Music Reading Expertise Modulates Hemispheric Lateralization in English Word Processing but not in Chinese Character Processing

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ABSTRACT

Music notation and English word reading both involve mapping horizontally arranged visual components to components in sound, in contrast to reading in logographic languages such as Chinese. Accordingly, music-reading expertise may influence English word processing more than Chinese character processing. Here we showed that musicians named English words significantly faster than non-musicians when words were presented in the left visual field/right hemisphere (RH) or the center position, suggesting an advantage of RH processing due to music reading experience. This effect was not observed in Chinese character naming. A follow-up ERP study showed that in a sequential matching task, musicians had reduced RH N170 responses to English non-words under the processing of musical segments as compared with non-musicians, suggesting a shared visual processing mechanism in the RH between music notation and English non-word reading. This shared mechanism may be related to the letter-by-letter, serial visual processing that characterizes RH English word recognition (e.g., Lavidor & Ellis, 2001), which may consequently facilitate English word processing in the RH in musicians. Thus, music reading experience may have differential influences on the processing of different languages, depending on their similarities in the cognitive processes involved.

Keywords: Music reading expertise; English word processing; Chinese character processing; visual word processing; EEG; event-related potential (ERP)

Introduction

Recent research has shown that different perceptual expertise domains may influence each other. For example, Gauthier, Curran, Curby, and Collins (2003) showed that car perception interfered with concurrent face perception in car experts (presumably also face experts), but not in car novices, suggesting that car and face expertise can influence each other (see also Gauthier, Skudlarski, Gore, & Anderson, 2000). A similar effect was observed in a visual search task with face targets, in which reaction time was increased by the appearance of car distracters in car experts but not in car novices (McGugin, McKeeff, Tong, & Gauthier, 2011). In an ERP study, Rossion, Kung, and Tarr (2004) showed that expertise with a non-face object type, greebles, led to substantial decrease in N170 amplitude in response to faces with concurrent greeble presentation, suggesting different expertise domains can influence each other in early perceptual processing.

Similarly, expertise in music reading may influence cognitive processes involved in other perceptual expertise domains. Indeed, recent research has suggested that music training may result in changes in brain development and enhancement in some cognitive skills. For example, music training at an early age has been reported to result in a thicker corpus callosum, suggesting enhanced hemispheric communication (e.g., Schlaug, Jäncke, Huang, Stagier, & Steinmetz, 1995; Münte, Altenmuller, & Jancke, 2002; see also Patston, Kirk, Rolfe, Corballis, & Tippett, 2007b). Consistent with this finding, music training is shown to enhance visuospatial abilities (e.g., Hassler, Birbaumer, & Feil, 1987; Rauscher, Shaw, & Key, 1993; Costa-Giomi, 1999; Graziano, Peterson, & Shaw, 1999; Hetland, 2000). Musicians are also found to have a more bilaterally represented visuospatial attention (e.g., Patston, Corballis, Hogg, Tippett, 2006; Patston, Hogg, & Tippett, 2007a), in contrast to non-musicians who typically have an asymmetry to the left side of the space due to stronger activation of the right hemisphere (RH) than the left hemisphere (LH) in response to visuospatial processing (Vingiano, 1991). These changes in visuospatial abilities are possibly due to developed music notation reading skills (Brochard, Dufour, & Despres, 2004).

Neuropsychological data have suggested that the LH plays an important role in music reading. Studies of brain injured musicians who lost the ability to read music notation consistently showed posterior LH damage, in particular in the left occipitotemporal (e.g., Judd, Gardner, & Geschwind, 1983) and posterior temporoparietal regions (e.g., Stanzione, Grossi, & Roberto, 1990; see Hébert & Cuddy, 2006, for a review). Consistent with this finding, Segalowitz, Bebout, and Lederman (1979) reported a right visual field (RVF)/LH advantage in a tachistoscopic music chord identification task in musicians, suggesting the involvement of LH processing in reading music notation (see also Salis, 1980).

LH processing has been shown to be analytic (Bradshaw & Nettleton, 1981), which facilitates decoding of music notations into pitch classes and rhythms. This decoding process is similar to the grapheme–phoneme correspondence in alphabetic languages (e.g., English). Indeed, recent research on visual word recognition has shown LH lateralization in reading words in alphabetic languages such as English. A classical RVF/LH advantage has been consistently reported in various tachistoscopic English word recognition tasks, such as word naming (e.g., Bradshaw & Gates, 1978; Brysbaert & d'Ydewalle, 1990) and lexical decision tasks (e.g., Barry, 1981; Measso & Zaidel, 1990). fMRI studies have shown a region inside the left fusiform area (Visual Word Form Area) responding selectively to words and pseudowords following the orthographic regularities in English (e.g., McCandliss, Cohen, & Dehaene, 2003). ERP studies also show that words elicit a larger N170 in the LH than the RH (e.g., Rossion, Joyce, Cottrell, &

Tarr, 2003). This RVF/LH advantage in English word processing has been argued to be due to left-lateralized phonological processing for grapheme-phoneme conversion (Rumsey et al., 1997; Maurer & McCandliss, 2008). Similarly, the RVF/LH advantage in identifying music chords (Segalowitz et al., 1979) may be related to the requirement of mapping individual notes to different pitches/fingerings. In addition, for both English words and music notations, components are horizontally arranged, and the reading direction is from left to right. This left-to-right reading direction may contribute to better word/music notation reading performance in the RVF/LH due to perceptual learning, since words/music notations are recognized in the RVF more often than the LVF during reading (Brysbaert & Nazir, 2005, Wong & Hsiao, 2012).

While the LH is shown to play an important role in both English word and music notation reading, the RH is also involved, particularly in visual form processing of words and notes. For example, in a lexical decision priming task, English word processing in the LVF/RH was shown to benefit from orthographically similar primes, whereas that in the RVF/LH benefited from phonologically similar primes. This result suggested that the RH and the LH had differential advantages in orthographic and phonological processing of English words (Lavidor & Ellis, 2003). Consistent with this finding, English word processing in the RH has been reported to be more sensitive to variations in visual word forms. For example, the word length effect in English lexical decisions (i.e., faster and more accurate responses to shorter words) was only observed when words were presented in the LVF/RH but not the RVF/LH, suggesting that RH word processing involves more letter-by-letter recognition/serial visual processing than that in the LH (Lavidor & Ellis, 2001). Similarly, in music note processing, a right lateralized or bilateral visual processing mechanism has been observed. For example, fMRI studies have shown that the right occipitotemporal region was associated with music sight-reading (Schön, Anton, Roth & Besson, 2002). Bilateral activations in the fusiform and inferior occipital gyri in musicians were also reported in a note selection task (Proverbio, Manfredi, Zani & Adorni, 2013).

Although previous research has suggested similarities between English word and music notation reading processes, it remains unclear how they influence each other. While both skills seem to involve both left and right hemisphere processing, they differ significantly in their involvement in lexical processing. More specifically, English words follow morphological and orthographic rules with clearly defined segment boundaries and lexical representations, whereas musical segments do not follow as strict sequencing rules as words and are not associated with specific phonological or semantic representations (Chan & Hsiao, 2016). Thus, the similarities in their processing may be mainly in the serial visual processing of horizontally arranged components that characterizes RH English word processing (e.g., Lavidor & Ellis, 2001). Also, since previous research has suggested that LH English word processing is more relevant to phonological processing of English words whereas RH English word processing is more sensitive to variations in visual word forms, the modulation of music reading experience on English word processing is more likely to be due to a shared visual processing mechanism in the RH.

In contrast to English word processing, the recognition of Chinese characters, a logographic writing system, has been shown to have a left visual field (LVF)/RH advantage in tachistoscopic character identification/naming (Tzeng, Hung, Cotton, & Wang, 1979; Cheng & Yang, 1989) and lexical decision tasks (Leong, Wong, Wong, & Hiscock, 1985). More recent research suggests an RH/LVF advantage in Chinese orthographic processing and an LH/RVF advantage in phonological processing (e.g. Yang & Cheng, 1999; Leong et al., 1985). In addition, the LH lateralization in phonological processing in Chinese character recognition depends on both character type and structure (Weekes & Zhang, 1999; Hsiao & Liu, 2010; Hsiao & Cheng, 2013). ERP and fMRI studies have also shown a more bilateral or RH-lateralized activation in the visual system with Chinese characters as compared with English words (e.g., Tan et al., 2000; Tan, Laird, Li, & Fox, 2005; Hsiao, Shillcock, & Lee, 2007).

The right-lateralized Chinese orthographic processing has been argued to be due to its logographic nature (e.g., Hsiao & Lam, 2013). More specifically, in Chinese orthography, each character is regarded as a morpheme and corresponds to a syllable in the pronunciation, and components of a character do not correspond to phonemes in the pronunciation. In other words, there is no grapheme-phoneme correspondence in Chinese, and consequently Chinese character recognition may involve less left-lateralized phonological processing for grapheme-phoneme conversion as compared with word recognition in alphabetic languages such as English (e.g., Maurer & McCandliss, 2008). In addition, different from English words and music notations, Chinese characters can be read in all directions (left to right, right to left, or vertically). The effect of perceptual learning due to reading direction thus may have less influence on lateralization effects in Chinese character recognition than in English word recognition. As for RH visual processing requirements, components of a Chinese character can appear in different configurations, including left-right, top-bottom, and enclosed structures. Also, left-right structured Chinese characters typically consist of only two to three components, in contrast to English words or musical segments. Thus, the recognition of Chinese characters does not rely on serial visual processing of horizontally arranged components as much as that of English words or music notations. Due to these differences, the modulation effect of music reading experience on Chinese character processing may be weaker than that on English word processing.

Accordingly, here we examine how music reading experience influences English word and Chinese character processing. We hypothesize that there will be a stronger modulation effect of music reading experience on English word processing than Chinese character processing due to the similarities between the processes involved in reading English words and music notations, and this modulation effect is likely to be related to RH visual processing mechanisms. To test these hypotheses, here we recruit musicians and non-musicians who are also Chinese-English bilinguals and investigate whether they differ in hemispheric lateralization effects in English word and Chinese character processing. In Experiment 1, we conduct English word and Chinese character naming tasks through the divided visual field paradigm (Bourne, 2006). We predict that musicians may perform better than non-musicians when English words are presented in the LVF/RH due to the similarities in visual processing between English word and music notation reading. In contrast, musicians and non-musicians may not differ in the lateralization effect in the Chinese character naming task. In Experiment 2, to examine the neural correlates of possible modulation effects of music notation reading experience on visual processing of English words, we conduct an ERP study in which participants perform a sequential matching task with English word stimuli. Following Rossion et al. (2004), we examine how N170 responses to English words are influenced by the processing of music notes in musicians and non-musicians. We expect that musicians will have a stronger reduction in N170 response to English word stimuli under the processing of music notes than non-musicians in the RH.

Experiment 1

Methods

Participants

Participants were 60 Chinese (L1)-English (L2) bilinguals from Hong Kong, whose age ranged from 18 to 29 (M = 21.98, SD = 2.70). They had a similar college education background. They were classified as musicians (n = 30) and non-musicians (n = 30), with 15 males and 15 females in each group. Musicians were well-trained pianists, who started music training at age 3-9 (M = 5.70, SD = 1.82). All of them were piano teachers, music undergraduate/postgraduate students, or church piano players. They had attained grade 8 piano or above in the graded music examinations of the Associated Board of The Royal Schools of Music (ABRSM) or equivalent, with 8-22 year experience in piano playing (M = 15.80, SD = 4.01) and regular music reading hours per week (M = 8.97, SD = 11.43). In contrast, non-musicians did not receive any formal music training or self-learning in instruments and voice since birth. They were not able to read music notes and chords. To further assess the overall music level of musicians and non-musicians, participants were asked to rate the familiarity of a music note (crotchet D5) on a 10-point Likert scale. Musicians were more familiar with the note as compared with non-musicians (Musicians (M): 8.43; Non-musicians (NM): 2.13; $t(58) = 16.632$, $p < .001$, $d = 4.293$). All participants were right-handed, had normal or corrected to normal vision, and started learning English as a second language formally at school at age 3-4 (M = 3.6, SD = 1.251, *range* = 2-7). Except for their music training background, musicians' and non-musicians' linguistic background was closely matched using the Lexical Test for Advanced Learners of English (LexTALE, Lemhöfer & Broersma, 2012; M = 70.89%; NM = 71.84%; $t(58) = -.330$, *n.s.*). Their handedness was assessed through the Edinburgh Handedness Inventory questionnaire and was closely matched (Oldfield, 1971; index scores, M = 74.83, 4^{th} right decile; NM = 69.50, 3^{rd} right decile; $t(58) = 1.127$, *n.s.*). Their IQ/working memory performance were also closely matched, as assessed in a letter–number sequencing task (WAIS-III, Wechsler, 1997; M = 12.07; NM = 11.70; $t(58) = .586$, *n.s.*).

