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Musical experience may help the brain respond to second language reading

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Abstract

A person's native language background exerts constraints on the brain's automatic responses while learning a second language. It remains unclear, however, whether and how musical experience may help the brain overcome such constraints and meet the requirements of a second language. This study compared native Chinese English learners who were musicians, non-musicians and native English readers on their automatic brain automatic integration of English letter-sounds with an ERP cross-modal audiovisual mismatch negativity paradigm. The results showed that native Chinese-speaking musicians successfully integrated English letters and sounds, but their non-musician peers did not, despite of their comparable English learning experience and proficiency level. However, native Chinese-speaking musicians demonstrated enhanced cross-modal MMN for both synchronized and delayed letter-sound integration, while native English readers only showed enhanced cross-modal MMN for synchronized integration. Moreover, native Chinese-speaking musicians showed stronger theta oscillations when integrating English letters and sounds, suggesting that they had better top-down modulation. In contrast, native English readers showed stronger delta oscillations for synchronized integration, and their cross-modal delta oscillations significantly correlated with English reading performance. These findings suggest that long-term professional musical experience may enhance the top-down modulation, then help the brain efficiently integrating letter-sounds required by the second language. Such benefits from musical experience may be different from those from specific language experience in shaping the brain's automatic responses to reading.

Keywords: Musical experience; Second language reading; English letter-sound integration; Top-down modulation

Introduction

Learning to read a second language is challenging. This is partly due to constraints from one's native language background, as shown by the brain's automatic responses (Hahne, 2001; Thierry and Wu, 2007), particularly when one's native language contrasts sharply with the second language (Wang et al., 2018; Yang et al., 2016), such as Chinese and English. Musical experience is linked to better phonological skills that help a person learn to read in both native language (Degé and Schwarzer, 2011; Nan et al., 2018) and second language (Herrera et al., 2011). However, it remains unclear whether musical experience may help one's brain overcome the constraints of one's native language and respond to reading a second language as native readers automatically do.

Chinese, a non-alphabetic language, is a native language used by the largest population in the world. In contrast, English, an alphabetic language, is the most widely learned second language. In mainland China, more than 390 million people have learned English as a second language (ESL; Wei and Su, 2012). While the letter-sound integration is critical for English reading (Ehri, 2005), it is absent in Chinese reading. Native Chinese readers failed to integrate letter-sound automatically in reading English, while both native English readers and native alphabetic (Korean) English learners succeeded (Wang et al., 2018; Yang et al., 2016). Thus, this study aimed to examine whether and how long-term professional music experiences may help the brain overcome the constraints of one's native language (Chinese) and develop automatic neural processing skills critical for reading a second language (English) but absent in one's native language reading.

Different writing systems often employ different units of spoken language for mapping onto orthographic units (DeFrancis, 1984). As an alphabetic language, English is phoneme-based in the sense that the basic writing unit is a letter or letter string corresponding to a phoneme (DeFrancis, 1984). For example, 'cat' pronounces as /kæt/, in which each grapheme corresponds to a phoneme. Thus, letter-sound conversion and integration is critical for reading an alphabetic language such as English (Ehri, 2005; Frith, 1985). To understand automatic brain responses to letter-sound integration for alphabetic reading, Froyen and his colleagues (2008) developed a cross-modal MMN (mismatch negativity) paradigm. The cross-modal MMN paradigm is an extension of the original unimodal MMN paradigm (Näätänen et al., 1978). The original unimodal MMN paradigm aims to examine the automatic detection of the mismatch between auditory standard and deviant stimuli (Näätänen et al., 1978; Näätänen, Paavilainen, Rinne, & Alho, 2007). In order to examine the letter-sound integration in reading, this cross-modal MMN paradigm includes an auditory-only condition and two audio-visual conditions. For the audio-visual conditions, a letter corresponding to the standard auditory stimulus (phoneme) appeared synchronously (AV0) or 200 ms earlier (AV200). Therefore, the cross-modal MMN paradigm sets up double deviants: one is the deviant between auditory standard and deviant stimuli, same as that in the auditory-only condition; the other is the deviant between the auditory deviant and the same visual stimuli. By comparing the MMN induced by the double deviants (i.e., the audio-visual condition) with the MMN induced by single deviants (i.e., the auditory-only condition), the enhanced MMN induced by the double deviants in both visual and auditory modalities indicates the letter-sound integration required by alphabetic reading (Froyen et al., 2008). Native adult alphabetic (Dutch) readers showed significantly larger cross-modal MMN in the synchronous audio-visual (AV0) condition than in the auditory-only condition (Froyen et al., 2008, 2009), while 11-year-old native Dutch children showed larger delayed (AV200) cross-modal MMN (Froyen et al., 2009). A recent study revealed the same enhanced synchronous letter-sound integration for native adult English readers (Wang et al., 2018).

