paavilainen, Rinne, & Alho, 2007). The MMN is typically elicited passively, i.e., when the participant is engaged in a distracter task (watching a movie or reading a book). It has been extensively utilized in basic and clinical research as an index of preattentive auditory discrimination (Kujala, Tervaniemi, & Schroger, 2007; Näätanen, et al., 2007). According to the memory model of MMN generation, the neural trace generated to the deviant stimuli violates the established neural trace of the repetitively presented standard (Näätänen, 2001). The MMN therefore, represents the integrity of the neural representation to the standard.

Language-experience modulates the MMN response to speech sounds

The MMN has been shown to be sensitive to language experience (Cheour, et al., 1998). In a landmark study, using a cross-language design, Näätänen and colleagues demonstrated larger MMN responses for native Estonians, relative to native Finns, for a prototypical vowel that occurs in the phonemic inventory of Estonian, but not in that of Finnish (Näätänen, et al., 1997). In addition, the Estonian MMN response for the prototypical vowel was larger in the left hemisphere (LH), relative to the right. In contrast, the Finnish MMN response did not show an asymmetric pattern. Based on these results, Näätänen et al. suggested that, in addition to the acoustics, the MMN response for native speakers is influenced by long-term stored categorical representations. Since this study, experience-dependent effects have been demonstrated for consonants (Sharma & Dorman, 2000), and other segmental aspects of phonology including phonotactics (Dehaene-Lambertz, Dupoux, & Gout, 2000), phoneme boundaries (Ylinen, Shestakova, Huotilainen, Alku, & Naatanen, 2006), and size of phoneme inventories (Hacquard, Walter, & Marantz, 2007). Apart from segmental information in speech, crosslanguage studies have also examined preattentive processing of suprasegmental features (i.e. duration, pitch, loudness) using the MMN. The MMN response was found to be sensitive to changes in duration associated with contrastive vowel length (e.g., / tuli / "fire" vs. / tu:li / "wind) in Finnish (Nenonen, Shestakova, Huotilainen, & Näätänen, 2003) and with changes in pitch associated with lexical contrasts (Chandrasekaran, Krishnan, & Gandour, 2007b).

A model of experience-dependent plasticity based on studies examining segmental information in speech suggests that in addition to an acoustic change detection process, the MMN responses for native speakers is modulated by a LH dominant phonetic change detection process (Näätänen, 2001; Näätänen, et al., 1997; Näätänen, et al., 2007). Since non-native speakers do not have long-term stored categorical representations for native phonemes, the model predicts that they rely purely on the acoustic change detection process. There are three key predictions made by the model. MMN modulation for native speakers results from a *language-specific* process that utilizes categorical phonetic representations. These long-term stored categorical representations, absent in non-native speakers, are hypothesized to drive experience-dependent plasticity for native speakers. The acoustic change-detection process is *language-universal*. In other words, up to the cerebral cortex, linguistically relevant sounds engage the auditory system in a similar manner for native and non-native speakers. MMN modulation to linguistically-relevant stimuli, as a function of language experience, is a LH dominant process. Presumably, this reflects the stored categorical representations for native speakers.

The Näätänen et al. model of neuroplasticity was based on cross-language studies using *segmental* units in speech. It is unclear if it has the potential to explain neuroplasticity due to experience with *suprasegmental* units. In this paper we review recent studies on preattentive processing of linguistic pitch, and discuss whether their model of neuroplasticity extends to linguistic pitch processing.

Tone languages as windows on neural processing of pitch

Mandarin Chinese is a tone language. In addition to consonants and vowels, Chinese has four tones: ma^1 'mother', ma^2 'hemp', ma^3 'horse', ma^4 'scold'. Tones 1 to 4 can be described phonetically as high level (T1), high rising (T2), low falling rising (T3), and high falling (T4), respectively (Howie, 1976). Voice fundamental frequency (f_0) contours provide the dominant cue for tone recognition (Xu, 1997). Perceptual data on Mandarin tones indicate that variation in F_0 yields high levels of recognition for isolated tones (Howie, 1976).

Thai is also a tone language. It has five tones: k^haa^M 'stuck', k^haa^L 'galangal', k^haa^F 'kill', k^haa^H 'trade', k^haa^R 'leg'). The mid tone (M) can be described phonetically as mid level with a final drop, low tone (L) as low falling, falling tone (F) as high falling, high tone (H) as high rising, and rising tone (R) as low rising (Tingsabadh & Abramson, 1993). Perceptually, f_0 contours have been shown to be the primary acoustic correlate of Thai tones (Abramson, 1962).