Materials

For the English word naming task, four- to six-letter English words ($n = 108$) were selected from Bryden, Mondor, Loken, Ingleton, and Bergstrom (1990). In English word recognition, information distribution within words has been shown to influence lateralization effects: words with informative beginnings have an advantage for recognition when being presented in the RVF over the LVF because the informative word beginnings are closer to the center of the visual field, where the highest visual acuity can be achieved, when the words are presented in the RVF. To control for this effect, in our materials we selected the same number of high frequency and low frequency words from the informative beginning and informative end word lists in Bryden et al. (1990). The average frequency of our English stimuli is 3,715 occurrences per 51,000,000 words (*range* = 7 to 30,736/51,000,000) according to the SUBTLEX-US corpus (Brysbaert, New, & Keuleers, 2012).

As for the stimuli for the Chinese character naming task, Hsiao and Cheng (2013) found that naming Chinese characters with different structures had different visual field asymmetry effects due to the difference in information distribution within the characters. Thus, to control for the influence from asymmetric information distribution within characters, here we used symmetric characters as the stimuli (Figure 1a). In addition, we included another type of character, semantic-phonetic (SP) compound characters, since it is the most dominant and representative character type in the Chinese orthography (Figure 1b). An SP character consists of a semantic radical (S) on the left and a phonetic radical (P) on the right. The semantic radical typically suggests the semantic category of the character, while the phonetic radical usually provides information about the character's pronunciation. With a phonetic radical on the right, the information distribution of an SP character for pronunciation is skewed to the right. According to Hsiao and Cheng (2013), SP character processing may have an advantage in the LVF over the RVF because the phonetic radical of an SP character is closer to the center, where the highest visual acuity can be achieved, when the character is presented in the LVF than the RVF. In total 108 symmetric characters and 108 SP characters were used. Both types of character had 12 average number of strokes (symmetric: *range* = 4-24, *SD* = 4; SP: *range* = 4-23, *SD* = 4) and 133 occurrences per 660,000 average character frequency (symmetric: *range* = 1 to 998/660,000, *SD* = 185; SP: *range* = 2 to 2,454/660,000, *SD* = 286). The number of strokes and character frequency were matched between the two character types according to a Chinese character database (Ho, 1998; number of strokes: $t(214) = -.082$, *n.s.*; character frequency: $t(214) = -.002$, *n.s.*).

善	懂
(a) Symmetric character	(b) Semantic-phonetic (SP) compound character

Figure 1. Examples of (a) symmetric and (b) semantic-phonetic (SP) compound characters in the Chinese character naming task

In addition to the English word and Chinese character naming tasks, we also included a music notation sequential matching task as an expertise task, and a Tibetan letter string sequential matching task to examine whether musicians' expertise in processing music notations can be transferred to the processing of novel symbol strings (none of the participants had experiences with Tibetan language/letters). For the music notation matching task, notes (*n* = 96; 96 pairs. Due to the limited number of music notes available, each note appeared in both same and different trials.) and chords (*n* = 216; 108 pairs), ranging from B3 to C5[i], were included. All chords were common chords without accidentals (C, F, G major, D, E, A minor, and B diminished chord in the root position, first inversion, and second inversion). Six types of time values were selected: semibreves (4 beats), dotted minims (3 beats), minims (2 beats), crotchets (1 beat), quavers (1/2 beats), and semiquavers (1/4 beats).

In the Tibetan letter string matching task, vertical three-letter Tibetan letter strings (*n* = 216; 108 pairs) and their mirror images were included. Mirror images were used to counterbalance the difference in information distribution between the two sides of the stimuli.

Design

Participants completed an English word naming task, a Chinese character naming task, a music note and chord sequential matching task, and a Tibetan letter string sequential matching task with the divided visual field design. The task with music notations aimed to examine whether musicians had better performance in processing music notations than non-musicians and whether musicians and non-musicians differed in lateralization effects in music notation matching. In the sequential matching task, participants matched two notes or chords sequentially and judged whether the note locations (i.e., pitch) were the same or different (regardless of their time value). A sequential matching task instead of a naming or playing task was used so that we could examine the difference between musicians and non-musicians in music notation processing when the task depended purely on visual processing of note locations (i.e., pitch) without the requirement of motor planning as in the playing tasks used in previous studies (e.g., Segalowitz et al., 1979).

In the word/character naming task, the design consisted of two within-subject variables: language (English vs. Chinese) and visual field (VF) location (LVF/center/RVF); and one between-subject variable: group (musicians vs. non-musicians). In the music notation and Tibetan letter string matching tasks, the design consisted of a within-subject variable: visual field (VF) location (LVF/center/RVF), and a between-subject variable: group (musicians vs. non-musicians). The dependent variable for all tasks was the accuracy and response time (RT) in the word/character naming and sequential matching tasks. In all tasks, the three visual field conditions (LVF/center/RVF) had the same number of trials. The center condition could be divided into center-top and center-bottom condition with equal frequency. English word length, number of strokes of Chinese characters, and word/character frequency were all matched across the LVF, RVF, and center conditions (Figure 2a). In the sequential matching tasks, stimuli used in the same and different trials and the three presentation conditions were counterbalanced across participants. The stimulus center was 2.8° of visual angle away from the center fixation in all VF location conditions (Figure 2b-e). Participants' viewing distance was 57 cm.

The English words were displayed in Times New Roman font. Each English word subtended a horizontal and vertical visual angle of 1.6° x 1.1° (4 letters), 2.0° x 1.1° (5 letters), or 2.4° x 1.1° (6 letters). The edge of the English word was 1.5° away from the center (Figure 2b). To avoid ceiling effects, the luminance of English words was adjusted to 59.95 cd/m^2. With 210 cd/m^2 background luminance, the Weber contrast of the English word stimuli was -0.715.

The Chinese characters were in Microsoft MingLiu font. Each Chinese character subtended a horizontal and vertical visual angle of 1.5° x 1.6°. The edge of the Chinese character was 2° of visual angle away from the center (Figure 2c). To avoid ceiling effects, the luminance of Chinese characters was adjusted to 153.5 cd/m^2, and the Weber contrast of the Chinese character stimuli was -0.269.

Each music note and chord stimulus subtended a horizontal and vertical visual angle of 1.2° x 2.3°. The edge of the stimulus image was 2.2° of visual angle away from the center (Figure 2d). To avoid ceiling effects, the luminance of notes and chords was adjusted to 8.97 cd/m^2 and 23.5 cd/m^2, and the Weber contrast was -0.957 and -0.889 respectively.

Tibetan letter strings were displayed in Himalaya font. Each Tibetan letter string subtended a horizontal and vertical visual angle of 1.2° x 1.9°. The edge of the string was 2.2° of visual angle away from the center (Figure 2e). To avoid ceiling effects, the luminance of the strings was adjusted to 25.85 cd/m^2, and the Weber contrast was -0.877.

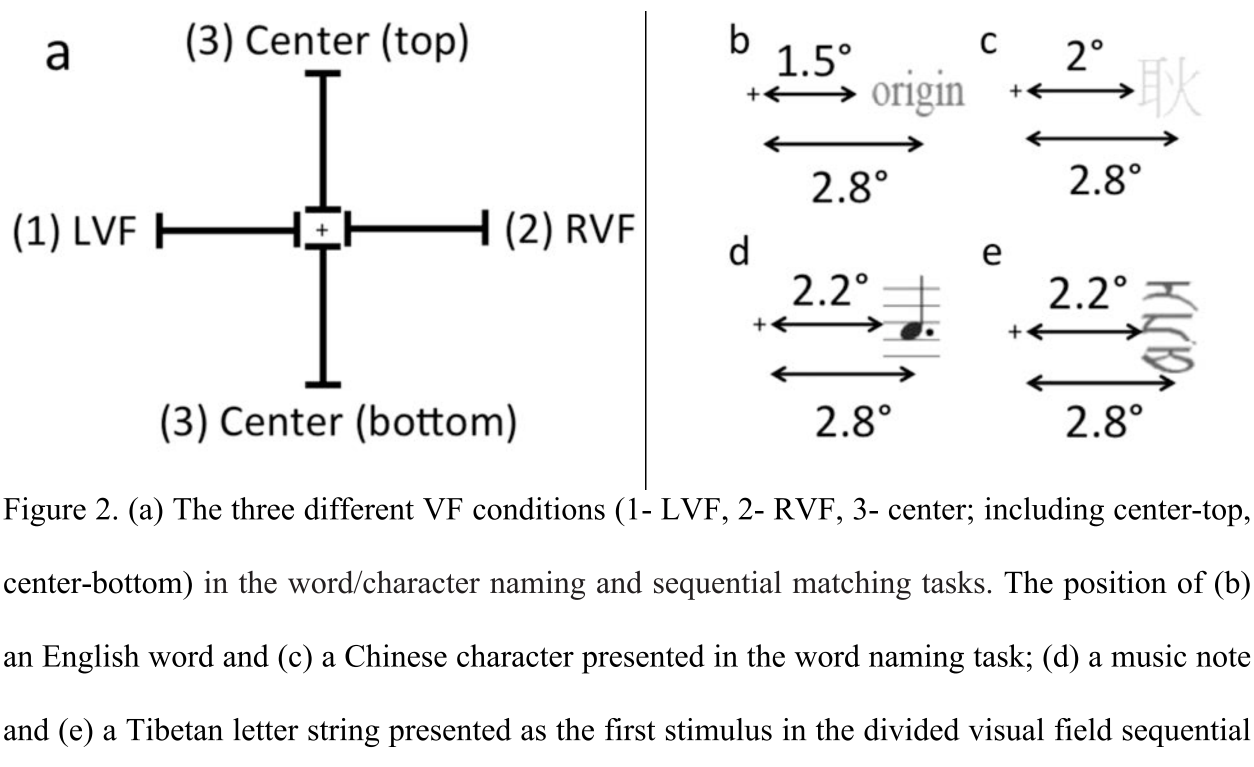


Figure 2. (a) The three different VF conditions (1- LVF, 2- RVF, 3- center; including center-top, center-bottom) in the word/character naming and sequential matching tasks. The position of (b) an English word and (c) a Chinese character presented in the word naming task; (d) a music note and (e) a Tibetan letter string presented as the first stimulus in the divided visual field sequential matching task.

Experiments were conducted using E-Prime v2.0 Professional Extensions for Tobii (Psychology Software Tools, Inc.), with a Tobii T120 eye tracker (Tobii Technology) to ensure participants' central fixation. A forehead rest was used to reduce participants' head movement. Calibration was performed before the start of each block. The block order was counterbalanced across participants and trials were randomized in each block.

Procedures

In all tasks, each trial started with a fixation cross at the center (horizontal length: 1 mm; vertical length: 2 mm). Participants' eye movement was monitored through a Tobii T120 eye tracker. After detecting the central fixation, a red box appeared around the cross. The experimenter then pressed a key to present the target stimulus. In the naming tasks, Chinese characters were presented for 90 ms whereas English words were presented for 150 ms, to minimize the possibility of the character/word being foveated. The screen then turned blank until participants' response (Figure 3). Participants were asked to read aloud the stimulus displayed either at the LVF, center (top/bottom), or RVF as soon as possible without moving their gaze away from the central fixation. The accuracy was recorded by the experimenter, while the RT was measured as the time difference between the stimulus presentation onset and the participant's pronunciation onset, detected by a microphone. Each stimulus was presented once in each naming task.

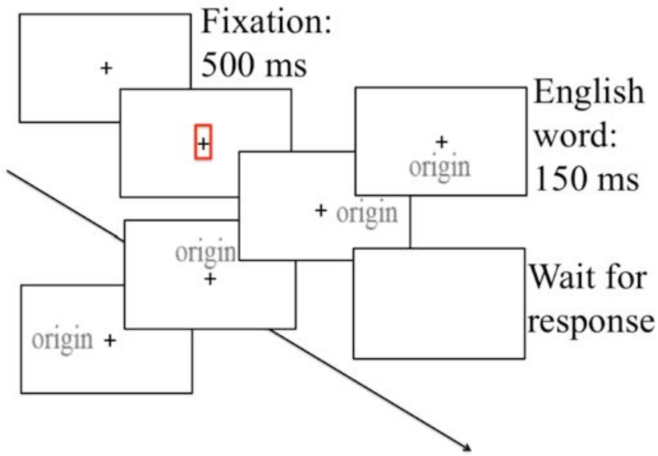


Figure 3. Procedure of the word naming task

In the sequential matching tasks, after detecting the central fixation, the first stimulus was presented either at the LVF, center (top/bottom), or RVF (for 100 ms for notes; for 110 ms for chords; for 170 ms for Tibetan letter strings), followed by a 250 ms mask. Then the second stimulus was presented at the center with the same duration as the first stimulus; the screen then turned blank until participants' response (Figure 4). Participants judged whether the two sequentially presented stimuli were the same or not as quickly and accurately as possible. Note that different luminance levels and presentation durations were used for different stimuli in order to avoid ceiling/floor effects and to make the performance level comparable across tasks for examining visual field effects. Music notation reading involves different types of operations that are suggested to be neuropsychologically separable, including pitch, rhythm, and symbol reading (Peretz & Zatorre, 2005). Here we focused on pitch reading, and thus the same-different judgments of notes or chords were based on note locations (pitches) only, regardless of the time value. In 'different' trials, the two stimuli differed by one note/symbol. Each stimulus was presented once in each sequential matching task except for the music note matching task. Due to the limited number of note stimuli available, each music note appeared twice, once in a 'same' trial and once in a ‘different’ trial. Participants responded by pressing buttons on a response box with both hands. Accuracy and RT were recorded.