In contrast to English language, Chinese does not entail any grapheme-to-phoneme correspondence since character as the basic writing unit corresponds to a syllable (DeFrancis, 1984). For example, any stroke of the Chinese character "猫" does not correspond to /m/, or /ao/. Therefore, grapheme-phoneme integration is absent in Chinese reading. As a result, native Chinese English learners employed phonological information significantly less in English reading than native alphabetic English learners (e.g., Korean: Wang et al., 2003; Persian: Gholamain and Geva, 1999). Native Chinese readers showed attenuated cross-modal MMN showing failure in integrating English letter-sound automatically, while both native English readers and native alphabetic (Korean) English learners succeeded by showing enhanced cross-modal MMN in either the synchronized or delayed condition (Wang et al., 2018; Yang et al., 2016). Even with advanced English proficiency that was comparable to native English readers on reading accuracy and speed, native Chinese readers still showed attenuated cross-modal

MMN, suggesting strong constraints from their native language on the automatic brain processing of reading a second language (Wang et al., 2018). It would be important to examine whether and how any experience may help the brain overcome the constraints of one's native language (Chinese) and respond to the unique requirements of reading a second language (English).

Musical experience may help a person learn to read in a second language. Musical learning and performance requires accurate sensorimotor processes that are often accompanied by audio-visual coordination while reading music notes. In many (but not all) musical genres, this is the case either during the performance or at least while practicing. Studies revealed that both long-term professional musical learning (Fisher, 2001; Register, 2001) and short-term musical learning significantly promoted native language reading (Nan et al., 2018). However, it remains unclear if musical experience may help second language reading. To our knowledge, the only study provided native Indian children with 3-58 months of self-reported music training did not find out significant improvement on English word reading (Swaminathan and Gopinath, 2013), which was partly due to the relatively limited musical experiences of unknown intensity and quality, and unknown English learning experience between music and non-music group. However, it is plausible that musical experience may help second language reading. On the one hand, long-term professional or short-term intensive musical experience may improve second language speech perception (Lee & Hung, 2008) and phonological awareness (Herrera, et al., 2011) which are closely related to reading (Dillon et al., 2011; Snowling et al., 2019). Furthermore, musical experience may improve learners' audio-visual integration (Gaser & Schlaug, 2003; Magne et al., 2006; Musacchia et al., 2007), and then may promote learning to read English as a second language particularly by improving efficient letter-sound integration. Musicians showed earlier and larger brainstem responses than non-musicians to speech in audio-visual conditions (Musacchia et al., 2007). In fact, letter-sound integration for English reading is a special case of audio-visual integration (Andres et al., 2011). So, musicians' better audio-visual integration may help them integrate English letter (visual)-sound (auditory) which is critical for English reading (Ehri, 2005). Therefore, in this study, we aimed to examine whether long-term professional music training experiences may enable the brain to automatically integrate letter-sounds that is required by learning to read English as a second language but absent in reading Chinese as a native language.

How may musical experience help brain responses to read a second language? Better perceptual bottom-up processing or top-down modulation may mediate the possible benefits of musical experience on letter-sound integration of English reading for second language learners. First, musical learning may enhance speech sound processing to help second language learners integrate letter-sound for reading in English. Both music and language have common fundamental properties of sound, such as pitch, intensity, timbre, frequency, and timing (Patel, 2012). And more efficient acoustic perception was found with professional musical experience (Kraus and Chandrasekaran, 2010; Nan et al., 2018). Moreover, since speech processing is built on auditory perception (Kelly et al., 2005), musical learning may help develop better speech sound processing (François et al., 2012; Patel, 2012), and thus may further support letter-sound integration for reading English. However, some previous studies found limited transferring effect of musical learning on second language phonological awareness (Delogu et al., 2010; Moreno et al., 2015). MMN is an index for early auditory processing and acoustic sound perception (Näätänen et al., 2007). MMN can also index expertise in both music and language (e.g., Nichols & Grahn, 2016; Tang et al., 2016). In this study, we compared native Chinese-speaking musicians and non-musicians, and native English readers on their MMN amplitudes to examine whether musicians may show more sensitive sound perception of the second language.

In addition, we also examined the delta oscillation to understand the auditory-perceptual bottom-up processing underlying the possible benefits of musical experience on English letter-sound integration for second language learners. The delta oscillation was proposed to help explain the connection between auditory sensory and phonological processing for reading acquisition (Goswami, 2011). Significantly larger delta oscillation was found among outstanding performers than that among the averaged performers in a MMN task for detecting the difference between syllables /ka/ vs. /ta/ (Liu, et al., 2008). Poor readers showed significantly weaker delta oscillation in a rhythmic expectancy task than their typically developing peers (Soltesz et al., 2013), and significantly worse speech encoding in the delta band (0–2 Hz) compared to both chronological age-matched and reading-level matched controls (Power et al., 2016). Also, the delta oscillation significantly predicted phonological awareness and reading performance (Soltesz et al., 2013). Therefore, the delta oscillation, as another biological marker for auditory-perceptual bottom-up processing, was also examined in this study.

