Chapter 42: Tone and Music Processing in Chinese

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Abstract

In tonal languages like Chinese, pitch is used to systematically differentiate word meanings. The use of pitch is not unique to language. In music, pitch also plays a fundamental role. Presumably due to the substantial overlap in pitch usage, cross-domain transfer effects between tonal language experience and musical expertise on pitch processing have been widely observed. This chapter will provide an overview of the behavioural evidence for such transfer and discuss the neural mechanisms that likely support the behavioural transfer effects to shed light on the broader question of how language and music are organized in the human brain.

Keywords: lexical tone, music, cross-domain transfer, Chinese, neural mechanism

Introduction

Language and music are similar in many ways. Both language and music are old and ubiquitous in all human cultures. In terms of structure, both language and music are abstract systems with complex hieratical structures (e.g., Jackendoff and Lerdahl 2006). Furthermore, language and music share many sound attributes (e.g., pitch and rhythm), especially the systematic use of pitch (e.g., Jackendoff and Lerdahl 2006). On the one hand, musical notes are based on pitch differences, which are hierarchically organized to form a melody. On the other hand, the use of pitch is universal in the world's languages (e.g., Wang 1972). All languages use pitch patterns to indicate intonation at the sentence level, such as question/statement (e.g., Pierrehumbert 1980), and to mark emotional states (e.g., Fairbanks and Pronovost 1939; Rodero 2011). In about half of the world's languages, pitch is further used at the word level to systematically differentiate word meanings (Yip 2002). These languages are called tonal languages, which have an even closer relationship with music. In a word, pitch is a fundamental building block in language as well as music.

Similarities between language and music have evoked important theoretical questions regarding the neural organization of language and music in the human brain (Lerdahl and Jackendoff 1985; Koelsch 2005; Koelsch and Siebel 2005; Patel 2007; Nan and Friederici 2013). It has been found that the processing of pitch, syntax and semantics in music recruits the same brain processes and brain regions involved in language processing, indicating that the neural organization of language and music overlaps with each other (Patel et al. 1998; Levitin and Menon 2003; Tillmann, Janata, and Bharucha 2003; Nan and Friederici 2013). Close acoustic and structural similarities between language and music have also led scholars to hypothesize a common evolutionary origin of the two (Darwin, 1871; Fitch 2006; Thompson et al. 2012; Wang 2015). It has been conjectured that language and music might have descended from a common evolutionary origin, for instance, a "musical protolanguage" used in courtship and expression of emotion (Darwin 1871; Fitch 2006; Thompson et al. 2012).

Despite the large body of studies that support the neural and evolutionary link between language and music, there have also been claims that language and music are distinct systems (Chomsky 1981; Fodor 1983; Peretz 2001; Rogalsky et al. 2011; Norman-Haignere, Kanwisher, and McDermott 2015). In line with these claims, separate brain processes and brain regions involved in language and music processing have been reported. For instance, Rogalsky et al. (2011) found substantial non-overlap between the processing of sentences and melodies, especially in Broca's Area, which was previously claimed to subserve hierarchical processing in both language and music (e.g., Levitin and Menon 2003). In a recent study, Norman-Haignere, Kanwisher, and McDermott (2015) used voxel decomposition to identify the primary components of brain response variations across natural sounds, including speech and music; they found distinct neural circuitries for music and speech in the non-primary auditory cortex. Thus, the neural link between language and music remains debated. Other than comparing the neural circuitries for language and musical processing in the human brain as did the aforementioned studies, another area of research that can shed some important light on this debate is the cross-domain transfer between language and music. It is reasonable to speculate that consistent cross-domain transfer between language experience and musical ability suggests a link of language and music in the human brain, whereas a lack of cross-domain transfer might suggest distinct neural pathways.

This chapter will review the cross-domain transfer effects of language experience and musical ability on pitch processing at the behavioural and neural level, focusing on tonal language. As mentioned, there is a close relationship between tonal language and music, as pitch is a fundamental building block for lexical tones in tonal languages and for musical notes and melodies in music. Previous studies have examined two ends of the musical ability spectrum, namely, superb musical ability (i.e., musicianship) and impoverished musical ability (i.e., congenital amusia). The following sections will first review behavioural studies, focusing on the positive transfer between musicianship and linguistic pitch (lexical tone) processing, and then the negative transfer between congenital amusia and linguistic pitch processing. After a review of the behavioural evidence, the underlying neural mechanisms that probably subserve such language-music transfer will be discussed. The theoretical and practical implications of these findings will be discussed in the last section.

