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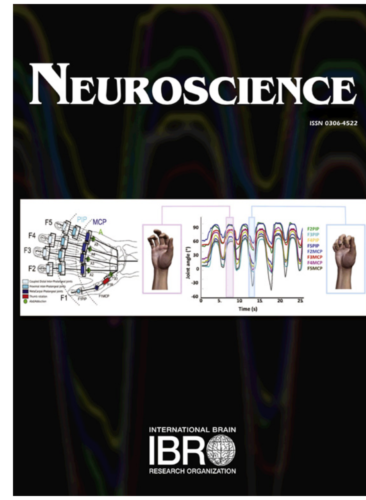

The Shared Neural Basis of Music and Language

Mengxia Yu, Miao Xu, Xueting Li, Zhencai Chen, Yiying Song, Jia Liu

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Title: The Shared Neural Basis of Music and Language

Abbreviated Title: Shared Neural Basis of Music and Language

Authors: Mengxia Yu[1]*, Miao Xu[1]*, Xueting Li[2], Zhencai Chen[1], Yiying Song[3], & Jia Liu[1]

* Equal contribution

Affiliation: [1]School of Psychology, Beijing Normal University, Beijing, 100875, China; [2]Department of Psychology, Renmin University of China, Beijing, 100872, China; [3]State Key Laboratory of Cognitive Neuroscience and Learning and IDG/McGovern Institute for Brain Research, Beijing Normal University, Beijing, 100875, China

Correspondence should be addressed to either of the following: Dr. Yiying Song or Zhencai Chen, State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing, 100875, E-mail: songyiying@bnu.edu.cn.

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Abstract

Human musical ability is proposed to play a key phylogenetical role in the evolution of language, and the similarity of hierarchical structure in music and language has led to considerable speculation about their shared mechanisms. While behavioral and electrophysioglocial studies have revealed associations between music and linguistic abilities, results from functional magnetic resonance imaging (fMRI) studies on their relations are contradictory, possibly because these studies usually treat music or language as single entities without breaking down to their components. Here, we examined the relations between different components of music (i.e., melodic and rhythmic analysis) and language (i.e., semantic and phonological processing) using both behavioral tests and resting-state fMRI. Behaviorally, we found that individuals with music training experiences were better at semantic processing, but not at phonological processing, than those without training. Further correlation analyses showed that semantic processing of language was related to melodic, but not rhythmic, analysis of music. Neurally, we found that performances in both semantic processing and melodic analysis were correlated with spontaneous brain activities in the bilateral precentral gyrus (PCG) and superior temporal plane at the regional level, and with the resting-state functional connectivity of the left PCG with the left supramarginal gyrus and left superior temporal gyrus at the network level. Together, our study revealed the shared spontaneous neural basis of music and language based on the behavioral link between melodic analysis and semantic processing, which possibly relied on a common mechanism of automatic auditory-motor integration.

Key words: music perception, linguistic ability, melodic analysis, semantic processing, functional magnetic resonance imaging

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Introduction

According to Darwin (1871), musical abilities play a key phylogenetical role in the evolution of language. Music and language are both unique human biological capacities with complex and meaningful sound structures, involving hierarchical sequences of discrete elements (Patel, 2003, Jackendoff and Lerdahl, 2006, Patel, 2007, Fitch and Martins, 2014). These similarities have led to considerable speculation about common mechanisms underlying human musical and linguistic abilities (Besson et al., 1998, Patel et al., 1998, Maess et al., 2001, Koelsch et al., 2002, Koelsch et al., 2004).