Second, better top-down modulation from musical leaning may also contribute to letter-sound conversion and integration for second language reading. A meta-analysis confirmed the associations between various top-down cognitive skills (e.g., working memory, switching, and inhibitory control) and word decoding across 65 studies involving 10,173 participants (Ober et al., 2020). In particular, for less proficient readers, working memory plays critical roles in word decoding (for a review, Peng et al., 2018). The theta oscillation (3~7 Hz) is a candidate biomarker for top-down modulation (Fiebelkorn & Kastner, 2019; Siegel et al., 2012; Uhlhaas and Singer, 2010). Stronger EEG theta oscillation appears with more active cognitive engagement, such as focused attention (Gundel and Wilson, 1992) and better working memory (Gevins et al., 1997). Musical experience may benefit the letter-sound integration required by alphabetic reading via better top-down modulation indicated by working memory and attention (Moreno and Bidelman, 2014; Von Stein et al., 2000). For example, native English speakers showed enhanced theta oscillation that facilitates French second language vowel perception after a 28-day music training (Carpentier, et al., 2016). Therefore, the present study employed the theta oscillation to examine if musicians may have better top-down modulation during letter-sound integration for second language reading.

Since musical experience is not specific to second language reading, it is plausible that musicians may show same or different brain responses to letter-sound integration for the second language reading when compared with native readers. In fact, music and language do have domain-specific requirements for cognitive neural processing (Peretz and Hyde, 2003; Peretz et al., 2015; Schön et al., 2004). Distinct brain regions were found between music and language processing (Rogalsky et al., 2011). Peretz and Coltheart (2003) present evidence from neurologically impaired adults to support the distinct brain regions between music and language. Thus, musical experience may not specific to second language reading, and we were interested in examining whether native Chinese speaking musicians may show the same or different automatic brain responses to native English readers for letter-sound integration.

In sum, the present study aimed to examine three research questions. First, we examined whether long-term professional musical experience may help native Chinese readers automatically integrate English letter-sounds. To this end, both native Chinese-speaking musicians and non-musicians with a comparable English learning experience and proficiency completed the cross-modal MMN tasks. We hypothesized that native Chinese-speaking musicians would successfully integrate English letter-sound while their non-musician peers would not. Second, since musical experience is not specific to second language reading, we hypothesized that compared to native English readers, native Chinese-speaking musicians would show similar as well as different cross-modal MMN patterns. Third, we examined how musical experience may help the brain respond to second language reading. We compared native Chinese-speaking musicians and non-musicians and native English readers on their MMN amplitudes in the auditory-only condition, delta and theta oscillations in the cross-modal MMN tasks. We hypothesized that musical experience may benefit English letter-sound integration for native Chinese speakers via better acoustic bottom-up processing or top-down modulation or both.

Materials and methods

Participants

Fifteen native Chinese-speaking musicians (8 females; mean age: 21.8 years, SD: 2.93), 15 non-musicians (8 females; mean age: 22.5 years, SD: 2.36), and 15 native English readers (6 females; mean age: 22.5 years, SD: 2.43) participated in this study. All native Chinese speakers were recruited through internet advertising from universities in Beijing. The native Chinese-speaking musicians were undergraduates or graduates who majored in music, while the non-musicians did not have any professional training in music. Musicians had started their professional music training at the average age of 5.3 years (SD = 2.61), and their average duration of continuous professional music training was 16.5 years (SD =2.82). Native Chinese-speaking musicians and non-musicians began to learn English at school at the age of 9-10 years, and their average duration of English learning at school was approximately 12 years (Table 1).

All participants were right-handed and had normal or corrected-to-normal vision, and none reported neurological impairment or any history of hearing or reading problems. Participants provided written informed consent and were compensated for their local transportation and time.

The present study was approved by the Institutional Review Board at the State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, and conducted according to the Declaration of Helsinki.

Behavioral measures

The English word reading task consisted of 200 words of various frequencies of occurrence from the national curriculum of college English of China (Greenall and Wen, 2008). The participants were asked to read words aloud as accurately and as fast as possible. We recorded both reading accuracy (the number of words read correctly) and vocal reaction time (RT). The Cronbach's α for this task in the present study was 0.82 for the musicians, 0.91 for the non-musicians, and 0.89 for the native English readers.

The pseudoword reading task consisted of 31 nonwords (Snowling et al., 1986) and 30 nonwords from Woodcock (1987). Participants were asked to read the pseudowords aloud as accurately and quickly as possible. We recorded both reading accuracy (the number of phonemes pronounced correctly) and RTs. The Cronbach's α for this task in our study was 0.83 for musicians, 0.91 for non-musicians, and 0.86 for native English readers.

In the rapid automatic letter naming (RAN-L; Denckla and Rudel, 1974) task, participants were required to name a 10 × 5 array of lower case English letters named as accurately and quickly as possible twice. We recorded the time used and errors for each trial. Since the error rate was very low (0.01%), we only analyzed the mean time over the two trials. The test-retest reliability was .86 for the musicians, 0.91 for the non-musicians, and 0.90 for native English readers.