Behavioural evidence for cross-domain transfer

Musicianship

With regard to musicianship, findings from previous studies have revealed a bidirectional transfer effect on pitch processing between tonal language experience and musicianship (Deutsch et al. 2006; Lee and Hung 2008; Pfordresher and Brown 2009; Lee, Lekich, and Zhang 2014), in that tonal language experience tends to boost musical pitch processing, while musicianship tends to boost lexical tone processing.

For the transfer from tonal language experience to musical pitch processing, an important discovery is that absolute pitch, or perfect pitch, an extraordinary ability to identify or produce a musical note without the aid of a reference note, is more common in Chinese-speaking musicians than in English-speaking musicians (Deutsch et al. 2006; Deutsch et al. 2009; Peng et al. 2013). Absolute pitch is a very rare ability, with an estimated prevalence rate of less than one in 10,000 (Profita et al. 1988). This ability is often found in musicians and is strongly correlated with the onset age of musical training, such that it is more likely for individuals with an early onset of musical training to have absolute pitch ability (Deutsch et al. 2006). Interestingly, the prevalence of absolute pitch was far greater among Chinese-speaking musicians than English-speaking musicians when the onset age of musical training was matched (Deutsch et al. 2006; Deutsch et al. 2009; Peng et al. 2013). Furthermore, it appears that the higher prevalence in Chinese-speaking musicians is primarily due to tonal language experience, suggesting that it is not genetically driven (Deutsch et al. 2009); for instance, among immigrants with an East Asian ethnic heritage in the US, their performance of absolute pitch decreases as tonal language fluency deteriorates.

It has been claimed that the ability to track absolute pitch appears to be universally present in early life (Saffran and Griepentrog 2001). It has also been argued that learning to systematically associate pitches with words in a tonal language helps to retain the ability of absolute pitch into adulthood (Deutsch et al. 2006), though the specific mechanism is not clear yet. For speakers growing up in a non-tonal language environment, this ability is eventually lost, unless musical training starts at a sufficiently early age. In a word, learning a tonal language early in life is parallel to learning music to some extent—both have a positive impact on the retention of absolute pitch ability.

The advantage in musical pitch processing associated with tonal language experience is not only found in musicians but also in ordinary individuals with little or no musical training. Pfordresher and Brown (2009) found that a mixed group of speakers of several tonal languages in South Asia (i.e., Mandarin, Vietnamese and Cantonese) with little or no musical training were better able to imitate pitch and perceptually detect small pitch incongruities in pairs of music melodies than a group of matched English non-musicians. This finding was replicated in a more homogeneous group of speakers who all spoke Cantonese and had minimal musical training (Bidelman, Hutka, and Moreno 2013). The Cantonese non-musicians outperformed the English non-musicians, who had no prior exposure to a tonal language, in a task requiring them to detect pitch incongruities as small as 50 cents between two six-note melodies. When the pitch incongruities decreased to 25 cents, the Cantonese non-musicians performed comparably to the English non-musicians, while both groups performed worse than the English musicians. These findings demonstrate that tonal language experience has a wide impact on fine-tuning pitch sensitivity among ordinary individuals without musical training to detect small musical pitch incongruities to some extent.

As for the transfer from musical expertise to lexical tone perception, there is also a substantial amount of supporting evidence. It has been found that English-speaking musicians were more accurate at identifying Mandarin tones than English-speaking non-musicians, no matter whether the tones were intact or deprived of acoustic information in the middle of a syllable (i.e., the silent-centre syllable) (Lee and Hung 2008). English speakers with better musical ability were more accurate in discriminating pairs of Mandarin tones than those with less superb musical ability (Alexander, Wong, and Bradlow 2005; Delogu, Lampis, and Olivetti Belardinelli 2006, 2010). In addition to tone identification and discrimination, English-speaking musicians also outperformed non-musicians in learning to categorize non-native Mandarin tones (Smayda, Chandrasekaran, and Maddox 2015).