In line with this speculation, behavioral and electrophysioglocial studies have revealed connections between music and language. Developmental studies have found that music capacity is associated with linguistic ability in children (Moreno and Besson, 2006, Patel and Iversen, 2007, Strait et al., 2011, Lorenzo et al., 2014). Moreover, music training can enhance linguistic ability for children and adults (For a review, see Tierney and Kraus, 2013). For example, event-related potentials (ERP) studies showed that both children and adults with music training are more sensitive to violations of linguistic and musical syntax than participants without music training (Jentschke & Koelsch, 2009; Fitzroy & Sanders, 2013) and professional musicians are better at semantic processing of novel words (Dittinger et al., 2016) and pitch processing of both music and language than non-musicians (Schön et al., 2004). As for the particular components of musical ability, both melodic (Lamb and Gregory, 1993, Anvari et al., 2002, Forgeard et al., 2008, Loui et al., 2011) and rhythmic processing have been shown to be connected with linguistic ability (Wolff, 2002, Overy, 2003, Huss et al., 2011, Strait et al., 2011, Moritz et al., 2013). Another line of research focused on particular cognitive processes shared by music and language, such as syntactic or semantic processing. For example, there are interactions between linguistic and musical syntactic processing reflected by behavioral responses (Fedorenko et al., 2009, Slevc et al., 2009) and ERP components (Patel et al., 1998, Koelsch et al., 2005). Likewise, researchers found semantic priming effect reflected by the N400 ERP component for target words preceded by musical excerpts as well as

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by sentences (Koelsch et al., 2004, Steinbeis and Koelsch, 2008).

However, functional magnetic resonance imaging (fMRI) findings concerning the relation between music and language are contradictory. Some studies have shown the involvement of classic language-related regions in music processing, including the Broca's and Wernicke's areas, the superior temporal gyrus (STG), Heschl's gyrus (HG), and planum temporale (PT) (Maess et al., 2001, Koelsch et al., 2002, Levitin and Menon, 2003, Tillmann et al., 2003, Schön et al., 2010, Kunert et al., 2015). In contrast, several recent fMRI studies using within-subject comparisons have suggested the existence of music- and language-specific modules, in line with early neuropsychological evidence showing double dissociations between language and music (e.g. Peretz, 1993; Peretz, et al., 1994; Piccirilli, et al., 2000; but see Patel, et al., 2008). For example, Fedorenko et al. (2011) found little fMRI activation to music in classic language regions defined in each subject individually, and multivariate pattern classification analyses (MVPA) showed that even in the overlapping regions, sentence and music perception elicited distinguishable activation patterns (Rogalsky et al., 2011). One possible reason for these inconsistent findings may be that music and language are complex systems involving multiple components; some components may be shared while others may be domain specific. Yet, some fMRI studies using within-subject approach have treated music and language as single entities with relatively coarse manipulations (Fedorenko et al., 2011, Rogalsky et al., 2011). We therefore addressed the relation between music and language by systematically examining the associations between basic music components (i.e., melodic and rhythmic analysis) and linguistic components (i.e., semantic and phonemic processing) at both behavioral and neural levels.

First, we compared the performances in language tests between the participants with music training experiences and those without training to see whether music training would improve linguistic ability. Then, to reveal the associations between different components of music and language, we conducted a series of correlation analyses between each pair of linguistic and musical components, and the correlation analyses were replicated in an independent sample of participants. Based on the

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behavioral results, we used resting-state fMRI (rs-fMRI) to investigate the shared neural basis of music and language, because rs-fMRI provides an easy-to-access neural measure especially for children and patients, and in a recent study we have shown that regional spontaneous activity measured by the fractional amplitude of low-frequency fluctuation (fALFF) is related to language ability (Xu, et al., 2015). Specifically, we explored whether the regional spontaneous activity and resting-state functional connectivity (rsFC) that were related to language processing also contributed to music processing.