EEG measures

Cross-modal MMN paradigm

The cross-modal MMN paradigm was adapted from Froyen et al. (2008) and used to examine the letter-sound integration for alphabetic reading (Froyen et al., 2008, 2009; Yang et al., 2016; Wang et al., 2018). As Figure 1 shows, three experimental conditions (one auditory-only condition and two audiovisual conditions) were presented. In the auditory-only condition, participants were asked to ignore the auditory stimuli and focus on the silent movie. In the audiovisual conditions, the visual stimuli appeared synchronously with the auditory stimulus (AV0) or 200 ms earlier (AV200), and participants were instructed to ignore the auditory stimuli and passively watch the visual letter "e". To ensure that participants could consistently perceive the visual stimuli, they were asked to press a button when a cartoon picture occurred. The visual task was not related to the stimuli of interest, and can be presumed not to influence the MMN (Froyen et al., 2008). The standard auditory stimuli were /i:/, and the deviant auditory stimuli were /æ/. The visual letter was always "e", which corresponded to standard auditory stimuli /i:/. The duration of auditory and visual stimuli presentation was the same that in as Yang et al. (2016) and Wang et al. (2018).

The auditory-only condition just included the auditory standard and deviant stimuli for being compared with the audiovisual conditions to detect the effects of cross-modal integration. In the audiovisual conditions, the visual stimuli appeared synchronously with the auditory stimulus (AV0) or 200 ms earlier (AV200). There were double deviants in the audiovisual conditions: the deviant between auditory standard and deviant stimuli, and the deviant between the auditory deviant and visual stimuli (Froyen et al., 2008). Therefore, the enhanced MMN in the audio-visual conditions induced by the double deviants compared with that of the auditory-only condition indicated the automatic letter-sound integration. Different from the AV0 condition in which the auditory sounds and visual letters occurred simultaneously, we presented the visual letters 200ms earlier than the auditory sounds in the AV200 condition, thus provided participants with more time to integrate the letter and sounds.

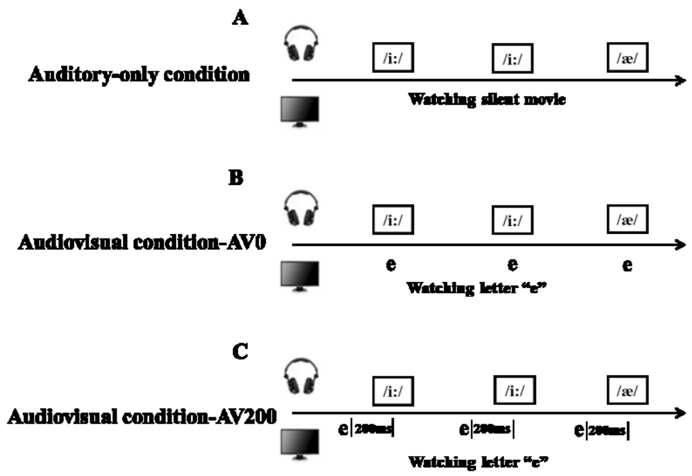

Figure 1 The procedure of the cross-modal MMN paradigm. (A) shows the auditory-only condition. The participants were asked to ignore the auditory stimuli and watch the silent movie. (B) shows the synchronized audiovisual conditions in which the visual stimuli appeared synchronously with the auditory stimulus (AV0). (C) shows the delayed audiovisual conditions

in which the visual stimuli appeared 200 ms earlier (AV200) before auditory stimuli. Participants were instructed to ignore the auditory stimuli and watch the letter “e” in both AV0 and AV200 conditions.

EEG recording and analysis

A 128-channel HydroCel Geodesic Sensor Net (Electrical Geodesics, Inc., Eugene, OR) was used for EEG recordings. The bandpass filter was 0.1-100 Hz, and the sampling rate was 500 Hz. Signals were referred to the Cz reference. The impedance was kept below 50 kΩ. The raw EEG data were digitally filtered with a 0.1-30 Hz bandpass filter and re-referenced offline to an average reference. For each trial, channels were marked as artifacts if signal variations exceeded 200 μV. Trials with artifacts in more than 10 channels were excluded from analysis. For trials with artifacts in less than 10 channels, we replaced bad channels by applying an algorithm that derived values from neighboring channels via spherical spline interpolation. Eye blinks and movements were mathematically corrected using the algorithm provided by Netstation 4.3 (Electrical Geodesics, Inc). We segmented the EEG data into epochs of 600 ms with a 200 ms prestimulus baseline. Baselines were corrected to the average voltage of the 200 ms prestimulus interval. In addition, epochs containing responses to the first 10 stimuli of each block were omitted from averaging. The mean number of epochs included in the averages for standard and deviant stimuli was 81 (range: 68–100) and 76 (63–99), respectively, in the auditory-only condition, 82 (range: 75–100) and 83 (62–98), respectively, in the AV0 condition, and 82 (range: 65–96) and 84 (64–99), respectively, in the AV200 condition. For the MMN calculation, we quantified MMN waveforms by subtracting the ERPs of standard stimuli from those elicited by deviant stimuli. First, we calculated the average ERP of both auditory standard and deviant stimuli for each participant under each condition. Second, the MMN was calculated by subtracting the average ERPs to the standard stimuli from average ERPs to the deviant stimuli for each participant under each condition. The calculation keeps the same as previous studies (Froyen et al., 2008).