Though the majority of studies have focused on Mandarin tones, similar positive transfer has been reported in other tonal languages. When given Taiwanese high/low-level tones to identify, English-speaking musicians outperformed non-musicians in judging the height (i.e., high/low) of the tones (Lee, Lekich, and Zhang 2014). In particular, these high/low-level tones were produced by 15 male and 15 female native speakers with varied pitch ranges. Identifying high/low-level tones produced by different speakers requires an ability to estimate an unfamiliar speaker's pitch range, since a tone produced by different speakers can vary dramatically in the absolute pitch height, but its location relative to a particular speaker's pitch range is often largely consistent (Peng et al. 2012; Zhang et al. 2012, 2013; Zhang and Chen 2016; Zhang et al. 2016). This finding thus suggests that musicians are not only more accurate in perceiving pitch but also in guessing an unfamiliar speaker's pitch range.

While the aforementioned studies have consistently confirmed the advantage of musical experience in non-tonal language speakers, it is less clear how musical experience affects tone processing in tonal language speakers. That is, for tonal language speakers who already have lexical tone exposure, does musical experience further improve their perception of lexical tones? The findings appear to be mixed. Wu et al. (2015) found that Mandarin-speaking musicians performed similarly to Mandarin-speaking non-musicians on the categorical perception of a lexical tone continuum (high-level tone—high-falling tone) in Mandarin, and the only advantage of the musicians was found in the discrimination of within-category stimulus pairs. Tang et al. (2016) found that Mandarin-speaking musicians were faster in the discrimination of Mandarin tones than non-musicians. However, among speakers of Cantonese, another tonal language, musical training was found to have little influence on the perception of Cantonese tones (Mok and Zuo 2012). Altogether, these findings suggest that the advantage of musicianship in tonal language speakers, if any, seems to be rather mild, mostly facilitating their accuracy of discriminating within-category pitch distinctions or response speed.

To summarize, the studies reviewed above support a bidirectional transfer effect on pitch processing between tonal language experience and musicianship. While tonal language experience enhanced musical pitch processing no matter whether tonal language speakers had musical training or not, musicianship led to better performance in the perception and learning of lexical tones, especially in non-tonal language speakers. Thus, the advantage of musicianship in tonal language speakers seems to be mild and not always consistent.

Congenital amusia

Congenital amusia is a lifelong neurogenetic disorder primarily influencing musical pitch processing (Peretz et al. 2002; Hyde and Peretz 2003, 2004). Individuals with congenital amusia often have difficulty in detecting mistuned melodies or memorizing familiar tunes, and it is estimated to influence about 3~4% of the population (Peretz et al. 2008; Nan, Sun, and Peretz 2010; Wong et al. 2012). Amusia can also occur during adulthood, for example, after a stroke or head injury (e.g., Schuppert et al. 2000). The symptoms and causes of acquired amusia are more variant and complex. The focus of discussion here will be on congenital amusia (amusia hereafter).

As mentioned, the prevalence rate of absolute pitch ability is higher in Chinese-speaking musicians than in English-speaking musicians (Deutsch et al. 2006; Deutsch et al. 2009; Peng et al. 2013), which leads to this question: Is congenital amusia *less* common in Chinese speakers? The results obtained so far are mixed, and the prevalence rate appears to be contingent on the complexity of the tonal system. It has been found that the prevalence rate of amusia is around 3.4% in Mandarin speakers, comparable to that in Canadians (Nan, Sun, and Peretz 2010). Interestingly, among speakers of Cantonese, a tonal language more complex than Mandarin, the prevalence rate appears to be lower than that in Canadians (Wong et al. 2012). Cantonese has a total of nine tones, with six unchecked tones carried by open syllables and three checked tones carried by short syllables with a stop coda (Bauer and Benedict 1997), whereas Mandarin has only four tones plus a fifth neutral tone that occurs only on unstressed syllables. This result seems to indicate that learning to speak a sufficiently complex tonal language, like Cantonese, might provide some protection against amusia. However, this result should be interpreted with caution for the following two reasons. First, Cantonese speakers recruited in a previous study (Wong et al. 2012) had longer musical training than the Canadians. Although it was confirmed that in a sub-group of Cantonese speakers with a matched length of musical training as the Canadians, the prevalence rate was still lower in the Cantonese speakers, so musical training could be the issue. Second, a study on Cantonese speakers was conducted using the online identification test of congenital amusia (Peretz et al. 2008), whereas the study on Mandarin speakers was conducted using a different test, the Montreal Battery of Evaluation of Amusia (MBEA) (Nan, Sun, and Peretz 2010). Although there was a strong correlation between the scores of the online test and the MBEA in individuals who took both tests (Peretz et al. 2008), the diagnostic results were not necessarily identical in all cases given these two tests. Thus, future studies with careful control of musical training and identical diagnostic tests are needed to shed more light on the question of whether experience with a complex tonal system provides some protection against amusia.