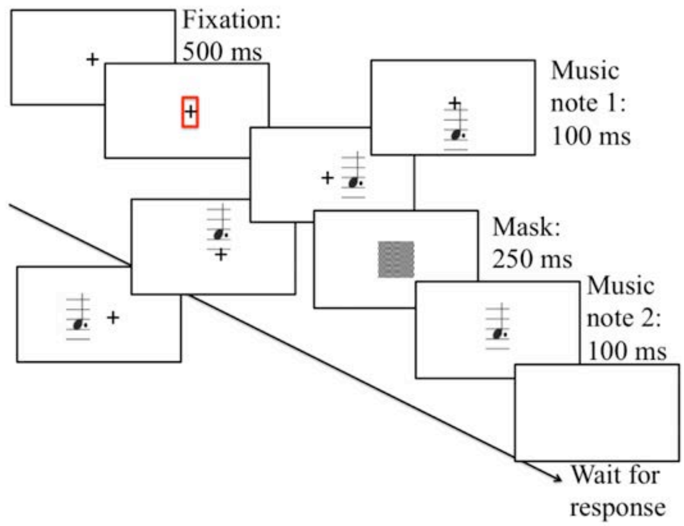


Figure 4. Procedure of the divided visual field sequential matching task

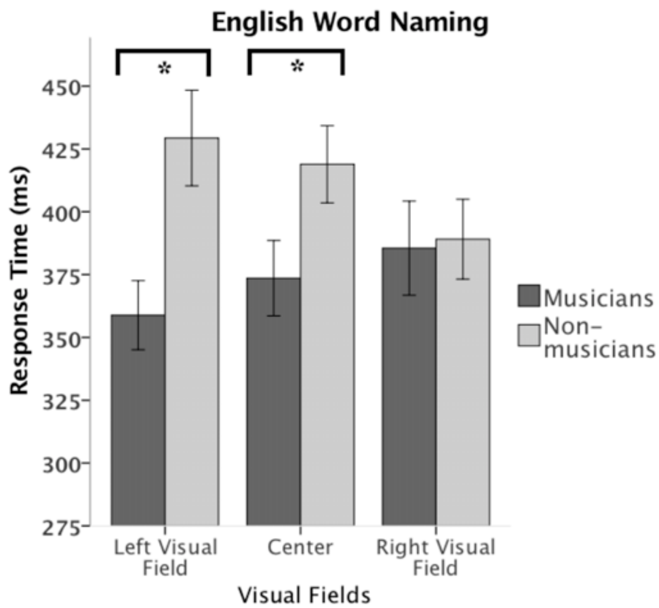
Prior to the tasks, a demographic and music background questionnaire, Edinburgh Handedness Inventory questionnaire (Oldfield, 1971), the Lexical Test for Advanced Learners of English (LexTALE, Lemhöfer & Broersma, 2012), and the Letter–Number Sequencing task from WAIS-III (Wechsler, 1997) were conducted to assess participants’ language background, handedness, English proficiency, and working memory capacity, respectively.

Results

English word and Chinese character naming

Repeated measures ANOVA was used to analyze participants’ accuracy and correct RT. In the word/character naming RT, a significant three-way interaction among language, VF, and group was observed, $F(2, 57) = 3.895$, $p = .026$, $\eta_p^2 = .120$, suggesting that musicians and non-musicians showed different VF effects between English word and Chinese character naming. To better understand this three-way interaction, we examined their performance in English word naming and Chinese character naming separately. In English word naming RT, a significant main effect of group was found, $F(1, 58) = 4.363$, $p = .041$, $\eta_p^2 = .070$: musicians named English words faster than non-musicians. In addition, a significant interaction between VF and group was observed, $F(1, 58) = 3.347$, $p = .042$, $\eta_p^2 = .105$, suggesting that musicians and non-musicians showed different VF effects in English word naming. When we examined the data in different VF conditions separately, musicians named English words faster than non-musicians when the words were presented in the LVF, $t(58) = -3.001$, $p = .004$, $d = -.774$, and center, $t(58) = -2.109$, $p = .039$, $d = -.544$, but not in the RVF ($t(58) = -.146$, $p = .885$, $d = -.037$, Figure 5)[ii]. This result was consistent with our hypothesis, suggested an LVF/RH advantage in musicians in English word processing as compared with non-musicians.

In contrast to English word naming RT, in Chinese character naming RT, we observed a significant main effect of VF, $F(2, 57) = 3.523$, $p = .036$, $\eta_p^2 = .110$: Participants performed better when Chinese characters were presented in the RVF than the center position, while similar performance were observed between the center and LVF conditions. This result was consistent with previous Chinese character naming studies (e.g., Hsiao & Cheng, 2013). However, this VF effect did not interact with group, $F(2, 57) = 1.160$, *n.s.* (Figure 5), suggesting that musicians and non-musicians did not differ in lateralization effects in Chinese character naming. This result was consistent with our hypothesis that music reading experience may influence lateralization effects in English word processing more than those in Chinese character processing, due to the similarities between English word and music notation reading.



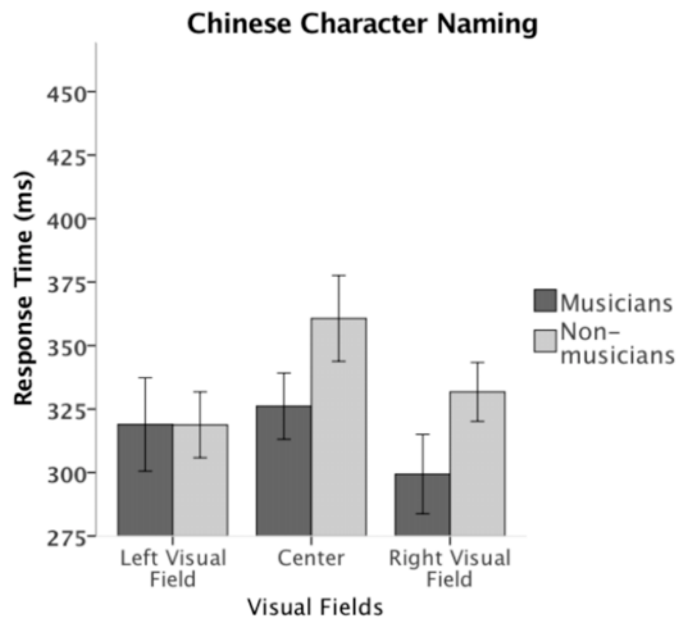


Figure 5. Mean RTs of English word naming and Chinese character naming between musicians and non-musicians across the three VFs (LVF, center, and RVF; error bars show one standard error; * $p < .05$).

In a separate analysis, we examined participants' Chinese symmetric and SP character naming RT separately. A significant main effect of VF was observed in symmetric characters, $F(2, 57) = 5.400$, $p = .007$, $\eta_p^2 = .159$. Participants performed similarly when symmetric characters were presented in either the LVF or RVF but had the worst performance in the center. No main effect of VF was observed in SP characters, $F(2, 57) = .803$, *n.s.*. We found that in either case, there was no significant interaction between VF and group (symmetric: $F(2, 57) = 1.606$, *n.s.* ; SP: $F(2, 57) = .397$, *n.s.*; Figure 6). In other words, musicians and non-musicians did not differ in lateralization effects in naming either symmetric or SP characters.

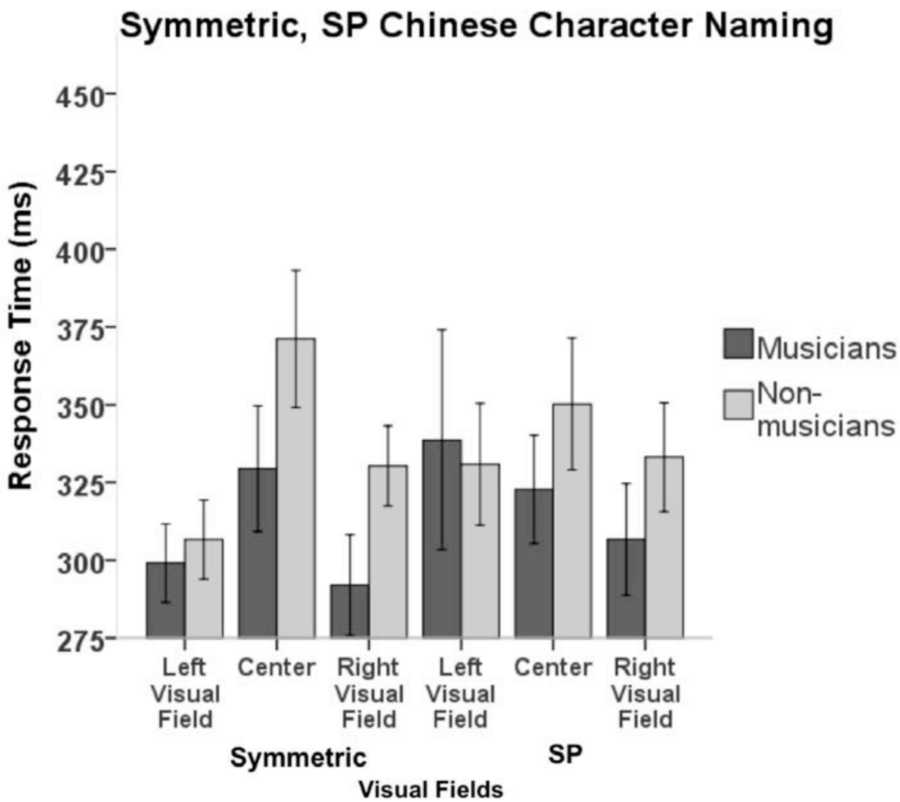


Figure 6. Mean RT in the symmetric and SP Chinese character naming tasks (error bars: +/- 1 SE; * $p < .05$)

In word/character naming accuracy, a significant interaction between language and VF was observed, $F(2, 57) = 48.926$, $p < .001$, $\eta_p^2 = .632$. In English word naming accuracy, a significant main effect of visual field was found, $F(2, 57) = 16.403$, $p < .001$, $\eta_p^2 = .365$. Participants performed the best when English words were presented in the RVF/LH, and had similar performances in the center and the LVF (Figure 7). In contrast, in Chinese character naming accuracy, a significant main effect of VF was found ($F(2, 57) = 133.503$, $p < .001$, $\eta_p^2 = .824$): Participants performed the best when Chinese characters were presented in the RVF, followed by the LVF and then the center, consistent with the RT data (Figure 8). No other significant effect was observed.

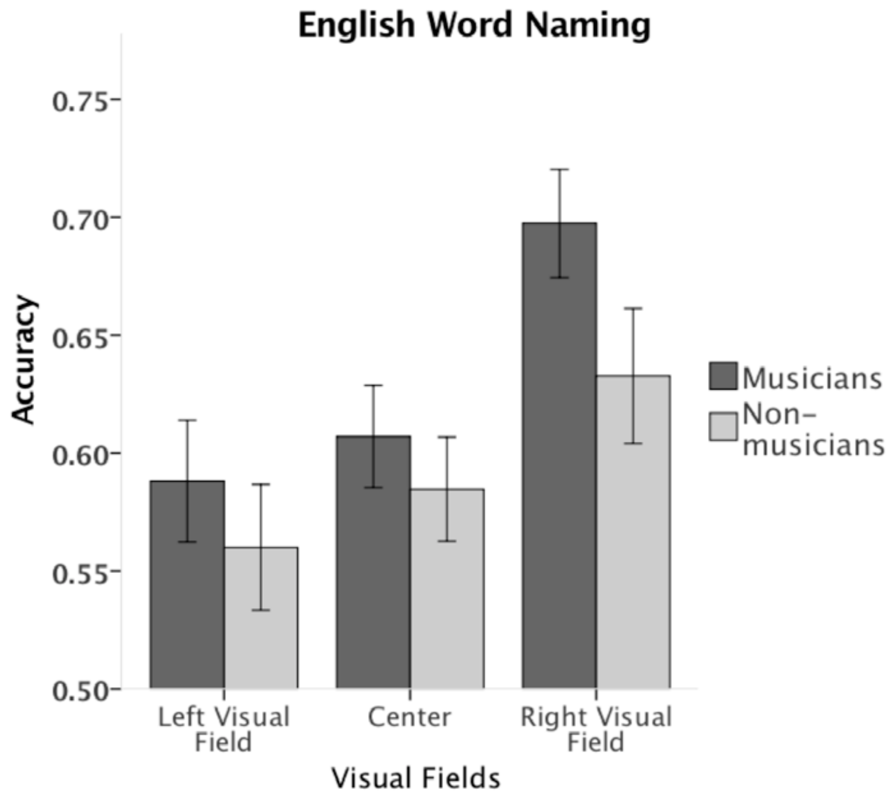


Figure 7. Mean accuracy in the English word naming task (error bars: +/- 1 SE).