As MMNs were distributed over fronto-central scalp locations (Näätänen and Alho,1995), we performed statistical analyses on 15 electrodes providing coverage of the frontal-central scalp (F1, F2, F3, F4, Fz; FC1, FC2, FC3, FC4, FCz; C1, C2, C3, C4, Cz). The MMN peak latency was measured individually at the point of greatest negativity within the 80–250 ms time interval and corrected after visual inspection (Schröger, 1998). For each participant, the individual peak latency was measured at the maximum peak amplitude at Fz within the MMN time window (Picton et al., 2000). We calculated the mean ERP amplitude across 30 ms centered on the individual peak latency of each difference waveform separately for each condition. The latency values in the present study were reported with respect to the onset of the auditory stimuli. ERP amplitude and latency characteristics of MMN were analyzed using a repeated-measure ANOVA with two within-subject factors (3 conditions and 15 electrodes). All reported *p*-values from the repeated measures ANOVA were Greenhouse-Geisser corrected. Bonferroni corrections were carried out for all post-hoc analyses.

In addition to the ERP analysis, time-frequency analysis of the cross-modal MMN paradigm was also performed. Time-frequency was computed by using wavelet analysis in MATLAB. We first calculated the time-frequency of each segment for each participant and then acquired the mean values by averaging the time-frequency across all segments. In mismatch paradigms, the most prominent brain oscillation is the theta frequency band (Isler et al., 2012; Fuentemilla et al., 2008). In addition, delta oscillation is a critically important EEG biomarker for English reading (Goswami, 2011; Leong and Goswami, 2015; Power et al., 2016). Therefore, we focused on the theta and delta oscillations in the time-frequency analysis. The difference time-frequency of the three conditions (auditory-only, AV0, and AV200) was calculated by subtracting the time-frequency of the standard stimuli from the time-frequency of the deviant stimuli.

Results

Behavioral results

Musicians and non-musicians were comparable on the average age of acquisition (AOA) of English learning, the average duration of English learning, English word and pseudoword reading, and rapid naming (Table 1). Native English readers performed significantly better than both musicians and non-musicians on all English reading measures (all p values < .01, Cohen's d > .26).

Table 1 Means (SDs) of English reading tasks in musicians and non-musicians

Behavioral tasks	Musicians		Non-musicians		Native English readers			
	M	*SD*	*M*	*SD*	*M*	*SD*	*F* (2,42)	*Post-hoc*
Age	21.8	2.93	22.5	2.36	22.5	2.43	0.845	
AOA	9.21	2.4	10.19	2.35	0	0	180.28***	E＜M, NM
Duration of English learning	12.59	2.3	12.31	2.41	22.5	2.43	99.08***	E＞M, NM
Word reading accuracy	167.87	23.03	167.12	9.3	199.33	2.47	20.51***	E＞M, NM
Word reading RT (ms)	1162.17	368.97	1122.9	206.7	872	108	5.08**	E＞M, NM
Pseudoword reading accuracy	192.07	26.76	193.6	22.47	238.91	2.39	21.83***	E＞M, NM
Pseudoword reading RT (ms)	1462.6	338.8	1492.3	231.2	1092	169	3.69*	E＞M, NM
Rapid naming (s)	14.56	1.31	14.69	1.28	12.87	1.26	3.61*	E＜M, NM

Note: M, musicians; NM, non-musicians; E, native English readers

Cross-modal MMN: Group differences and interactions between group and conditions

We conducted one-sample t-tests separately on each of 15 electrodes to test whether vowel deviant stimuli elicited a reliable MMN in each of the three conditions (auditory-only, AV0, AV200). For the three groups for each of the three conditions, the MMN mean amplitude values were significantly different from zero: for the musicians, t [14] = -10.11 to -2.32, all p values < .05; for the non-musicians, t [14] = -9.23 to -2.31, all p values < .05; for the native English readers, t [14] = -10.29 to -2.33, all p values < .05. Figure 2 shows the grand average ERPs for standard stimuli, deviant stimuli, and the corresponding difference waveforms for each of the three conditions for the three groups. Table 2 shows the grand-mean peak latency and mean amplitude values of the MMN for each of the three conditions for the three groups.

We compared the differences in MMN amplitudes across the auditory-only and two audiovisual conditions among musicians, non-musicians, and native English readers. Three-way mixed ANOVA, including two within-subject factors (3 conditions, 15 electrodes) and one between-subject factor (3 groups), was performed separately for the MMN amplitude and latency. Repeated measures ANOVA on the latency of the MMN over the conditions and language groups did not show any significant main or interaction effect ($p > .05$). A significant interaction between conditions and groups was found for the cross-modal MMN amplitude (F [4, 84] = 5.38, $p < .05$, $\eta 2 = .21$). Post-hoc analyses revealed a significantly larger mean MMN amplitude in the auditory-only condition than in the AV0 and AV200 conditions for native Chinese-speaking non-musicians (t [14] = -4.67, -4.17, all $ps < .01$), which replicated previous findings for native Chinese English learners. In contrast, for native Chinese-speaking musicians, significantly larger MMN amplitudes were found in both AV0 and AV200 conditions than in the auditory-only condition (t [14] = -2.37, -2.36, all ps < .05). As expected, native English readers showed significantly larger MMN amplitudes in the AV0 condition than in the auditory-only condition (t [14] = -3.72, $p < .05$). Figure 3 shows cross-modal MMN patterns by group.