Using tone languages to explore experience-dependent plasticity to linguistic pitch patterns

In tone languages, pitch variations are important in every syllable. This information is as important for native speech processing as consonants or vowels. They give us an opportunity to examine the linguistic role of pitch at attentive and preattentive stages of processing.

As pitch itself is multidimensional in nature, multidimensional scaling studies (Gandour, 1983; Gandour & Harshman, 1978) have revealed that although pitch dimensions are shared in common regardless of language typology, these dimensions are differentially weighted as a function of language experience. Across the board, native speakers of a tone language place more emphasis on pitch contour, characterized by pitch direction and slope, than on pitch height, whereas just the opposite is true for speakers of a non-tone language (English). These data suggest that long-term language experience shape the relative saliency of pitch dimensions at perceptual stages of processing.

Functional neuroimaging studies using PET (positron emission tomography) and fMRI (functional magnetic resonance imaging) have examined pitch processing in native vs. nonnative speakers of tone languages at the level of the cerebral cortex (Gandour, 2006a, 2006b, 2007; Zatorre & Gandour, 2008, for reviews). These studies have consistently implicated the LH in pitch processing when pitch patterns are linguistically relevant to the listener. For example, Thai tones do not elicit LH activation when discrimination judgments are performed by Mandarin speakers. The influence of long-term categorical representations on pitch processing has been further demonstrated using hybrid stimuli, created by superimposing Thai tones onto Mandarin syllables (*tonal chimeras*) and Mandarin tones onto the same syllables (real words) (Xu, et al., 2006). In the left planum temporale, a double dissociation occurs between language experience (Chinese, Thai) and neural representation of tonal contours (native, nonnative), such that stronger activity is elicited in response to native as compared to non-native tones.

From a neural perspective, these PET and fMRI findings would lead us to predict that suprasegmental information is similar to segmental information at attentive stages of processing. Lexical tones are processed in the LH for native speakers, suggesting that tonal categories drive experience-dependent plasticity, and moreover, that experience-dependent plasticity to linguistic pitch is language-specific.

We have recently expanded our knowledge base of how linguistic pitch patterns are neutrally instantiated by examining *preattentive* stages of processing in the cerebral cortex. Specifically, we have investigated the nature and limits of plasticity to linguistic pitch contours by using both crosslanguage (Chinese, English) and cross-domain (Chinese, non-native musicians and non-musicians) experimental designs. The cross-language design compared the MMN to pitch from speakers of a tone language (Chinese) and a non-tone language (English). The cross-domain design compared the MMN to pitch from those with expertise in linguistic pitch (i.e., native speakers of Mandarin) to those with expertise in musical pitch (i.e., amateur musicians). We next discuss the results of these studies within the framework of the Naatanen et al. model of neuroplasticity.

Do long-term stored categorical representations modulate preattentive neuroplasticity to linguistic pitch?

We first compared MMN responses from Mandarin and English speakers to linguistically-relevant pitch contours (T1, T2, T3) embedded in a speech context (*/yi/*) (Chandrasekaran, Krishnan, et al., 2007b). All three stimuli represented real Mandarin words. Our aim was to examine whether cross-language differences can be observed at early preattentive stages of processing in the cerebral cortex. In one condition (T1/T3), we compared T1, the standard, to T3 as a deviant. In (T2/T3), we compared T2, the standard, to T3 as a deviant. We predicted that, by virtue of their long-term expertise with tonal categories, Mandarin speakers would demonstrate enhanced MMN responses across conditions. Instead, we found experience-dependent enhancement of the MMN for the T1/T3 condition, but not T2/T3.

Since all three stimuli exhibited prototypical f_0 trajectories of Mandarin tones, these results cannot be explained on the basis of long-term stored representations for native speakers Rather, they suggest that the MMN may be indexing the relative saliency of perceptual dimensions that underlie lexical tones. The contour dimension has been shown to be important in separating Mandarin speakers from English (Gandour, 1978). Since T2 and T3 are very similar in f_0 contour and direction, we argue that a condition involving the two tones (T2/T3) does not provide a processing advantage for native speakers at the preattentive stage of processing.