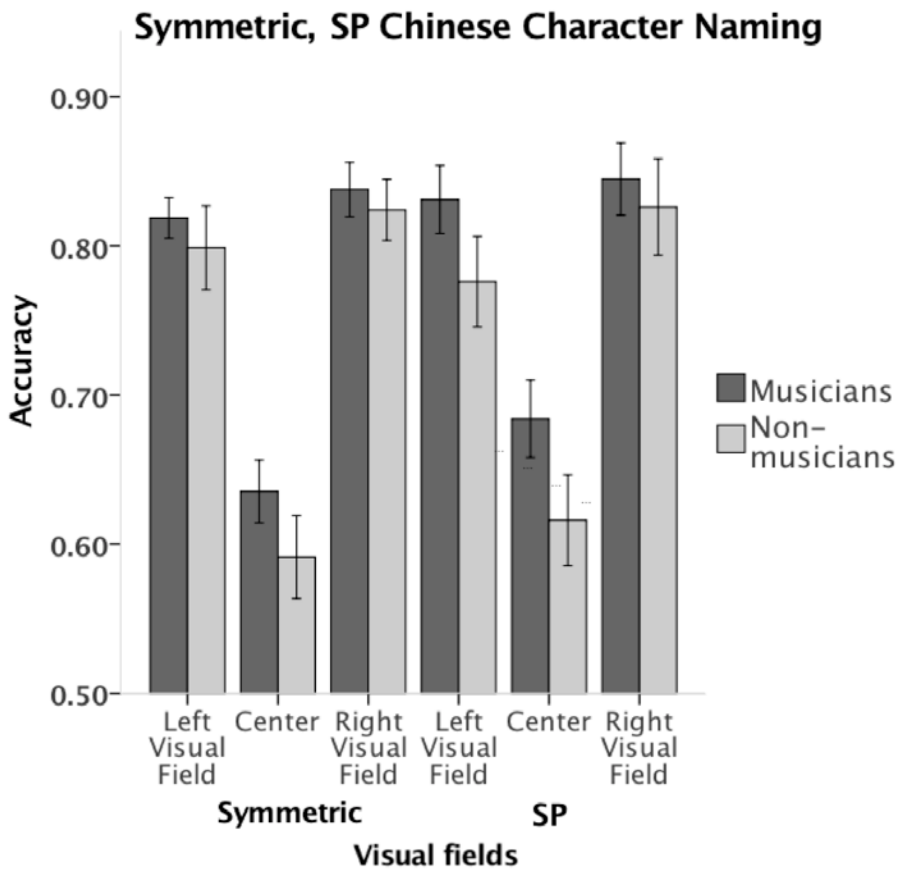


Figure 8. Mean accuracy in the symmetric and SP Chinese character naming tasks (error bars: +/- 1 SE).

To further examine the differential modulation effect of music reading experience on lateralization effects in English word and Chinese character naming RT, in a separate analysis we calculated the participants' laterality index of English word and Chinese character naming RT as (LVF – RVF)/(LVF + RVF) (Seghier, 2008; Seghier, Kherif, Josse, & Price, 2011). We analyzed this laterality index using ANOVA with language (English vs. Chinese) and group (musician vs. non-musician) as the independent variables. The results showed a significant interaction between language and group, $F(1, 58) = 8.049$, $p = .006$, $\eta_p^2 = .122$. When we examined the data in English word naming and Chinese character naming separately, musicians and non-musicians differed significantly in the laterality index of English word naming RT, $t(58) = -2.644$, $p = .011$, $d = 0.682$ (M = -.0297; NM = .0472), but not in the laterality index of Chinese character naming RT, $t(58) = 1.671$, *n.s.* (M = .0288; NM = -.0221). These results again suggest that music reading experience may influence lateralization effects in English word processing more than those in Chinese character processing.

Music notation sequential matching

For the music notation sequential matching task, we performed an ANOVA with type of notation (note vs. chord), VF, and group as the variables. In the accuracy data, a significant main effect of type of notation (note vs. chord) was found ($F(1, 58) = 28.585$, $p < .001$, $\eta_p^2 = .330$): Participants processed notes better than chords. There was also a significant main effect of group ($F(1, 58) = 120.351$, $p < .001$, $\eta_p^2 = .675$): musicians showed higher accuracy than non-musicians. This group effect interacted with type of notation ($F(1, 58) = 13.944$, $p < .001$, $\eta_p^2 = .194$): the group effect was stronger in the note task than the chord task. Also, a significant main effect of VF ($F(2, 57) = 26.877$, $p < .001$, $\eta_p^2 = .485$) was found: Participants performed similarly when music notes/chords were presented in either the LVF or RVF but had the worst performance in the center (Figure 9). This phenomenon maybe related to the finding that visual span in reading is typically larger horizontally than vertically, which may be related to horizontal reading directions (see, e.g., Yu, Park, Gerold & Legge, 2010). In the RT data, a significant main effect of type of notation ($F(1, 58) = 12.984$, $p = .001$, $\eta_p^2 = .183$) was found: notes were processed faster than chords. Also, a significant main effect of VF ($F(2, 57) = 16.545$, $p < .001$, $\eta_p^2 = .367$) was found: the worst performance was observed in the center condition (Figure 10). There was no significant main effect of group, or significant interaction between VF and group.

To examine lateralization effects in music notation sequential matching, in a separate analysis we analyzed the participants' lateralization index measures in accuracy and RT using ANOVA, with type of notation and group as the independent variables. In the accuracy data, a significant main effect of type of notation (note vs. chord) was found ($F(1, 58) = 7.065$, $p = .010$, $\eta_p^2 = .109$): Participants processed notes better than chords. There was no significant main effect of group, or interaction between type of notation and group. In the RT data, no significant effect was observed. In summary, whereas musicians had better performance in the music notation sequential matching task than non-musicians, the two groups did not differ in the lateralization effects.

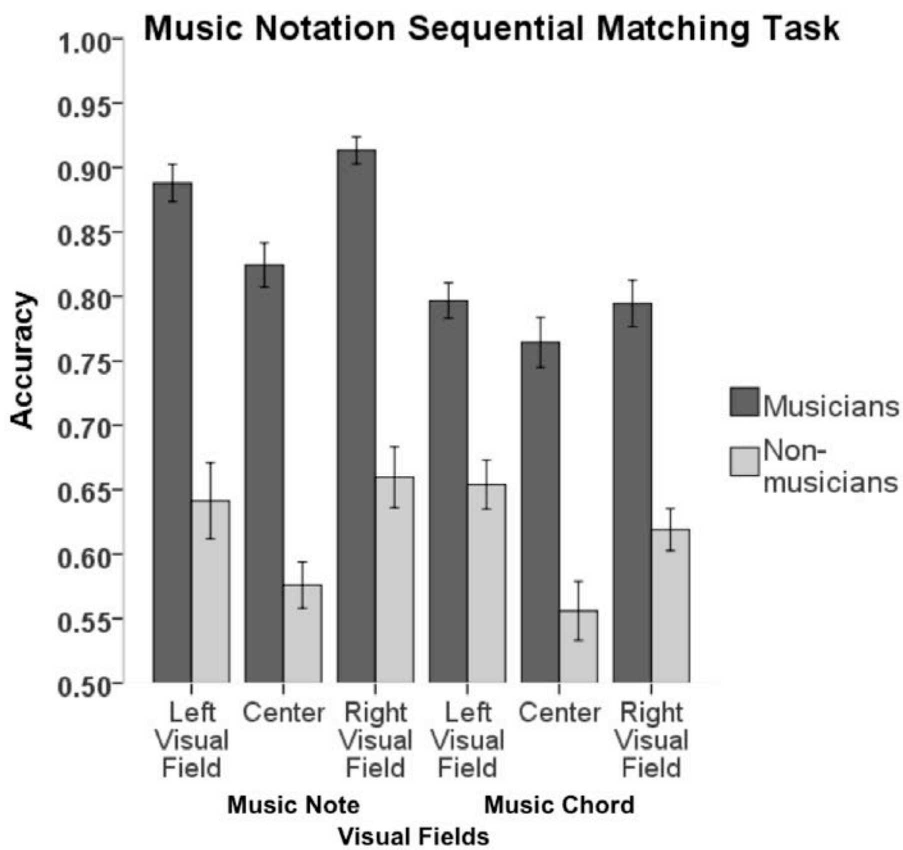


Figure 9. Mean accuracy in the music note and chord reading task (error bars: +/- 1 SE).

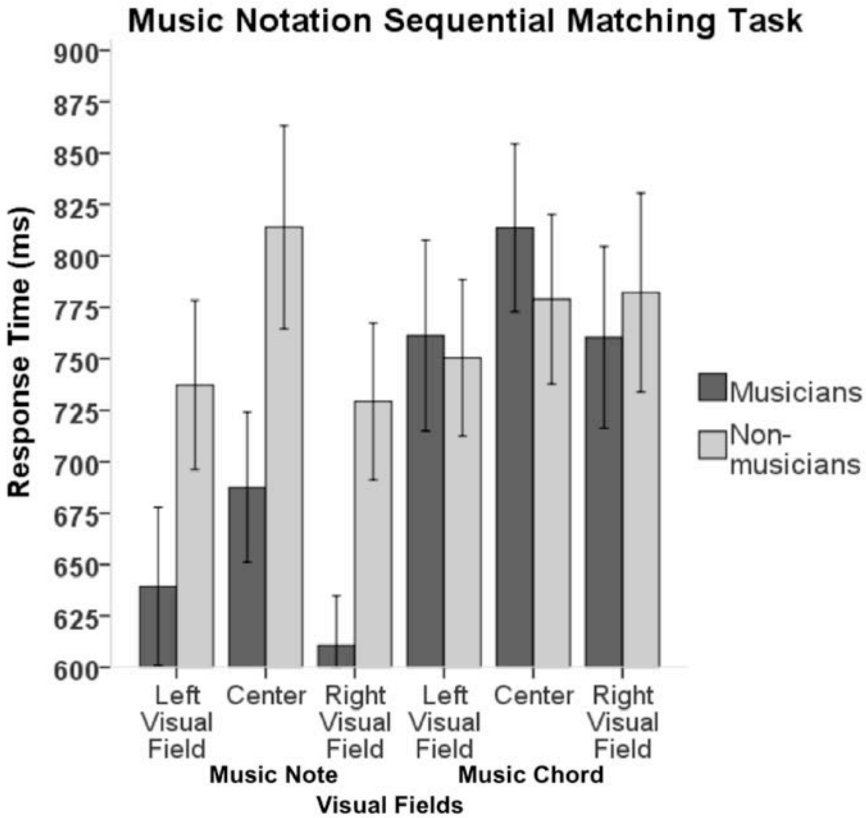


Figure 10. Mean RT in the music note and chord reading task (error bars: +/- 1 SE).

To investigate whether the lateralization effect in English word naming was indeed related to participants' music reading expertise, we examined the correlations between participants' performances in the music notation sequential matching task and laterality index measures in the English word naming task. Participants' laterality index in English word naming RT was negatively correlated with their accuracy in note matching (r = -.372, p = .003, Figure 11a) and chord matching (r = -.315, p = .014, Figure 11b)[iii]. Similarly, participants' RT in the English word naming task was negatively correlated with their accuracy in note matching (r = -.311, p = .015) and chord matching (r = -.263, p = .043). In other words, the better the participants performed in music notation matching, the weaker the RVF/LH advantage they had in English word naming. In contrast, these correlations were not significant in the Chinese character naming task. These results suggest that the reduced RVF advantage/increased LVF advantage in English word naming in musicians as compared with non-musicians is due to musicians' expertise in reading music. In contrast, the lateralization effect in Chinese naming was not influenced by participants' music reading experience.