Table 2 Grand means (SEMs) of the MMN amplitude and peak latency averaged over the 15 fronto-central electrodes in the three conditions for three groups

MMN	Auditory-only	AV0	AV200
Musicians			
Amplitude (μV)	-1.14 (0.94)	-1.82 (0.69)	-2.09 (0.92)
Latency (ms)	128(9.22)	135 (5.32)	131 (5.68)
Non-musicians			
Amplitude (μV)	-1.31 (0.42)	-0.77 (0.55)	-0.83 (0.38)
Latency (ms)	129 (5.91)	132 (7.35)	135 (6.25)
Native English readers			
Amplitude (μV)	-0.91 (0.16)	-1.74 (0.24)	-1.02 (0.13)
Latency (ms)	136(8.12)	137 (4.5)	135 (4.79)

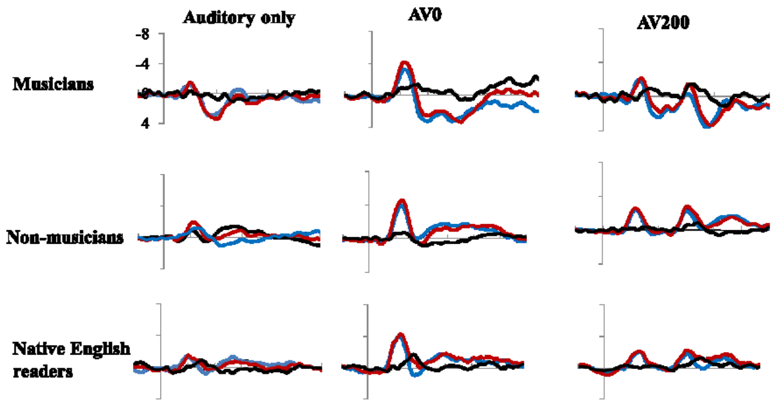

Figure 2 Grand average ERPs and difference waveforms for the three groups. Grand average ERPs at Fz for standard stimuli (blue line), deviant stimuli (red line), and MMN (black line) in auditory-only, AV0, and AV200 conditions

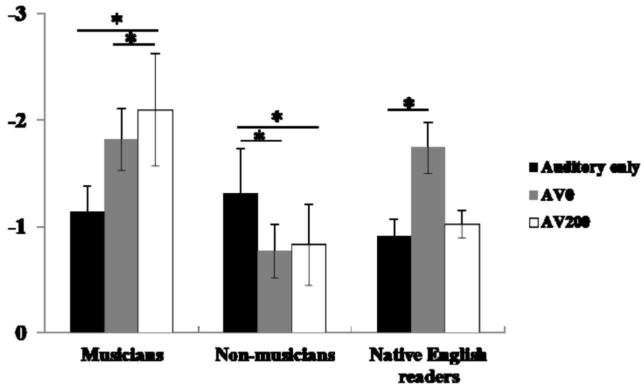

Figure 3 Grand mean MMN amplitude values. Grand mean MMN amplitude values averaged over 15 frontal-central electrodes under auditory-only, AV0, and AV200 conditions for three groups. Error bars are the standard error of the mean. * $p < .05$

Auditory-only MMN: Group differences

To unravel why native Chinese-speaking musicians show enhanced cross-modal MMN, we first examine whether it was due to their enhanced speech discrimination abilities as indexed by the MMN. This has been suggested by previous studies (Magne et al., 2006; Marie et al., 2012; Marques et al., 2007). We compared the MMN amplitudes in the auditory-only condition among the three groups. A two-way mixed ANOVA of the mean MMN amplitude under the auditory-only condition, including one within-subject factor (15 electrodes) and one between-subject factor (3 groups), was performed. No significant difference was found among groups in the auditory-only MMN amplitude (F [2, 42] = 1.19, $p > .05$, $\eta 2 = 0.05$). Mixed ANOVA of the latency also did not show any significant difference among groups (F [2, 42] = 1.05, p

$>$ .05, $\eta 2$ = .04). Therefore, it may not be that the superior speech perception that native Chinese-speaking musicians showed enhanced cross-modal MMN in this study.

The delta/theta oscillations and their correlation with English reading performance

We then employed time-frequency analysis to investigate delta/theta oscillation. A three-way mixed ANOVA for delta, including two within-subject factors (3 conditions, 15 electrodes) and one between-subject factor (3 groups), was performed. The main effect of group (F [2, 44] = 6.53, $p < .05$, $\eta 2$ = .24) and condition (F [2,84] = 13.83, $p < .05$, $\eta 2$ = .46) and the interaction between condition and group (F [4,84] = 24.03, $p < .05$, $\eta 2$ = .53) were found. Post-hoc analyses revealed that significantly larger delta oscillations in the AV0 condition than in the auditory-only condition were found for native English readers (t [14] = -5.81, $p < .001$) (Figure 4). Both musicians and non-musicians showed significantly larger delta oscillations in both AV0 and AV200 conditions than in the auditory-only condition (musicians: t [14] = -8.64, -6.71, all $ps < .001$; non-musicians: t [14] = -5.12, -4.11, all $ps < .001$). In addition, native English readers showed stronger delta oscillations than non-musicians in the AV0 condition ($p < .05$), while no other between-group differences were found (all $ps > .05$). The CrossAV0 delta oscillation significantly correlated with word reading (accuracy: $r = .46$, $p = .04$; RT: $r = -.58$, $p = .002$) and pseudoword reading (accuracy: $r = .41$, $p = .05$) only for native English readers (Figure 5).