A second question is, does amusia lead to an inferior performance in lexical tone processing? As has been found, individuals with musicianship demonstrated an advantage in lexical tone perception. Studies on amusia have consistently pointed out that amusia leads to a disadvantage in lexical tone perception, which is a mirror image of the scenario of musicianship. Among non-tonal language speakers, individuals with amusia exhibited reduced accuracy in discriminating non-native lexical tones (Nguyen et al. 2009; Tillmann et al. 2011). As for tonal language speakers, the evidence also confirmed that amusia led to impairment in lexical tone perception, irrespective of the complexity of the tonal systems (Nan, Sun, and Peretz 2010; Liu et al. 2015; Vuvan, Nunes-Silva, and Peretz 2015; Huang et al. 2016; Shao et al. 2016). These findings are not contradictory to the possible protective effect of experience with a complex tonal language against amusia mentioned above (Wong et al. 2012). Even if speaking a sufficiently complex tonal language might reduce the rate of amusia, for those tonal language speakers who are actually amusic, there appears to be a negative effect of amusia on lexical tone processing.

Nan, Sun, and Peretz (2010) found that about half of 22 Mandarin-speaking amusics performed worse than the musically intact Mandarin-speaking controls in both the identification and the discrimination of Mandarin tones. Among them, six amusics further performed three standard deviations (SDs) below the mean accuracy of the controls. Such severe impairment led the authors to propose that these six amusics had "lexical tone agnosia"—an inability to recognize lexical tones. In Cantonese, impaired lexical tone perception in amusics has also been reported. Liu et al. (2015) found that a group of Cantonese-speaking amusics was less accurate in identifying Cantonese tones than the musically intact controls. In particular, these amusics were more likely than the controls to confuse acoustically similar tones (e.g., high-rising/low-rising tone, mid-level/low-level tone and low-level/low-falling tone), as indicated by their identification errors. Shao et al. (2016) further confirmed that Cantonese-speaking amusics were less accurate than the controls in both the identification and the discrimination of Cantonese tones, though the disparity between the amusics and the controls was larger in identification than discrimination, perhaps because the discrimination task was easier.

Importantly, there is accumulating evidence that the pitch deficit in tonal language speakers is not purely auditory in nature but extends to higher-level phonological processing of lexical tones (Nan, Sun, and Peretz 2010; Jiang et al. 2012b; Wang and Peng 2014; Huang et al. 2015; Zhang, Shao, and Huang 2017). Nan, Sun, and Peretz (2010) found that the impairment of Mandarin-speaking amusics in tone discrimination was most pronounced when the carrying syllables were different. This implies that amusics might have a phonological deficit related to extracting tonal information from syllables or noting the information of the lexical tone category despite syllable variations (e.g., noting that the tone was the same even when the carrying syllables were different).

Most critical evidence for Chinese amusics' deficit in phonological processing has come from studies on the categorical perception of lexical tones (Jiang et al. 2012b; Huang et al. 2015; Zhang, Shao, and Huang 2017). An early study on Mandarin-speaking amusics found that whereas the amusics showed a comparably abrupt response shift to the controls in the identification of two lexical tone continua (i.e., high-level/high-rising tone and high-level/high-falling tone), they failed to exhibit a robust discrimination peak across the categorical boundary (Jiang et al. 2012b). This suggests that Mandarin-speaking amusics failed to perceive tones categorically. A recent study further confirmed that some Mandarin-speaking amusics were impaired in the categorical perception of lexical tones, failing to exhibit a sharp response shift across the categorical boundary in identification, as well as an enhanced peak in discrimination, though there were individual variations among the amusics (Huang et al. 2015). The finding of the impaired categorical perception of lexical tones was again reported in Cantonese-speaking amusics. It has been found that Cantonese-speaking amusics exhibited less benefits in the between-category discrimination of lexical tone stimuli (high-level/high-rising tone) than the musically intact controls (Zhang, Shao, and Huang 2017). This indicates that Cantonese-speaking amusics perceived lexical tones less categorically than the controls, a finding consistent with those reported for Mandarin-speaking amusics.