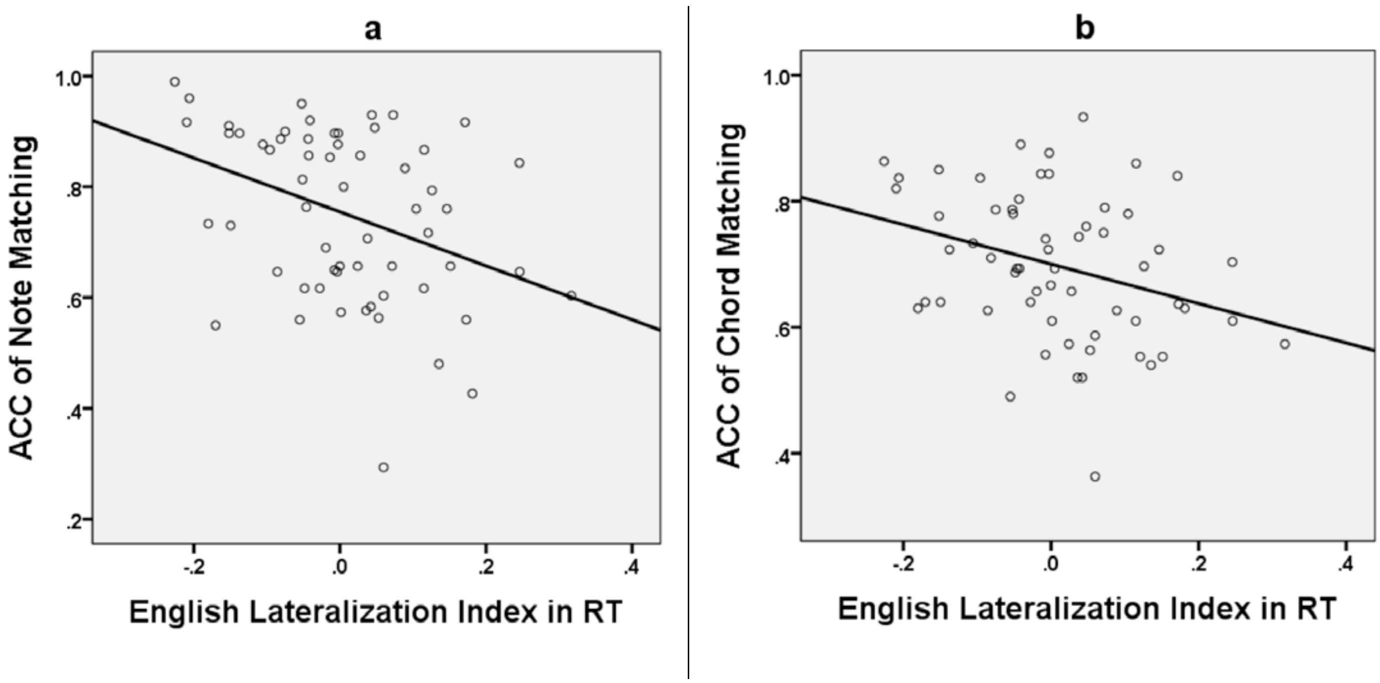


Figure 11. Scatterplots of the relationship between participants' laterality index measures in English word naming RT and their accuracy in (a) note matching (r = -.372, p = .003) and (b) chord matching (r = -.315, p = .014).

For the Tibetan letter string matching task, ANOVA was used with VF and group as the independent variables. In the accuracy data, a significant main effect of VF was found, $F(2, 57) = 4.677$, $p = .013$, $\eta_p^2 = .141$: participants performed similarly when the stimuli were presented in either the LVF or RVF, and the worst in the center. There was a marginal main effect of group, $F(1, 58) = 3.922$, $p = .052$, $\eta_p^2 = .063$ (Figure 12): musicians performed better in Tibetan letter string matching than non-musicians, suggesting enhanced novel symbol string processing due to music notation reading experience. This marginal group effect did not interact with VF. In addition, participants' accuracy in Tibetan letter string matching was positively correlated with their accuracy in note matching, $r = .425$, $p = .001$, and chord matching, $r = .446$, $p < .001$. This effect further suggested that the better the participants were in matching music notations, the more advantage they had in Tibetan letter string matching. In the RT data, a significant main effect of VF was found, $F(2, 57) = 15.654$, $p < .001$, $\eta_p^2 = .355$: Participants performed the worst in the center condition. There was no main effect of group or interaction between group and VF (Figure 13). In a separate analysis, laterality index measures were used to examine lateralization effects. No significant group difference was found in either accuracy, $t(58) = -.758$, *n.s*, or RT, $t(58) = .865$, *n.s*. These results suggested that musicians did not differ significantly from non-musicians in lateralization effects in processing Tibetan letter strings.

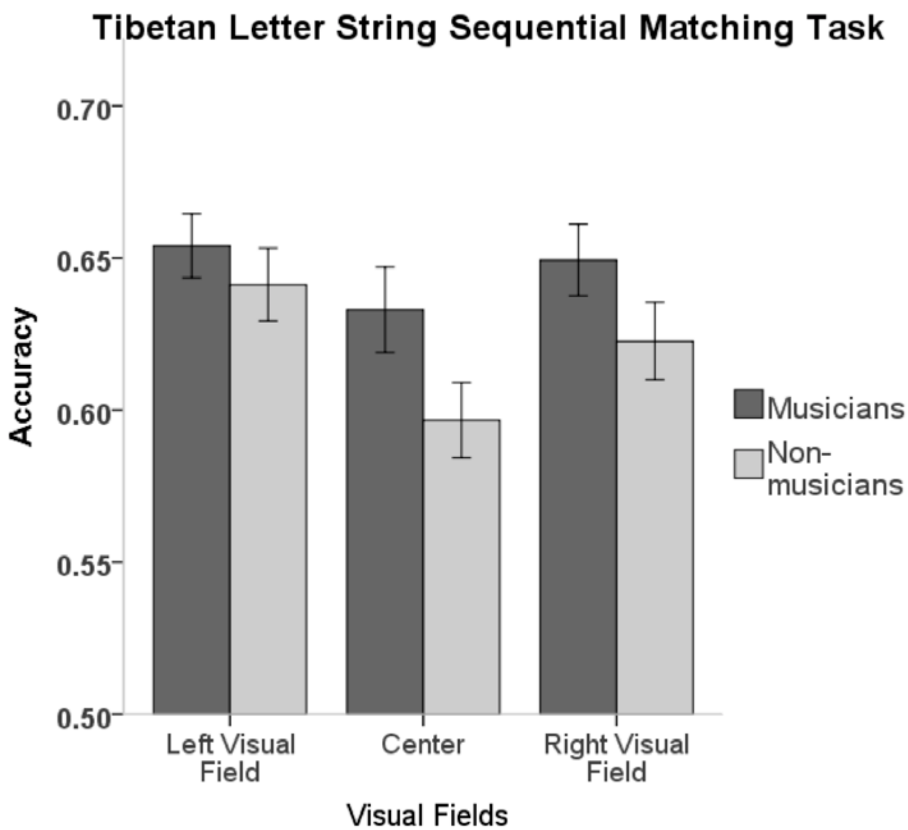


Figure 12. Mean accuracy in the Tibetan letter string reading task. (error bars: +/- 1 SE)

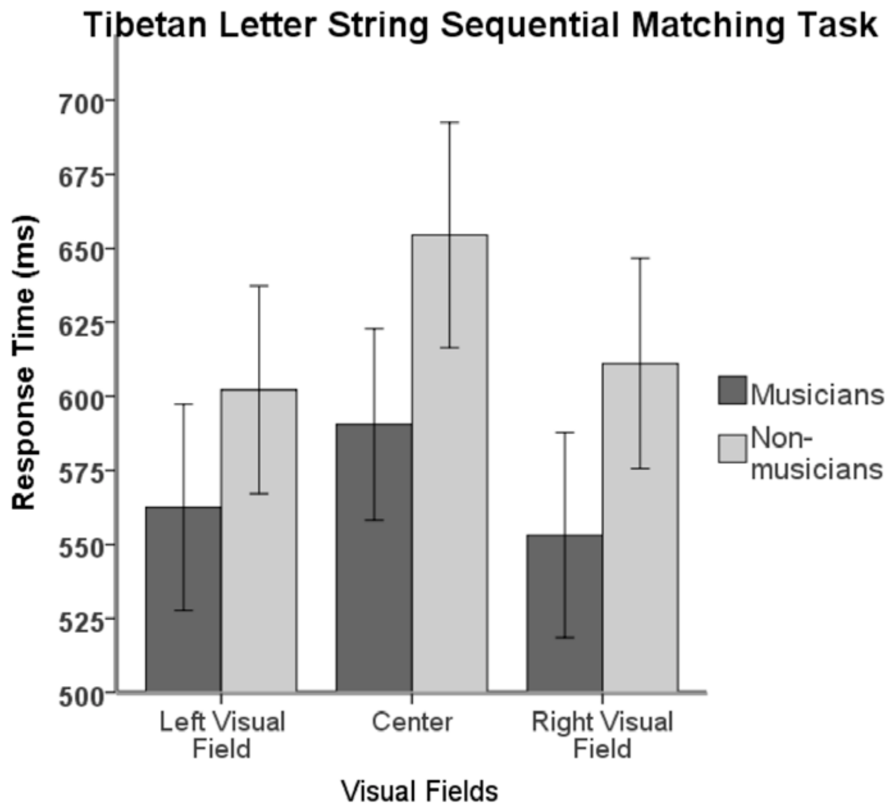


Figure 13. Mean RT in the Tibetan letter string reading task. (error bars: +/- 1 SE)

Experiment 2

In Experiment 1, we found that in English word naming, musicians responded significantly faster than non-musicians when words were presented in either the LVF or the center position. This effect suggested a facilitation of RH English word processing due to music reading experiences. Here we test the hypothesis that this phenomenon may be due to the similarities between music notation and English word reading processes in the RH accommodate each other, making the relevant processes more efficient and consequently facilitating RH English word processing. More specifically, RH English word processing has been characterized by letter-by-letter, serial visual processing (e.g., Lavidor & Ellis, 2001), which is similar to the visual processing requirements in music notation reading. In addition, this modulation may be stronger in English non-word processing than the processing of real or pseudo-words, since non-words do not follow morphological rules and are not associated with lexical representations, similar to musical segments. To test these hypotheses, here we conduct an ERP study with a sequential matching paradigm to focus our examinations on how music reading expertise influences visual processing of English stimuli. We expect that musicians will have a stronger reduction in N170 response to English stimuli under the processing of musical segments than non-musicians in the RH due their expertise in reading both English stimuli and musical segments (e.g., Rossion et al., 2004), and this effect may be stronger in English non-words than real words.

Methods

Participants

A similar group of participants were recruited for Experiment 2. Participants were 60 Chinese (L1)-English (L2) bilinguals from Hong Kong, whose ages ranged from 18 to 29 (M = 21.02, SD = 2.77). They had similar language and college education backgrounds, with normal or corrected to normal vision. They were categorized as 30 musicians (14 males, 16 females) and 30 non-musicians (12 males, 18 females).

Musicians were well-trained pianists, who started music training at age 3-8 (M = 5.33, SD = 1.47). All of them were either piano teachers, music major students, or frequent piano players. They had attained grade 8 or above in the graded piano examinations of the Associated Board of The Royal Schools of Music (ABRSM) or equivalent, with 8-25 year experience in piano playing (M = 15.03, SD = 3.89) and regular music reading hours per week (M = 7.16, SD = 12.33). Musicians outperformed non-musicians in musicality, as assessed by music note familiarity rating on a 10-point Likert scale (M: 9.90; NM: 2.93; $t(29.911) = 15.553$, $p < .001$, d = 4.018) and the Goldsmiths Musical Sophistication Index (Gold - MSI; Müllensiefen, Gingras, Musil, & Stewart, 2014), including active engagement (M: 34.47; NM: 22.70; $t(49.232) = 6.753$, $p < .001$, $d = 1.744$), perceptual abilities (M: 49.63; NM: 33.93; $t(58) = 7.981$, $p < .001$, $d = 2.060$), musical training (M: 14.767; NM: 7.20; $t(45.212) = 6.005$, $p < .001$, $d = 1.551$), emotions (M: 31.90; NM: 24.40; $t(58) = 5.72$, $p < .001$, $d = 1.477$), singing abilities (M: 34.33; NM: 22.33; $t(58) = 7.513$, $p < .001$, $d = 1.958$) and general sophistication (M: 79.833; NM: 48.467; $t(58) = 9.970$, $p < .001$, $d = 2.574$). In contrast, non-musicians did not receive any formal music training or self-learning in instruments and voice since birth and were not able to read music notes and chords.

Aside from their music background, musicians and non-musicians were closely matched in handedness and language exposure. Most participants were right-handed, which was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971; M: 54.33, 3^{th} right decile; NM: 64.33, 3^{rd} right decile, $t(58) = -1.241$, *n.s.*). All participants started learning English as a second language at age 3 ($M = 3.3$, $SD = 1.306$, *range* = 0-6) and have similar self-reported English reading hours (M: 27.48; NM: 18.77; *n.s.*). No participants had experience with the Tibetan language.

Materials

The materials consisted of 3 types of English words (real, pseudo, and non-words with 4-6 letters) as target stimuli, and two types of comparable pre-/post-stimulus masks: musical segments with 4 random notes without clefs ($n = 1323$; Figure 14a) ranging from D4 to G5 and Tibetan letter strings with 4 random letters ($n = 1323$; Figure 14b). Tibetan letter strings, a novel stimulus type that no participants had any experience with, were included as a control condition.