Thus, we conclude that MMN modulation to pitch contours reflects cross-language differences in the acoustic weighting of pitch dimensions. In a companion study, using a multidimensional scaling analysis of the MMN, we examined the number and nature of dimensions underlying the preattentive tonal space in Mandarin and English speakers (Chandrasekaran, Gandour, & Krishnan, 2007). We discovered two dimensions, interpreted as 'contour' and 'height' that defined the shared MMN tonal space across groups. Consistent with perceptual studies, Mandarin speakers attached more importance to 'contour' than to 'height'. Discriminant function analysis on the dimension weights further revealed that the contour, but not the height dimension, effectively separated the two groups.

Taken together, these studies clearly demonstrate cross-language differences in the weighting of acoustic dimensions. However, we were unable to rule out lexical effects on the MMN responses because all stimuli in the above-mentioned MMN studies were actually-occurring words in Mandarin. Lexical status of stimuli (words vs. nonwords) has been shown to modulate the MMN (Pulvermüller, et al., 2001; Pulvermüller & Shtyrov, 2006). To eliminate this potential lexical-semantic confound, we next examined MMN responses to non-speech pitch contours modeled after Mandarin tones using iterated rippled noise (IRN) stimuli

(Chandrasekaran, Krishnan, & Gandour, 2007a). Similar to speech stimuli, the nonspeech, time-varying IRN stimuli also elicited experience-dependent plasticity. Thus, we conclude that neuroplasticity to linguistic pitch is not specific to the speech context.

A follow-up study was conducted to examine whether acoustic or phonetic change detection processes contribute towards neuroplasticity to nonspeech linguistic pitch contours (Chandrasekaran, Krishnan, & Gandour, in press). MMN responses from Chinese and English were collected in response to two conditions. In one condition, the Mandarin high level tone (T1) was compared with a convex high rising tone (inverted T2; 'T2i') that occurs as a contextual variant of T1 in running speech. In the other, the concave high rising tone (T2) was compared to T2i. Phonetically, T1/T2i represents a within-category contrast for native speakers, whereas T2/T2i represents a between-category contrast. Nonetheless, the between-category pair (T2/T2i) is more similar acoustically than the within-category pair (T1/T2i). At attentive stages of processing, as predicted, the Chinese group was less accurate than the English in discriminating the within-category contrast (T1- T2i). However, with respect to the MMN, native speakers showed larger MMN responses than English speakers in both conditions. Indeed, within the Chinese group, larger MMN responses were elicited for the within-category condition (T1/T2i) condition relative to the across-category condition (T2/T2i). These findings demonstrate that experience-dependent neural effects at early *preattentive* stages of processing may be driven primarily by acoustic features of pitch contours that occur in natural speech. At attentive stages of processing, perception is strongly influenced by tonal categories and their relations to one another. The mismatch negativity is a useful index in examining long-term plasticity to linguistically-relevant acoustic features.

Is experience-dependent plasticity to linguistic pitch patterns language-specific?

The Naatanen et al. model predicts that neuroplasticity to linguistically-relevant segmental information is language-specific. To test this prediction for linguistic pitch, we examined MMN responses to linguistic pitch contours from Mandarin speakers, and nonnative English-speaking musicians and non-musicians (Chandrasekaran, Krishnan, & Gandour, 2009). If neuroplasticity were indeed language-specific, we would expect to see no differences between musicians and non-musicians in the processing of linguistically-relevant pitch. Instead, we found graded neuroplasticity, as reflected by the robustness of the MMN response (Mandarin > musicians > nonmusicians). Comparing musicians and non-musicians, we found that musical experience modulated the MMN response to linguistic pitch contours. Thus, neuroplasticity was found to be domain-general and not specific to language. These data are consistent with another recent study which demonstrated that music experience modulated preattentive brainstem responses to Mandarin pitch contours (Wong, Skoe, Russo, Dees, & Kraus, 2007). Since the amateur musicians in these studies had no previous exposure to Mandarin, and therefore, no long-term stored representations of tonal categories, neuroplasticity can only be explained as more robust acoustic representation for musicians relative to non-musicians.

Is experience-dependent neural plasticity to linguistic pitch restricted to the cerebral cortex?