To summarize, there seems to be a bidirectional transfer effect on pitch processing between tonal language experience and amusia. Learning to speak a sufficiently complex tonal language like Cantonese might provide some protection against amusia, though this result is subject to further scrutiny in future studies. As for the influence of amusia on lexical tone processing, the findings have consistently pointed out that amusia leads to a worse performance in lexical tone perception in non-tonal as well as tonal language speakers. Furthermore, there is growing evidence that the pitch deficit in tonal language speakers with amusia is not confined to auditory pitch processing but extends to phonological processing.

Neural bases of cross-domain transfer

As reviewed above, a plethora of behavioural studies have demonstrated bidirectional transfer between tonal language experience and musical ability. While musicianship is associated with superb performance in lexical tone perception, amusia is associated with poor lexical tone performance. This leads to the question of the neural mechanisms of such cross-domain transfer: Where in the auditory neural pathway does the transfer occur between lexical tones and music? Similar to the organization of the previous section, neuroimaging studies on musicianship will be reviewed first, and then studies on amusia, in this section.

Musicianship

Current evidence suggests that neural transfer between musicianship and tonal language experience occurs via subcortical sensory processing; neural transfer might further occur at the cortical level, though the evidence is less consistent, partly due to the lack of studies. Traditionally, subcortical sensory processing at the brainstem is believed to be rigid and unchangeable, partly because of a lack of studies on subcortical processing. Recent studies have revealed that subcortical sensory processing is actually plastic and shapeable by long-term experience (Krishnan et al. 2004, 2005; Bidelman, Gandour, and Krishnan 2011) and short-term training (Russo et al. 2005; Song et al. 2008), presumably via a cortical feedback mechanism (Tzounopoulos and Kraus 2009). In particular, the frequency-following response (FFR), which is an auditory-evoked potential in response to periodic or nearly periodic auditory stimuli generated at the brainstem (e.g., the inferior colliculus), is shaped by long-term experience (Krishnan et al. 2004; Wong et al. 2007; Chandrasekaran, Gandour, and Krishnan 2009a; Bidelman, Gandour, and Krishnan 2011).

It has been found that the faithfulness of brainstem pitch encoding, as reflected by the similarity between the periodicity of the FFR and the auditory stimuli, is enhanced by long-term experience with tonal language as well as music (Wong et al. 2007; Bidelman, Gandour, and Krishnan 2011). On the one hand, Mandarin speakers showed more faithful pitch tracking of music notes than English speakers, though both groups had no musical training, which suggests the transfer from tone language experience to musical processing at the brainstem (Bidelman, Gandour, and Krishnan 2011). On the other hand, English-speaking musicians showed more accurate pitch tracking of Mandarin tones than English-speaking non-musicians, though both groups had no tonal language experience, which suggests the transfer from musical training to lexical tone processing at the brainstem (Wong et al. 2007; Bidelman, Gandour, and Krishnan 2011). Thus, there appears to be a bidirectional transfer between tonal language experience and musicianship in terms of brainstem pitch encoding; faithful pitch tracking at the brainstem likely minimizes the loss or distortion of the pitch information to be transmitted to the cortex for further processing down the stream.

As for cortical-level transfer, a couple of studies have looked at this issue, but the evidence is less consistent and appears to depend on the direction of the transfer. For the transfer from tonal language experience to pitch processing, there is little evidence for cortical enhancement associated with tonal language experience. One study by Hutka, Bidelman, and Moreno (2015) examined this question but found no neural enhancement in mismatch negativity (MMN), an early automatic cortical response to acoustic changes in auditory stimuli, in Cantonese-speaking non-musicians compared to English-speaking non-musicians, despite the clear behavioural advantage of Cantonese-speaking non-musicians in detecting small pitch incongruities in pairs of musical melodies. In other words, there was no clear evidence for the enhancement of early, preattentive cortical activities in refined pitch changes associated with tonal language experience. Nonetheless, the lack of evidence might be due to the scarcity of studies, so more neuroimaging studies in the future are critical for a better understanding of this issue.