(a) Musical segments with 4 random notes

(b) Tibetan letter strings with 4 random letters

Figure 14. Examples of pre-/post-stimulus masks in the English word sequential matching task: (a) Musical segments with 4 random notes and (b) Tibetan letter strings with 4 random letters

English real words (*n* = 126) were selected from Bryden et al., (1990), the SUBTLEX-US corpus (Brysbaert et al., 2012) and Wuggy (a word generator, Keuleers & Brysbaert, 2010). To control for information distribution within a word, the same number of high-frequency words and low-frequency words were selected within the informative beginning and informative end subsets in Bryden et al. (1990). Word frequency was closely matched between 'same' and 'different' trials in the matching task and between music and Tibetan conditions. The average frequency of our English stimuli is 3,782 occurrences per 51,000,000 words (*range* = 2 to 39,491/51,000,000) according to the SUBTLEX-US corpus (Brysbaert et al., 2012). For 'same' trials, two target stimuli were identical. For 'different' trials, half trials had shared beginnings (e.g. banker, banner), while the other half had shared ends (e.g. salary, notary).

English pseudo-words (i.e. non-existing words with legal letter strings at the word beginning and word end, *n* = 126) were created by extracting and recombining word beginnings and ends from our English real word list. This is to control information distribution at the word beginnings and ends between real and pseudo-word stimuli. For 'same' trials, two target stimuli were identical. For 'different' trials, half trials had shared beginnings (e.g., banher, banord), while the other half had shared ends (e.g., saliew, supiew).

English non-words (i.e., illegal letter strings, *n* = 126) were created by re-ordering the letters in the word beginnings and word ends from our English pseudo-word list such that the letter combinations do not follow morphological rules in English. This is to closely match the letters used in all conditions. For 'same' trials, two target stimuli were identical. For 'different' trials, half trials had shared beginnings (e.g. nbaerh, nbaodr), while the other half had shared ends (e.g. alsiwe, spuiwe). The non-words were checked against the morphologically ambiguous syllables in the ARC Nonword database (Rastle, Harrington, & Coltheart, 2002) to ensure their suitability for our task.

Design

To focus on visual processing of English words, a sequential matching task similar to Gauthier et al. (2003) was used. The design consisted of two within-subject variables: English word type (real vs. pseudo vs. non-words) and stimulus mask (musical segments vs. Tibetan letter strings), and one between-subject variable: group (musicians vs. non-musicians). In the ERP data analysis, an additional variable hemisphere (LH vs. RH) was included. Participants completed the task with English real, pseudo, and non-word stimuli with both musical segment and Tibetan letter string masks in separate blocks (Figure 15). For each mask type, 36 'same' and 36 'different' trials were included for each word type condition. Half of the stimulus pairs in 'same' and 'different' trials were different in the two mask conditions to avoid practice effects.

English words were displayed in Courier (a serif font with fixed width) to ensure constant center-to-center spacing between letters. Under the viewing distance 50 cm, each English word subtended a horizontal and vertical visual angle of 4.06° x 0.95° (4 letters), 5° x 0.95° (5 letters), or 6.35° x 0.95° (6 letters). Musical segments with 4 random notes in crotches (1 beat) with the five-line staff subtended a horizontal and vertical visual angle of 6.90° x 1.62°. Tibetan letter strings with 4 random letters were presented in Himalaya font and subtended a horizontal and vertical visual angle of 6.90° x 1.62°. All stimuli were presented in black with a white background on a CRT monitor. Experiments were conducted using E-Prime v2.0 with 64-channel ANT EEG recording at a sampling rate of 512 Hz. All impedances were kept below 30 kΩ. A chinrest was used to reduce head movement. The block and trial orders were randomized.

Procedures

Each trial started with a central fixation with a randomly determined presentation duration between 400-600 ms. A pre-stimulus mask (a musical segment or a Tibetan letter string) was presented for 600 ms, followed by an 800 ms presentation of the first target stimulus (a real/pseudo/non-word). Then, a post-stimulus mask (a musical segment or a Tibetan letter string) was presented for 600 ms, followed by an 800 ms presentation of the second target stimulus (a same or different real/pseudo/non-word; Figure 15). All stimuli were presented at the center of the screen. Participants judged whether the two target stimuli were the same or not by pressing buttons with both hands. The trial did not proceed to the 800 ms 'blink' period until receiving participants' response. Accuracy and RT were recorded by Eprime with EEG recording.

Prior to the English word sequential matching task, a demographic and music background questionnaire, the Goldsmiths Musical Sophistication Index (Müllensiefen et al., 2014) and Edinburgh Handedness Inventory (Oldfield, 1971) were conducted to assess participants' language, music background, and handedness.

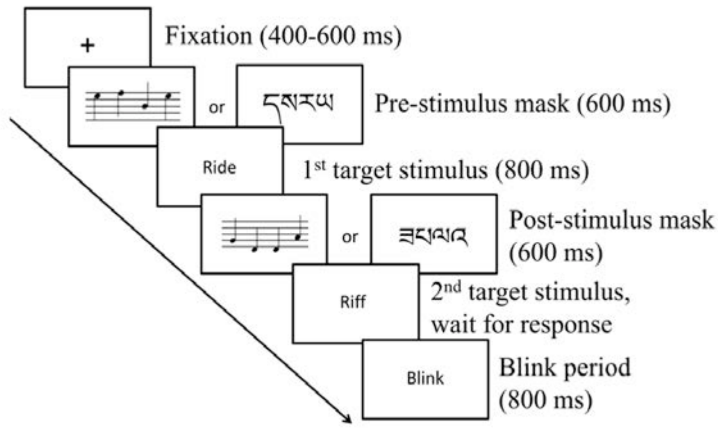


Figure 15. Procedure of the English word sequential matching

EEG data analysis

The 64-channel EEG data were analyzed using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) in MATLAB. Bin-based epochs were extracted from -100 ms to 600 ms of the stimulus onset and corrected from baseline deviations using a pre-stimulus window of 99 ms. Filtering was carried out using a high-pass filter with 0.1 Hz cut-off and a low-pass filter with 30 Hz cut-off. ERPs from each participant were then averaged in each block to obtain the grand average data after removing trials with artifacts. The analyses of the N170 component were based on the electrode pairs with the largest N170 amplitude from the grand average data. Accordingly, electrodes PO7 (LH) and PO8 (RH) were selected for the analysis of N170 response to the pre-stimulus masks (musical segments vs. Tibetan letter strings), while electrodes P7 (LH) and P8 (RH) were selected for N170 responses to the first presentation of the English real, pseudo, and non-words preceded by musical segments or Tibetan letter strings, using repeated measures ANOVA. Note that we only analyzed the N170 responses to the first presentation of the English word stimuli since the EEG responses to the second stimulus may be contaminated by button responses.

Results

In the behavioral data, we performed an ANOVA with word type (real vs. pseudo vs. non-words) and group (musicians vs. non-musicians) as the variables. In the accuracy data, there was a significant main effect of group, $F(1, 58) = 4.643$, $p = .035$, $\eta_p^2 = .074$ (Table 1): musicians showed higher accuracy than non-musicians in matching the stimuli. No significant main effect of word type, or interaction between word type and group was found in accuracy. Similarly, in the RT data, a significant main effect of group was found, $F(1, 58) = 5.916$, $p = .018$, $\eta_p^2 = .093$ (Table 1): musicians had faster RT than non-musicians in matching the stimuli. There was no significant main effect of word type, or interaction between word type and group in RT. These behavioral results suggested that musicians had higher accuracy and faster RT overall, although both musicians and non-musicians had a similar within-group performance level in matching stimuli with different lexicalities.

Accuracy/(RT)	Average	Real words	Pseudo-words	Non-words
Musicians	96.5%* (603.327 ms)*	97.2% (612.961 ms)	96.9% (594.467 ms)	95.4% (602.554 ms)
Non-musicians	93.2%* (709.384 ms)*	93.8% (736.496 ms)	93.0% (710.948 ms)	92.8% (680.708 ms)

Table 1. The comparison in accuracy and RT between musicians and non-musicians in the English word sequential matching task, * $p < .05$

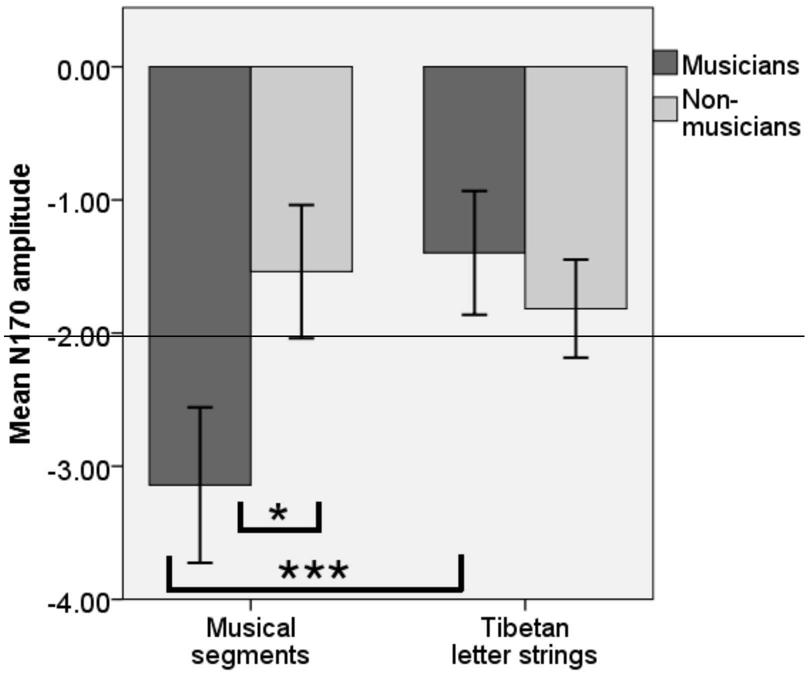


Figure 16. Average N170 amplitude at PO7 and PO8 in response to musical segments and Tibetan letter strings (error bars = +/- 1 *SE*; *** $p < .001$, * $p < .05$).

In the ERP N170 response to the pre-stimulus mask, a significant interaction between mask type (music vs. Tibetan) and group (musicians vs. non-musicians) was observed, $F(1, 52) = 31.797$, $p < 0.001$, $\eta_p^2 = .379$. When we examined the data in different mask type conditions separately, musicians had a larger N170 amplitude than non-musicians in response to musical segments, (M = -3.142 μV, *SD* = 3.093; NM = -1.538 μV, *SD* = 2.554, $t(52) = -2.069$, $p = .044$, $d = 0.565$; Figure 16), whereas no difference was observed between the two groups in response to Tibetan letter strings (M = -1.398 μV, *SD* = 2.463; NM = -1.817 μV, *SD* = 1.878, $t(52) = .701$, *n.s.*). When we split the data by group, musicians had a larger N170 amplitude in response to musical segments than to Tibetan letter strings, $F(1, 27) = 68.980$, $p < 0.001$, $\eta_p^2 = .719$ (Figure 16), whereas non-musicians did not show any significant differences in response to musical segments and Tibetan letter strings. These findings were consistent with the perceptual expertise literature showing that visual expertise increases the N170 amplitude in response to the stimuli in experts as an expertise marker (Rossion et al., 2004). No main effects or interactions with hemisphere were observed in response to musical segments or Tibetan letter strings (Figure 17).

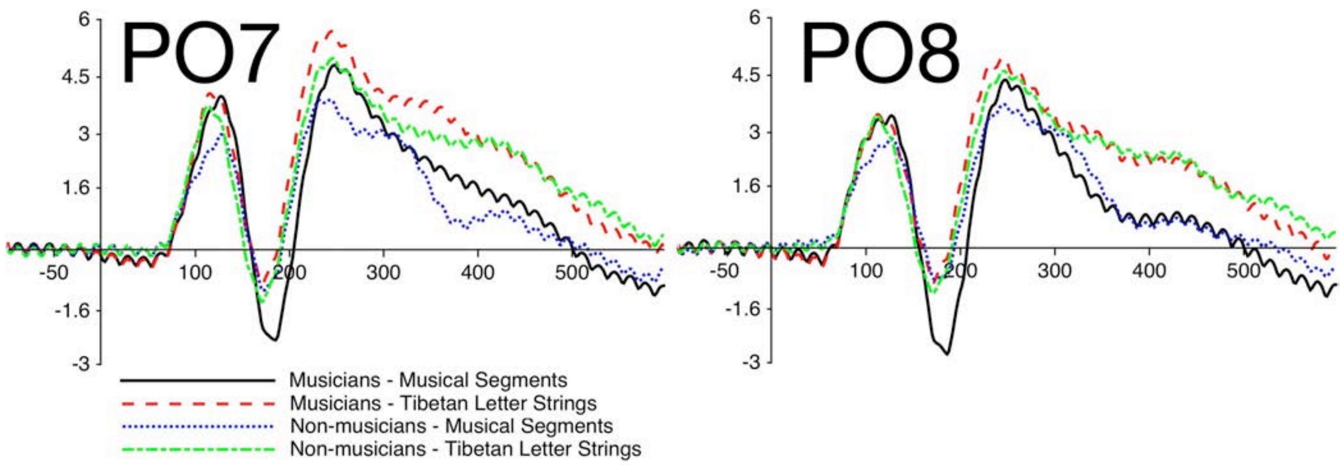


Figure 17. N170 amplitude in response to musical segments and Tibetan letter strings between musicians and non-musicians in PO7 (LH) and PO8 (RH).