The overwhelming majority of cross-language studies on language and the brain have focused on neuroplasticity at the level of the cerebral cortex. Therefore, until recently, neuroplasticity in the brain has been viewed exclusively as a cortical phenomenon. But recent work suggests that *subcortical* processing at the level of the brainstem is also shaped by long-term experience with linguistic and musical pitch patterns (Kraus & Banai, 2007; Krishnan &

Gandour, in press, for reviews). A seminal cross-language (Chinese, English) study examined the effects of language experience on the frequency-following response (FFR) (see Krishnan, 2006, for tutorial on the FFR; Krishnan, Xu, Gandour, & Cariani, 2005), a preattentive evoked response that reflects sustained neural phase-locking in the rostral part of the brainstem. Results showed that long-term experience with linguistically relevant pitch patterns modulates the FFR. Mandarin speakers, relative to the English, have more robust linguistic pitch representation at the level of the brainstem. Music experience also shapes brainstem processing of nonnative linguistic pitch (Wong, et al., 2007). Taken together, these two studies clearly demonstrate experience-dependent plasticity to linguistic pitch as early as the brainstem irrespective of the domain of pitch expertise of the listener. Thus, the subcortical auditory system is not simply a way station that transmits information from the ear to the cerebral cortex. As in the cortex, these data imply that early sensory processing is subject to experience-dependent neural plasticity.

Is preattentive processing of linguistic pitch patterns left-hemisphere dominant?

A number of studies have demonstrated larger MMN responses in the LH for native speakers when listening to native segmental contrasts. These results have been interpreted in terms of modulation of the MMN by long-term phonetic representations residing in the LH. Consequently, bilateral or right hemisphere (RH) dominant activity has been viewed as purely acoustic processing. As reflected by fMRI, at attentive stages of processing, native speakers engage the LH when making discrimination judgments of native tones (Xu, et al., 2006).

To our knowledge, only one study has examined hemispheric asymmetries in preattentive processing of linguistic pitch contours (Luo, et al., 2006). MMN responses were elicited from native speakers when listening to Mandarin syllables in which a consonant or tone was varied in passive oddball sequences. A comparison of consonants to tones showed that MMN for linguistic pitch changes is RH dominant, with the opposite pattern, i.e., LH dominance for segmental information. Given the distinct acoustic features between a lexicaltone and a consonant, this opposite lateralization pattern suggests the dependence of hemisphere dominance mainly on acoustic cues before speech input is mapped into a semantic representation in the processing stream.

Neurobiological basis for neuroplasticity in the early cortical processing of linguistic pitch

In summary, the three key predictions of the Naatanen et al. model of neuroplasticity to linguistically-relevant stimuli do not hold up when we consider the processing of linguistic pitch. Neuroplasticity at preattentive stages appears to be acoustically driven, not language-specific, and lateralized predominantly to the RH. Their model of neuroplasticity based on segmental information does not generalize to suprasegmentals. At present, it remains an empirical question whether pitch processing is a special case. It is more likely that we need to re-conceptualize how sensorial and cognitive components interact in generating the MMN for all linguistically relevant stimuli, pitch or otherwise.

From a neurobiological perspective, it has been demonstrated that the cortex modulates activity in the brainstem via corticofugal pathways. According to an animal model of neuroplasticity (Suga, Gao, Zhang, Ma, & Olsen, 2000; Suga, Ma, Gao, Sakai, & Chowdhury, 2003; Suga, Xiao, Ma, & Ji, 2002), the cortex shapes the brainstem processing to repetitive sounds via the corticofugal feedback mechanism. This *short-term plasticity* improves the response properties of the auditory cortex to the incoming stimulus stream regardless of its behavioral relevance. Once the stimuli achieve behavioral relevance, there is an increase in corticofugal feedback, resulting in more enhanced subcortical tuning, and consequently *long-term cortical plasticity.*

The mismatch negativity to linguistically relevant stimuli is modulated by language-experience. A memory-based model of neuroplasticity derived from data on segmental units suggests that long-term categorical representations, residing in the LH, drive MMN modulation for native speakers. This model is unable to explain experience-dependent plasticity to linguistic pitch. The data reviewed herein reveals cross-language and cross-domain effects on the relative weighting of pitch features underlying the MMN. An explanation based simply on phonetic categories is not supported. Instead, they strongly reflect the malleability of acoustical encoding of pitch at early stages of auditory processing, and point to the involvement of both hemispheres that are differentially engaged in the generation of the MMN depending on acoustic/auditory features associated with segmental or suprasegmental information (Poeppel, 2003; Poeppel, Idsardi, & van Wassenhove, 2008; Zatorre & Belin, 2001; Zatorre & Gandour, 2008). The experience-dependent plasticity for pitch reflected in the more robust MMN responses for native listeners may reflect subcortical inputs that are enhanced by corticofugal influence on brainstem pitch mechanisms.

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