On the other hand, evidence has been reported for the cortical enhancement of lexical tone processing associated with musical experience. Chandrasekaran, Krishnan, and Gandour (2009b) found larger MMN responses to non-speech analogues of Mandarin high-level and high-rising tone contrast in English-speaking musicians compared with English-speaking non-musicians; native Mandarin speakers exhibited even larger MMN responses than English-speaking musicians. This demonstrates that musical and tonal language experience enhances MMN responses to the linguistic pitch contour presented in a non-speech context. In another study, enhancement of cortical activities associated with musicianship was found in the processing of lexical tones with active attention (Marie et al. 2010). French-speaking musicians showed an earlier peaking N2/N3 component and an enhanced P3b component than non-musicians when they attentively listened to Mandarin tones, accompanied by more accurate discrimination of those tones behaviourally. These findings indicate that musicianship enhances preattentive and attentive neural processing of pitch in non-native lexical tones.

In a functional magnetic resonance imaging (fMRI) study, Nan and Friederici (2013) examined the neural substrates of musical and lexical tone processing in a group of Mandarin-speaking musicians with similar experience across two domains. Though this study did not address the question of cross-domain transfer between tonal language experience and musicianship on pitch processing, it shed some light on the neural substrates of musical and lexical tone processing in the brain. The authors found common pitch processing networks between music and lexical tones, including the pars triangularis within Broca’s Area and the right superior temporal gyrus (STG), with the latter region being more sensitive to music than to lexical tones. This finding therefore provides some evidence for a shared cortical neural network of music and lexical tones in the brains of Mandarin speakers, which might be part of the neural network that supports the transfer between tonal language experience and music.

To summarize, the neural enhancement of pitch tracking associated with tonal language experience and musicianship has been consistently found subcortically in the FFR response. Cross-domain transfer has also been found at the cortical level, though a full understanding of this issue remains to be achieved with more neuroimaging studies in the future. While there is little evidence for the cortical enhancement of pitch processing associated with tonal language experience as yet, evidence has been reported for enhanced preattentive and attentive neural processing of linguistic pitch contour associated with musicianship. A shared neural network of lexical tone and musical processing, including Broca's Area and the right STG, likely supports the cortical-level transfer. Enhanced subcortical-level pitch tracking and cortical-level pitch processing likely cumulatively contribute to the language-music transfer observed behaviourally in the previous section.

Congenital amusia

So far, very few studies have looked at the transfer between amusia and lexical tone at the neural level. It is yet unclear where in the auditory pathway the transfer occurs between amusia and lexical tone processing. At the subcortical level, Liu et al. (2015) found that the FFR pitch tracking of tonal and musical stimuli in the brain of Cantonese-speaking amusics was comparable to that of the musically intact controls. This finding led the authors to suggest that the neural impairment of Cantonese-speaking amusics was in cortical-level pitch processing. However, different findings were reported by Lehmann et al. (2015), who found that the auditory brainstem response to the complex sound /da/ was impaired in amusics. The auditory brainstem response exhibited reduced spectral amplitude in higher harmonic components and was delayed in timing in amusics. Although this study did not look at tonal language speakers, it provided some evidence for potentially impaired subcortical processing of complex speech sounds in amusics. Due to the different findings, how subcortical processing is affected in the amusia brain remains inconclusive.

At the cortical level, the results are also not very clear, but a general picture is emerging from the available data. In brief, it appears that cortical processing deficits of amusia in tonal language speakers might be different from those in non-tonal language speakers, and might overlap with neural circuitries of lexical tone processing, which suggests an influence of tonal language experience. In non-tonal language speakers, despite some dispute, several studies have shown that the auditory cortices of amusics respond normally to pitch, especially in preattentive pitch processing (Peretz, Brattico, and Tervaniemi 2005; Peretz et al. 2009; Hyde, Zatorre, and Peretz 2011; Moreau, Jolicœur, and Peretz 2013; Omigie et al. 2013; Norman-Haignere et al. 2016). Instead, the neural deficits are localized in the right hemisphere fronto-temporal network (Albouy et al. 2013), especially in a music-selective region in the right inferior frontal gyrus (IFG) (Hyde, Zatorre, and Peretz 2011), which is involved in musical pitch encoding and pitch memory (Zatorre, Evans, and Meyer 1994; Holcomb et al. 1998; Griffiths et al. 1999).