A three-way mixed ANOVA for theta oscillation was performed, including two within-subject factors (3 conditions, 15 electrodes) and one between-subject factor (3 groups). A significant interaction between conditions and groups was found (F [4, 84] = 8.96, $p < .05$, $\eta 2$ = .35). Post-hoc analyses revealed significantly larger theta oscillations in both AV0 and AV200 conditions than in the auditory-only condition for musicians (t [14] = -4.94, -3.23, all $ps < .001$) (Figure 4). In contrast, no significant difference in theta in the three conditions was found for non-musicians or native English readers (all $ps > .05$). In addition, no significant correlations were found between theta and reading performance among each of the three groups (all $ps > .05$).

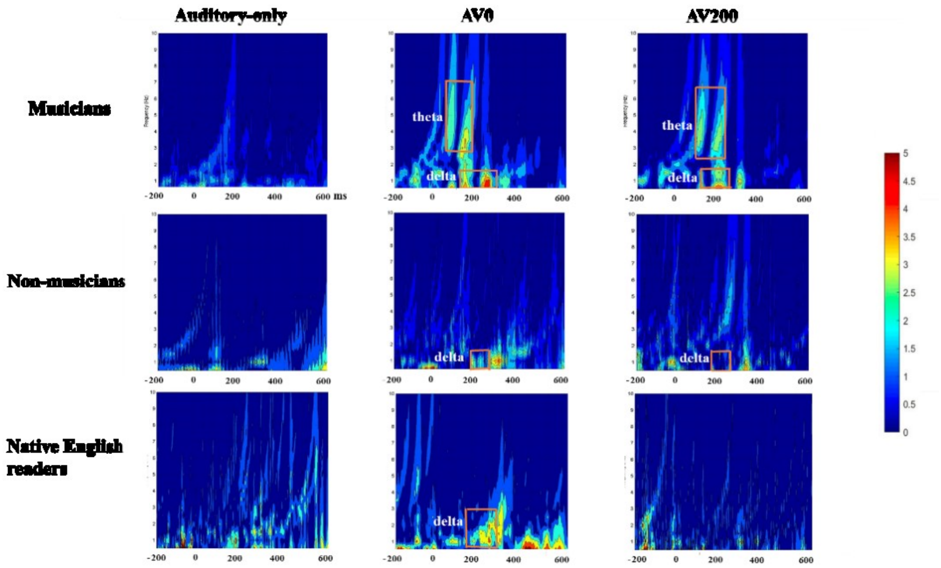

Figure 4 The dynamic time-frequency of rhythmic brain activity in the cross-modal MMN paradigm for the three groups.

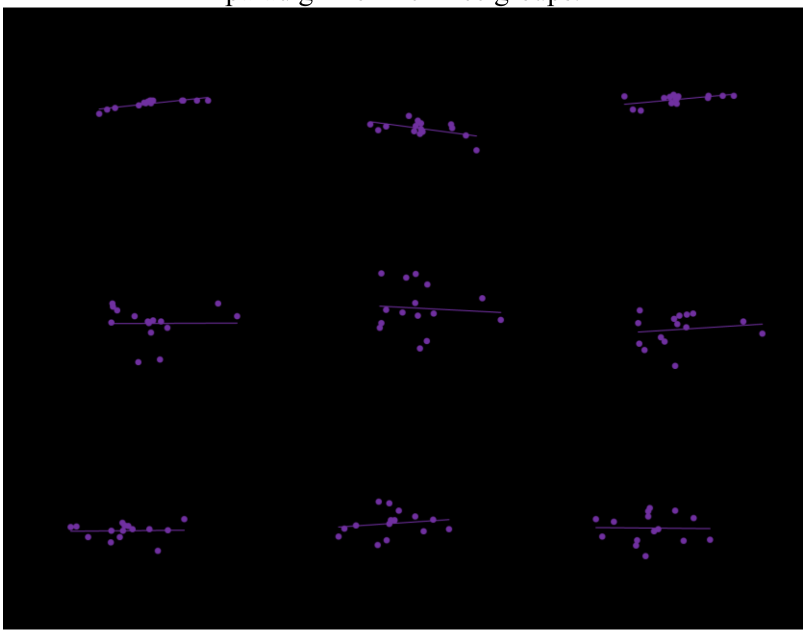

Figure 5 CrossAV0 delta oscillations significantly correlated with word reading accuracy, word reading RT, and pseudoword reading accuracy for native English readers but not for musicians or non-musician English learners.