For N170 responses to English words (the first target stimulus), a significant four-way interaction, mask type (music vs. Tibetan) x word type (real vs. pseudo vs. non-words) x hemisphere (LH vs. RH) x group (musicians vs. non-musicians), was observed, $F(2, 53) = 3.323$, $p = .044$, $\eta_p^2 = .111$[iv]. To better understand this interaction, we examined the N170 amplitude in response to real, pseudo, and non-words separately (Figure 18). A significant interaction among mask type, hemisphere, and group was found in English non-words, $F\ (1, 54) = 6.269$, $p = .015$, $\eta_p^2 = .104$, but not in real or pseudo-words. This three-way interaction suggested that musicians and non-musicians had different N170 amplitudes in response to non-words preceded by musical segments and Tibetan letter strings in the LH and the RH. This effect was not found in real or pseudo-words.

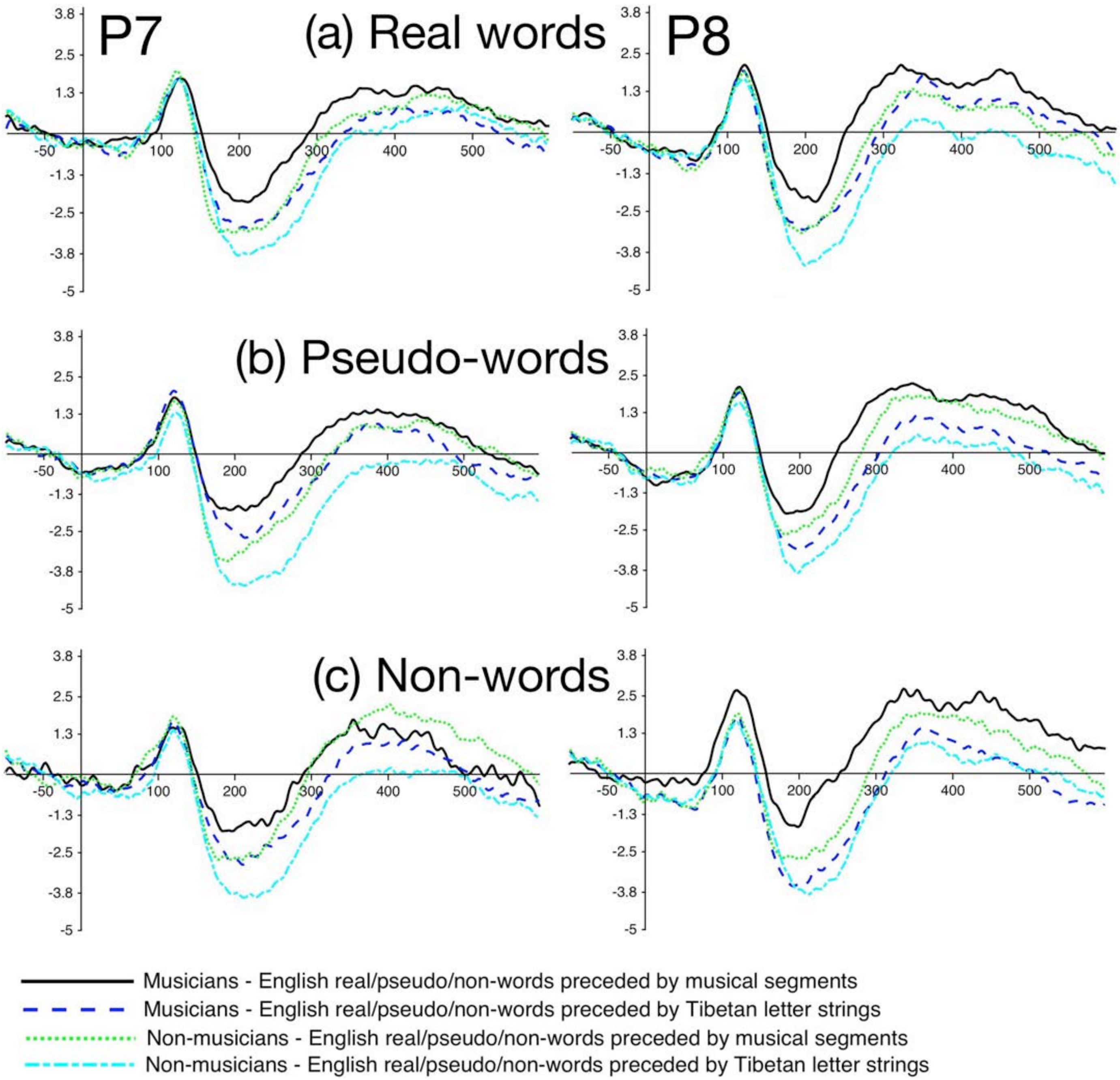
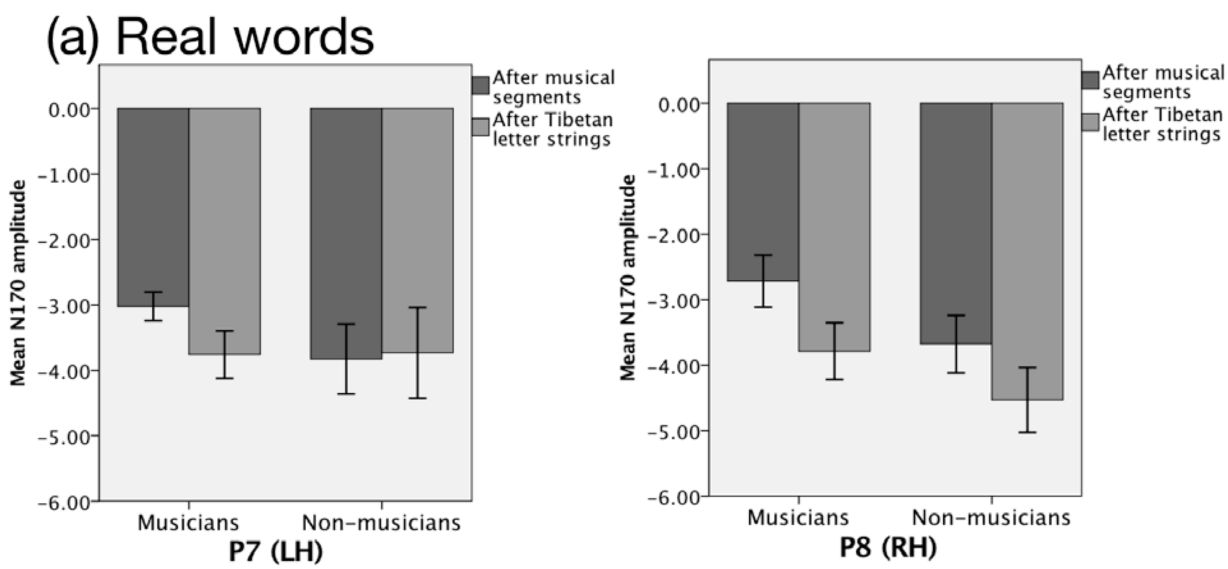


Figure 18. N170 amplitude in response to English (a) real, (b) pseudo and (c) non-words preceded by musical segments and Tibetan letter strings between musicians and non-musicians in P7 (LH) and P8 (RH) in sequential matching.

When we examined the data of non-words in two participant groups separately, musicians showed a significant interaction between mask type (music vs. Tibetan) and hemisphere (LH vs. RH), $F(1, 26) = 10.601$, $p = .003$, $\eta_p^2 = .290$, whereas non-musicians did not. When we examined musicians' data in the two hemispheres separately, a significant main effect of mask type (music vs. Tibetan) was observed, $F\ (1, 26) = 9.004$, $p = .006$, $\eta_p^2 = .257$: musicians had a smaller N170 amplitude in response to English non-words preceded by musical segments (-2.176 μV, *SD* = 3.884, Figure 19c) than those preceded by Tibetan letter strings in the RH (-4.110 μV, *SD* = 2.113). This mask type effect was not observed in the LH. Note that this mask type effect was also not observed in either participants' N170 responses to real (Figure 19a) and pseudo-words (Figure 19b), or non-musicians' N170 responses to non-words (Figure 19c). This phenomenon demonstrates a modulation of musicians' musical segment processing on English non-word processing in the RH.



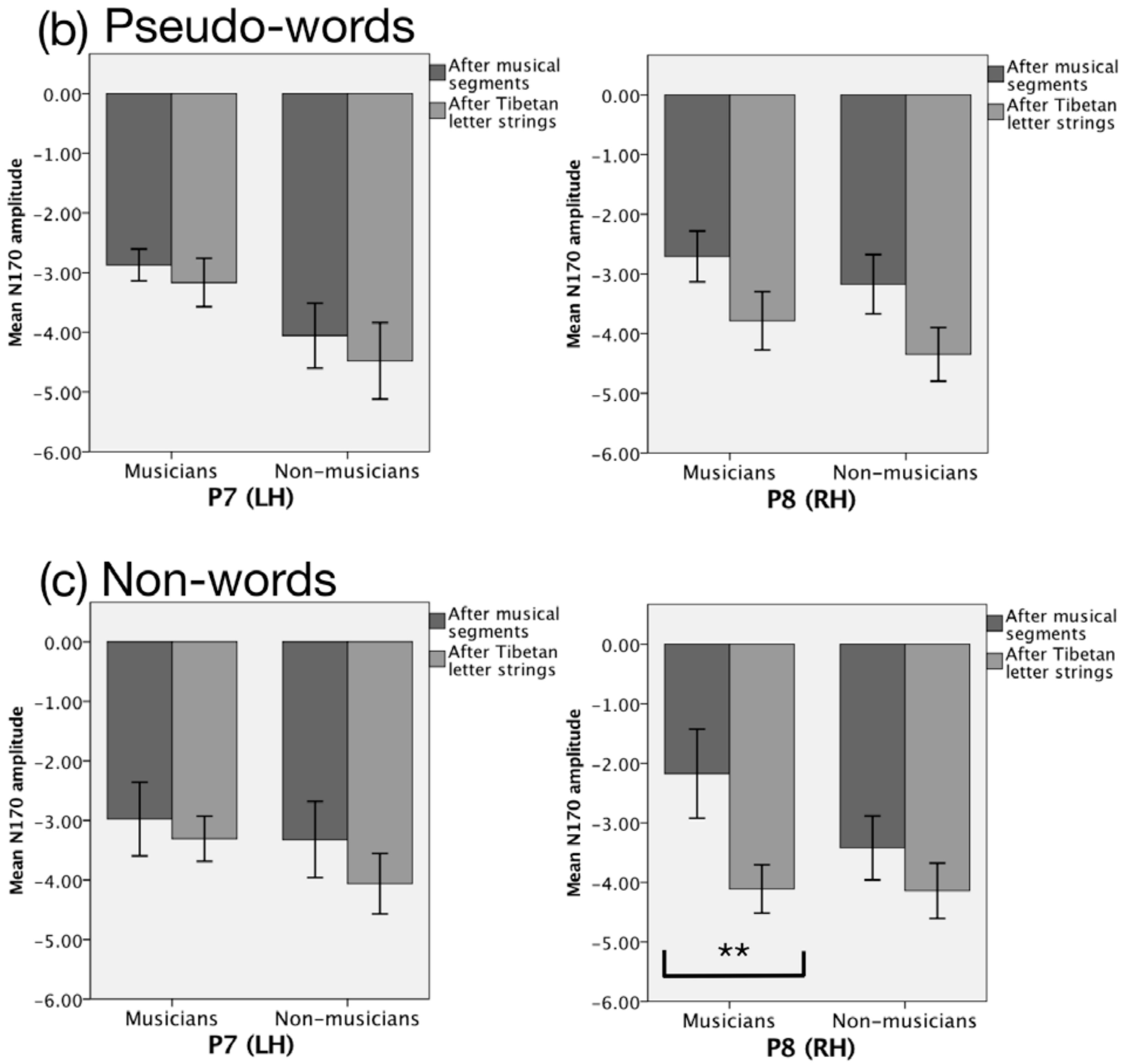


Figure 19. N170 amplitude in response to English (a) real, (b) pseudo and (c) non-words preceded by musical segments and Tibetan letter strings between musicians and non-musicians in P7 (LH) and P8 (RH) in sequential matching (error bars = +/- 1 *SE*; ** $p < .01$).