So far, there have been few neuroimaging studies on tonal language speakers with amusia. Nonetheless, several studies converged in finding that pitch processing in auditory cortices is likely to be deficient in Chinese amusics, which appears to be different from non-tonal language speakers. Jiang et al. (2012a) found that the neural deficit of Mandarin-speaking amusics during the active processing of illegal intonation patterns started as early as in the N100 time window, which is an early auditory processing component presumably generated in the auditory cortices (Griffiths et al. 1998; Seither-Preisler et al. 2004). In another study, Nan et al. (2016) found that preattentive auditory processing of lexical tones, as indexed by MMN, was abnormal in Mandarin-speaking amusics, who also exhibited a lexical tone perception deficit behaviourally. These amusics showed reduced MMN responses to lexical tone changes compared with the musically intact controls, whereas the MMN responses to consonant changes were normal, as expected. Since the primary source of MMN is located in the auditory cortex (with a secondary source in the frontal lobe) (Alho 1995), this result implies that Mandarin-speaking amusics might be impaired in pitch processing in auditory cortices. These findings thus deviate from those on non-tonal language speakers to some extent. However, a normal auditory (N100) response in Chinese amusics has been reported. Lu et al. (2015) found that the N100 was normal in Mandarin-speaking amusics during the processing of intonation patterns (i.e., statement/question) carried by emotion words; as a later response, the N2 showed reduced amplitude in amusics during the processing of pairs of words with different intonation patterns.

In an fMRI study, Zhang et al. (2017) provided more evidence for the cortical deficits of amusia in tonal language speakers. The brain activations of Cantonese-speaking amusics and controls were compared while they listened to pitch-matched Cantonese-level tones and musical stimuli. For each type of stimuli (i.e., level tones or music), eight pairs of stimuli were presented, with the pitch interval between two non-identical stimuli in a pair manipulated in three conditions: (1) repetition condition (eight pairs of lexical tone/musical stimuli repeated, with identical pitch interval and identical pitch height); (2) fixed interval condition (eight pairs of lexical tone/musical stimuli presented, with identical pitch interval but varied pitch height); and (3) varied interval condition (eight pairs of lexical tone/musical stimuli presented, with varied pitch interval and varied pitch height). Cantonese-speaking amusics exhibited abnormal activities in a widely distributed neural network. Most importantly, the right STG in the controls' brains exhibited habituation to repeated pitch intervals in the repetition and fixed interval conditions, and release from habituation in the varied interval condition in lexical tone stimuli, which suggests that the right STG picked up the constancy of pitch intervals in the lexical tone stimuli in the controls' brains. In contrast to the controls, the amusics exhibited an abnormal lack of activation in the right STG in response to the release from habituation by repeated pitch intervals in the same comparison. Furthermore, no significant difference was found between the amusics and the controls in the activation of the right IFG. These findings imply that neural deficits in tonal language speakers might differ from those in non-tonal language speakers and overlap partly with neural circuitries of lexical tone processing (e.g., the right STG).

In summary, a preliminary picture is emerging from the available data, suggesting that cortical deficits of amusia in tonal language speakers might be different from those in non-tonal language speakers, in that pitch processing in auditory cortices, including the right STG, appears to be deficient in tonal language speakers. This discrepancy between tonal and non-tonal language speakers presumably reflects an influence of tonal language experience. Future fMRI studies that directly compare tonal and non-tonal language speakers with amusia with the same design are needed to shed more light on this question.

Discussion

There has been a long-lasting debate over the neural organization of language and music in the human brain (Patel et al. 1998; Peretz 2001; Levitin and Menon 2003; Tillmann, Janata, and Bharucha 2003; Koelsch 2005; Patel 2007; Rogalsky et al. 2011; Norman-Haignere, Kanwisher, and McDermott 2015). While many studies have found shared neural circuitries of language and musical processing (Patel et al. 1998; Levitin and Menon 2003; Tillmann, Janata, and Bharucha 2003; Nan and Friederici 2013), evidence that language and music are distinct neural systems has also been reported (Peretz 2001; Rogalsky et al. 2011; Norman-Haignere, Kanwisher, and McDermott 2015). An important area of research that can shed light on this debate is the cross-domain transfer between tonal language and music. Consistent cross-domain transfer between tonal language experience and musical ability can provide evidence for a link between language and music in the human brain, while the lack of cross-domain transfer might suggest distinct neural pathways.