Discussion

The present study investigated the effects of prior long-term professional musical experience on neural cross-modal audiovisual processing for second language reading. Native Chinese-speaking musicians and non-musicians with more than 10 years of English learning were compared with each other and with native English readers regarding their auditory brain responses to English letter-sound integration. The results showed not only that long-term professional musical experience may help facilitate brain automatic processing of second language reading but also that musical experience may affect responses in a manner different from that of language-specific experience.

For the first time, the results show that long-term professional musical experience may enhance brain automatic responses specifically required by reading in a second language but absent in one's native language reading. Native language background may exert profound and lasting constraints on one's automatic brain responses to letter-sound integration when learning to read English as a second language (Wang et al., 2018; Yang et al., 2016). In contrast to that letter-sound integration is the critical skill for alphabetic language reading (Blomert, 2011; Ehri, 2005; Frith, 1985), such a skill is not required to read in Chinese. Therefore, compared with native English readers and English learners with native alphabetic language backgrounds, native Chinese readers failed to integrate English letters and sounds automatically, regardless of their English proficiency level (Wang et al., 2018; Yang et al., 2016).

Can any experience help overcome such constraints? We found that musical experience may help. Previous studies mainly revealed the effects of musical experience on second language reading-related skills, such as tone discrimination (Delogu et al., 2010; Lee and Hung, 2008), pitch processing (Marques et al., 2007; Martínez-Montes et al., 2013), and phonological awareness (Herrera et al., 2011). In this study, native Chinese English learners with more than 10 years of professional music training showed an enhanced cross-modal MMN for letter-sound integration, while their peers without professional music training did not. Therefore, the present study extended the previous findings by revealing that at least long-term professional musical experience helps overcome the constraints from a person's native language background and optimize a learner's automatic brain response to reading in a second language.

We also found that the roles of musical experience in facilitating automatic brain responses required by second language reading may be different from that of the specific language experience. Native Chinese speaking musicians showed enhanced cross-modal MMN for both synchronized and delayed conditions, in contrast to an enhanced cross-modal MMN shown only for the synchronized condition in native English readers. Thus, professional musical experience may induce general enhanced automatic responses to multisensory integration that may not be specialized to the second language reading. Since letter-sound integration is actually a special case of audio-visual integration (Andres et al., 2011; Froyen et al., 2008, 2009), professional musical experience may facilitate one's ability to learn to read English as a second language in a domain-general way.

The auditory MMN and delta oscillations reflect the auditory perceptual abilities of speech processing. Both stronger auditory MMN and delta oscillations usually indicate better reading skills in previous studies (Goswami, 2011; Näätänen et al., 1978). The present study did not show significant advantages in auditory MMN or delta oscillations for musicians, suggesting that the auditory-perceptual bottom-up processing of speech and phonological skills may not account for the facilitation from musical experience on automatic English letter-sound integration for native Chinese musicians. The present study also found that delta oscillation correlated with English word and pseudo-word reading only for native English readers, but not for English learners no matter what they had professional musical experience or not. Therefore, the findings from the present study did not support the enhanced auditory-perceptual bottom-up processing hypothesis for optimizing brain responses to second language reading. Despite that music and language may share acoustic processing (Patel, 2003; Patel et al., 2009), they may not be completely isomorphic in the fine processing of language. For example, with advanced training in music and a second language (Mandarin), native Italian speakers performed significantly better in tone discrimination; however, musical experience did not help their phonological identification abilities, while second language learning did help with this task, indicating that music training may help acoustic processing, but may not directly help individuals process the fine details of second language reading (Delogu et al., 2010).

While non-musicians and native English readers did not show stronger theta oscillations in either audiovisual condition, native Chinese musicians showed stronger theta oscillations in both the two audiovisual conditions compared with auditory-only condition, as they showed enhanced cross-modal MMN in both the two audiovisual conditions. The enhanced theta oscillations in musicians suggest that musicians may engage more top-down modulation (Fiebelkorn & Kastner, 2019; Uhlhaas and Singer, 2010) to complete English letter-sound integration. Therefore, long-term professional musical experience may equip second language learners with better top-down modulation, then helps the brain overcome the constraints from learners' native language and automatically integrate letter-sound required by a second language.

However, there were limitations in the present study. First, the participants in the present study were adult musicians, and we could not rule out the influence of genetic predisposition and talent factors (Schellenberg, in press). Therefore, the differences between musicians and non-musician groups cannot be fully attributed to the roles of music experiences. Future studies may use randomized controlled trial interventions for second language learners who have not received professional music training to investigate this question. Second, the present study did not examine if some certain English learning experience, e.g., watching English films, may have any effects. Previous research found that English subtitles facilitated native Dutch speaker's recognition of spoken English words (Mitterer & McQueen, 2009). However, a lab-based RCT study did not find significant benefits from watching English films on English vowel perception among native Chinese speakers (Hu et al., 2016). Therefore, the effects of watching English films with English subtitles on native Chinese speakers' English reading may need further examination.

In conclusion, long-term professional musical experience may help the brain overcome the constraints of native language background on automatic responses to second language reading. Musical experience may enhance the top-down modulation, but may not directly benefit second language reading in the same way as that of the native language background.

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