Discussion

Here we examined how music reading expertise influences hemispheric lateralization effects in English word and Chinese character reading through both behavioral and ERP studies. While both the LH and the RH seem to play an important role in music notation and English word reading, in contrast to English words, musical segments do not follow strict morphological rules and are not associated with phonological/semantic representations. Accordingly, we hypothesized that the modulation of music reading experience on English word reading may be mainly due to a shared visual processing mechanism in the RH. More specifically, it may be the requirement of serial processing of horizontally arranged components with similar sizes, which has been shown to be the information processing style engaged in the RH for recognizing English words (i.e., letter-by-letter recognition; e.g., Lavidor & Ellis, 2001). In contrast, reading Chinese characters, a logographic orthography, does not involve grapheme-phoneme correspondence. Also, Chinese characters typically have much fewer components than English words or musical segments, and the components can appear in different configurations in addition to a left-right structure. Thus, the recognition of Chinese characters may rely less on serial visual processing of components, and consequently may be less influenced by music reading experience.

Consistent with our hypothesis, we found that music reading experience modulates lateralization effects in English word processing but not in Chinese character processing, and this modulation effect was observed in the RH. More specifically, in Experiment 1, we found that in English word naming, whereas non-musicians and musicians did not differ in naming speed when words were presented in the RVF/LH, musicians responded significantly faster than non-musicians when words were presented in either the LVF/RH or the center position. In addition, participants' laterality indices of English word naming RT were negatively correlated with their accuracy in note and chord matching: the better the performance in music notation matching, the weaker the RVF/LH advantage in English word naming. In contrast, in Chinese character naming, musicians did not perform significantly differently from non-musicians in lateralization effects.

In the ERP data in Experiment 2, we found that in English word sequential matching, musicians showed smaller N170 amplitude in response to English stimuli preceded by musical segments than by novel symbol strings in the RH, whereas non-musicians did not show this modulation effect. In addition, this effect was only observed in non-word but not in real or pseudo-word stimuli. This result is consistent with our speculation that the modulation effect was not related to lexical processing of English words; instead, it may be related to a shared visual processing mechanism in the RH between music notation and English non-word reading. This result also suggests that the interaction between visual English word and music notation processing depends on the similarities of the cognitive processes involved. More specifically, in contrast to English real and pseudo-words, non-words and musical segments do not follow any morphological or orthographic rules (Chan & Hsiao, 2016). Given that they share similar global forms, containing components of similar sizes arranged horizontally, their recognition may both rely on component by component serial processing, giving rise to the modulation effect. Consistent with this speculation, an RH advantage in the perception of global forms has been consistently reported (Sergent, 1982). English word processing in the RH is also shown to be more sensitive to variations in visual word forms than the LH, such as words in case alternation (Lavidor & Ellis, 2001). In particular, Lavidor and Ellis (2001) found that the word length effect in English lexical decisions (i.e., faster responses to shorter words) was observed only when words were presented in the LVF/RH but not in the RVF/LH. However, when words in MiXeD CaSe were used, encouraging letter-by-letter processing, the word length effect was observed in both visual fields. These results suggest a letter-by-letter, serial processing engaged in the RH word recognition, in contrast to a left-lateralized, automated, whole-word lexical processing unaffected by word lengths (see also Lavidor, Ellis, & Pansky, 2002). Similarly, patients with LH lesions retained the letter-by-letter reading ability, suggesting that the nature of RH word processing involves letter-by-letter recognition (Cohen et al., 2004). Our results here were consistent with these findings, suggesting that RH English word processing was modulated by music notation reading experience due to their similarity in letter-by-letter or note-by-note visual processing. Consistent with our finding, Proverbio et al. (2013) reported that musicians recruited the right fusiform gyrus and the right inferior occipital gyrus in an orthographic letter recognition task, whereas non-musicians showed activations at the corresponding regions in the LH. This finding again suggests that music reading expertise modulates English word reading in the RH.

Note that in Experiment 2, the lack of the N170 modulation effect in real and pseudo-words does not necessarily mean that this modulation from music notation reading experience does not affect real word and pseudo-word processing. English word recognition involves the processing of visual word forms, phonology, and semantics. While the LH is shown to involve critically in lexical processing, the RH is reported to be important for the processing of visual word forms. Our current results suggest that the modulation of music experience is mainly in the RH. Since the processing of real and pseudo-words involves both visual word form and lexical/sublexical processing, these lexical effects may also influence N170 amplitudes measured in both hemispheres. Indeed, Ziegler, Besson, Jacobs, Nazir and Carr (1997) showed that real and pseudo-words elicited more negative early visual ERPs than non-words in bilateral posterior regions in a lexical decision task, with this difference appearing earlier in the LH than the RH. Thus, the RH N170 modulation effect of music reading expertise may have been contaminated by lexical/sublexical effects in real and pseudo-word processing. It is also possible that the lack of the modulation effect in real and pseudo-word processing is because random musical segments were used. Future work will examine whether musical segments from real musical pieces (motifs) will have different modulation effects.

In contrast to English word reading, musicians and non-musicians showed similar lateralization effects in Chinese character naming, and no correlation was observed between participants' lateralization effects and their music reading expertise as measured in the music notation matching task. Since Chinese is a logographic language, Chinese character reading does not involve grapheme-phoneme conversion/letter-sound mapping as English word reading or note-pitch mapping as music notation reading. In addition, components of a Chinese character are not always horizontally arranged, and characters with horizontally arranged components typically have much fewer components (typically only two or three) than English words or musical segments (although segmentation of music notations remains controversial; see Chan & Hsiao, 2016). Thus, Chinese character recognition may involve less letter-by-letter (or component-by-component), serial visual processing. This difference between Chinese character and English word recognition may also be related to the observation that orthographic processing of Chinese characters is typically more bilateral/right-lateralized as compared with that of English words (e.g., Tan et al., 2000; Tan et al., 2001; Tan et al., 2005; Tzeng et al., 1979; Hsiao & Lam, 2013; Hsiao & Cheung, 2016). Consequently, music notation reading experience does not influence visual processing of Chinese characters in the RH as much as that of English words, even though Chinese orthographic processing is typically more right-lateralized than English orthographic processing. Thus, our results suggest that how different visual expertise domains influence each other depends on their similarities in the cognitive processes involved. Stronger modulation effects may take place when the expertise domains rely on similar information processing mechanisms in the brain (e.g., music notation reading and English word reading expertise), but not when they involve less overlapping information processing mechanisms (e.g., music notation reading and Chinese character reading expertise).

Note also that the current results do not rule out possible modulation effects of music reading experience on phonological processing of English words. The naming task used in Experiment 1 involved both visual and phonological processing, and thus the observed lateralization difference between musicians and non-musicians could be due to either a modulation effect on visual word processing or phonological processing. In Experiment 2, we used a sequential making task, which involved mainly visual processing, to test the hypothesis about the possible modulation effect due to similarities between English word and music notation reading in visual processing mechanisms. Thus, it remains unclear whether music reading experiences also modulate phonological processing of words. Previous studies have reported benefits of music training on the phonological processing of English words, as shown in phonological skill training (Degé & Schwarzer, 2011). Thus, musicians' LVF/RH advantage in English word naming over non-musicians observed in Experiment 1 could also be related to modulation effects of music reading experience on English phonological processing in the LH. Future work will examine this possibility.

In the current study, we also found that when a note recognition task relies purely on visual processing of note locations (i.e., pitch reading), as in our music notation sequential matching task in Experiment 1, both musicians and non-musicians showed bilateral processing, although musicians were more accurate in note and chord reading and responded faster than non-musicians in note reading. Similarly, in the ERP study in Experiment 2, musical segments (as the pre-stimulus masks) elicited similar N170 amplitudes in the two hemispheres in both musicians and non-musicians, although musicians had a larger N170 amplitude than non-musicians in general. Our findings were consistent with previous studies showing bilateral activations in music notation processing in a note detection task (Proverbio et al., 2013) and a musical segment reading task (Stewart et al., 2003). As the tasks used here were limited to pitch judgments (Experiment 1) and passive viewing (Experiment 2), it remains unclear whether other components in music notation reading, such as rhythm and symbol reading, involve different lateralization effects. In brain lesion studies, Midorikawa and Kawamura (2000) showed that a piano player who suffered from left upper parietal lobule lesion was impaired in rhythm writing but not in pitch writing. Fasanaro et al. (1990) showed that a professional musician who suffered from left temporoparieto-occipital lesion had impaired note reading ability, while his rhythm and musical symbol (i.e., dynamic marking, articulation, and clef) reading ability retained. These findings suggest that different aspects of music notation reading (e.g., pitch, rhythm, and symbol reading) may involve different processing mechanisms (Hébert & Cuddy, 2006; Krumhansl, 2000).

Note that our result is in contrast to Segalowitz et al.'s (1979) study, which showed an RVF/LH advantage in chord processing in a piano playing task. As compared with a visual processing task such as sequential matching, piano playing tasks may involve more left-lateralized processes for motor planning. Thus, the lateralization effects in music notation processing may depend on the task requirements. Consistent with this speculation, d'Anselmo et al. (2015) showed that in a divided visual field piano playing (sight reading) task, musicians had an RVF/LH advantage when playing with one hand (either left or right), whereas a LVF/RH advantage was found when playing with both hands. While the RVF/LH advantage found in the single hand condition supports analytic processing of music notations in the LH, the LVF/RH advantage observed in the two-hands condition may illustrate the RH's role in the coordination of simultaneous responses (d'Anselmo et al., 2015). Thus, different task requirements may result in different lateralization effects in music notation processing.

As for novel symbol string (i.e., Tibetan letter string) processing, we found that musicians and non-musicians did not differ in lateralization effects in either Experiment 1 or Experiment 2. Nevertheless, in Experiment 1, we observed a marginal advantage of musicians over non-musicians in response accuracy, and a positive correlation between participants' accuracy and their music notation reading expertise as assessed in the music notation matching task. These effects suggest again benefits from music reading experience in sequential symbol processing, although the observed advantage in Tibetan letter string processing did not interact with hemisphere/visual field condition. Consistent with our finding, previous research has shown that musicians have better visuospatial skills than non-musicians (e.g., Sluming, Brooks, Howard, Downes, & Roberts, 2007; Patston et al., 2007a; Brochard et al., 2004), especially in tasks that involve processing of sequentially presented stimuli (e.g., Weiss, Biron, Lieder, Granot, & Ahissar, 2014; Jakobson, Lewycky, Kilgour, & Stoesz, 2008). For example, Weiss et al. (2014) showed that musicians outperformed non-musicians in a spatial frequencies discrimination task only when stimuli were presented sequentially, but not when they were presented simultaneously. Accordingly, the authors argued that musicians' superiority in visuospatial ability is due to enhanced general working memory ability instead of enhancement in general visuospatial skills. Future work will further examine this possibility.

To conclude, here we examined how music reading expertise influences hemispheric lateralization effects in English word and Chinese character processing through a divided visual field naming study and an ERP study. In the naming study, we observed an LVF/RH advantage in English word naming speed in musicians as compared with non-musicians, whereas no significant behavioral difference was observed between musicians and non-musicians in Chinese character naming. In the ERP study, we found that music notation and English non-word reading may share similar visual processing mechanisms in the RH, as demonstrated in the reduced N170 responses to English non-words under the processing of musical segments. This shared mechanism may be related to the letter-by-letter, serial visual processing that characterizes RH English word recognition, which may consequently facilitate English word processing in the RH in musicians. This result shows that music reading experience can have differential influences on word reading in different languages, suggesting that how different expertise domains influence each other depends on their similarities in the cognitive processes involved. Future work may use Korean Hangul stimuli, in which letters are arranged into a square shape instead of horizontally, to examine whether the modulation effect of music reading expertise in the RH was restricted to words with a global form similar to music notations (i.e., components of a similar size arranged horizontally) or could be applied to words in alphabetic languages in general.

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Footnotes

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[i] B3 to C5 ranges across two octaves from the B note below one lower ledger line to the C note with two upper ledger lines.

[ii] We have rerun the English word naming task following the divided visual field design recommended by Hunter and Brysbaert (2008). The results showed a significant interaction between group and visual field in accuracy, $F(1, 48) = 5.501$, $p = 0.023$, $\eta_p^2 = .103$: while musicians performed significantly better than non-musicians in both the LVF/RH and RVF/LH conditions, this advantage was significantly larger in the LVF/RH than the RVF/LH. This result is consistent with the finding in Experiment 1, demonstrating musicians' advantage in the LVF/RH. Note that this effect was not observed in RT.

[iii] When we examined musicians' and non-musicians' data separately, the correlation between English lateralization index in RT and accuracy of note matching was significant only in musicians ($r = -.449$, $p = .013$), but not in non-musicians. This result suggested that this correlation was indeed related to participants' music reading expertise. In contrast, the correlation between English lateralization index in RT and accuracy of chord matching was not significant in either musicians or non-musicians after we split the data.

[iv] In a separate study, we used the same ERP design with Chinese character stimuli. Consistent with our behavioral data in Experiment 1, this four-way interaction was not significant with Chinese character stimuli.