The behavioural studies reviewed so far have provided corroborative support for systematic cross-domain transfer between tonal language and music. In terms of musicianship, there was a positive bidirectional cross-domain transfer between tonal language and music, such that tonal language speakers exhibited an advantage in musical pitch processing compared with non-tonal language speakers, while musicians demonstrated an advantage in lexical tone processing compared with non-musicians. In terms of amusia, there was a negative cross-domain transfer, such that impoverished musical ability led to poor lexical tone perception.

At the neural level, a picture is emerging from the available data, revealing that the neural circuitries of lexical tone and musical processing are intricately interlinked, with transfer effects observed at the subcortical as well as cortical level. At the subcortical level, context-free neural enhancement (i.e., FFR) associated with tonal language experience and musicianship has been found, such that tonal language speakers showed more faithful FFR pitch tracking no matter whether they listened to lexical tones or musical stimuli, and musicians showed more faithful FFR pitch tracking no matter whether they listened to musical or lexical tone stimuli (Wong et al. 2007; Bidelman, Gandour, and Krishnan 2011). The auditory brainstem thus appears to be an important centre for neural transfer between tonal language and music. At the cortical level, there is further evidence for cross-domain transfer. On the one hand, musicians exhibited enhanced preattentive (MMN) and attentive (e.g., P3b) neural processing of linguistic pitch contour, suggesting that the cortical processing of lexical tones is facilitated by musical experience. On the other hand, tonal language speakers with amusia exhibited functional brain deficits in auditory cortices, including the right STG, which was different from non-tonal language speakers with amusia. This suggests that the cortical deficits of amusia might be modulated by tonal language experience and might overlap partly with neural circuitries of lexical tone processing.

Altogether, the neuroimaging evidence suggests that language and music processing likely share neural circuitries substantially at the subcortical and cortical level. This is consistent with the claim that language and musical processing share neural circuitries in the human brain (Patel et al. 1998; Levitin and Menon 2003; Tillmann, Janata, and Bharucha 2003; Nan and Friederici 2013). This does not mean that the neural circuitries of language and musical processing are identical. Indeed, the neural circuitries of language and musical processing diverge at some point in neural processing (Chomsky 1981; Fodor 1983; Peretz 2001; Rogalsky et al. 2011; Norman-Haignere, Kanwisher, and McDermott 2015). For instance, it is well established that language is predominately processed in the left hemisphere, whereas music is predominately processed in the right hemisphere (e.g., Van Lancker and Fromkin 1973, 1978; Zatorre, Belin, and Penhune 2002; Best 2008).

From an application point of view, cross-domain transfer between language and music helps in understanding the underlying mechanisms of musical therapy used to improve language ability in populations with language impairment. It has been found that musical training enhances auditory and language abilities in young children (Strait, Hornickel, and Kraus 2011; Kraus and Anderson 2014; Kraus et al. 2014a; Kraus et al. 2014b; Slater et al. 2014; Woodruff et al. 2014). At-risk children from disadvantaged backgrounds with learning and social problems, who received two years of musical training, were better able to distinguish stop consonants in the auditory brainstem response, which suggests enhanced auditory processing at the subcortical level (Kraus et al. 2014a). Musical training also has proven to be efficient in speech therapy for patients with aphasia (Sparks, Helm, and Albert 1974; Schlaug, Marchina, and Norton 2008; Norton et al. 2009) and dementia (e.g., Brotons and Koger 2000). It has been observed that many patients with non-fluent aphasia are capable of singing words to familiar tunes without having the ability to say those same words (Sparks, Helm, and Albert 1974). This observation led to the design of melodic intonation therapy, which utilizes the preserved skill in singing to facilitate spoken language production (Norton et al. 2009). It was found that after seven weeks of melodic intonation therapy, a patient with aphasia following a right hemisphere stroke showed improved ability of auditory comprehension and repetition, longer average phrase length and more elicited gestures (Morrow-Odom and Swann 2013). In patients with dementia, melodic intonation therapy also significantly improved speech fluency (Schlaug, Marchina, and Norton 2008).

In conclusion, cross-domain transfer between tonal language and music has been widely observed at the behavioural and neural level. Such cross-domain transfer has shed important light on the debate over the neural organization of language and music in the human brain. From an application point of view, cross-domain transfer helps in understanding the underlying mechanism of using musical training to improve language abilities in various populations.

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