Experimental procedures

Participants

Two samples of college students were recruited from Beijing Normal University (BNU). The first sample consisted of 225 participants (118 females; mean age = 20.63 years, SD = 1.06 years), participating only in behavioral tests. The second sample consisted of 306 participants (180 females; mean age = 20.27 years, SD = 0.85 years), participating in both behavioral tests and MRI scanning. All participants were native Chinese Mandarin speakers who reported no history of neurological or psychiatric disorders. They all had normal or corrected-to-normal vision. The study was approved by the Institutional Review Board of BNU. Informed written consent was obtained from all participants before starting the experiment. This study was a part of ongoing project (Gene, Environment, Brain, and Behavior) (e.g., Li, et al., 2014; Xu, et al., 2015; Zhang, et al., 2015; Wang, et al., 2016a; Wang, et al., 2016b; Kong, et al., 2017)

Behavioral measurements

For both datasets of participants, an animal-word cancellation test and an onset cancellation test (Zou et al., 2012, Xu et al., 2015) were used to assess the linguistic abilities of semantic and phonological processing respectively, mainly in categorization and phoneme processing. And two music tests, an interval task and a rhythmic task, were adopted to assess the abilities of melodic and rhythmic analysis respectively. General cognitive ability was assessed with the Raven's Advanced Progressive Matrices (Raven's APM) and a symbol cancellation test. Additionally,

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participants in the first dataset finished a Music Training Questionnaire (MTQ).

Language tests

Animal-word cancellation test. An animal-word cancelation test was employed to measure participants' semantic processing ability. This test consisted of 220 two- or three-character words, 74 of which were animal words (e.g., 小猫, "xiao3 mao1", kitten) designated as target words, while the other 146 were non-animal words (e.g., 南瓜, "nan2 gua1", pumpkin). The animal and non-animal words were randomly intermixed and printed on a piece of paper, line-by-line. Participants were instructed to distinguish animal words from non-animal words by marking the animal words with a slash "/" as quickly as possible, while leaving the non-animal words untouched. The time limit of this test was 50 seconds, which was insufficient for all participants to process all items in the test. Ten practice items (three animal words and seven non-animal words) printed on two lines were provided before the formal test to familiarize the participants with the task.

Onset cancellation test. An onset cancelation test was employed to measure participants' phonological processing ability. The test consisted of 308 high frequency single-character words, 100 of which were initialized with the consonant /b/ (e.g., 八, "ba1", eight) and were designated as the targets to be canceled, while the other 208 words' initial phonemes were not /b/ (e.g., 民, "min2", people). The procedures of this test were similar to the animal-word cancellation test, except that the time limit for this test was 80 seconds.

For both language tests, Q scores were computed to index participants' efficiency in detecting the target words using the following formula (Hills and Geldmacher, 1998, Xu et al., 2015): $Q\ score = hit\ rate \times \frac{number\ of\ \text{cancelled}\ target\ words}{the\ time\ limit}$. A higher Q score thus indicates higher linguistic ability.

Music tests

Interval test. To assess participants' ability of melodic analysis, a simplified version of the interval test in the Montreal Battery of Evaluation of Amusia (MBEA, Peretz et

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al, 2003) was employed, which was modified by Li et al. (2014). There were twenty experimental trials and a catch trial in the test. Each experimental trial was preceded by a warning tone, and then, participants were successively exposed to two melodies with a 2-second interval. Each melody was presented as a synthetic piano sound generated with music production software, ranging from 7 to 21 notes and lasting 4.0–6.4 s (M = 5.1 s). Half of the experimental trials consisted of two identical melodies (‘‘same’’), whereas in the other half, the second melody differed from the first one in a single randomly positioned note (‘‘different’’). These two types of trials were randomly interleaved in the test. Participants were instructed to determine whether the two melodies were the same or different by using a computer mouse to select the ‘‘same’’ or “different’’ button presented on the screen. The catch trial consisted of a melody and a series of random notes that had no musical structure, so it was very easy for an attentive participant to make the correct response. Participants who made a wrong response in the catch trial would be excluded. The catch trial was randomly inserted in the sequence of the experimental trials. Before formal testing, participants were asked to finish two practice trials, which were the same as the experimental trials except that feedback was given to indicate whether the response was correct or not. The practice procedure would repeat until the participants could respond correctly to the two trials. The accuracy rate for the twenty experimental trials was used to indicate participants’ ability of melodic analysis.

Rhythmic test. To assess the ability of rhythmic analysis, a simplified version of the rhythm subtest of the MBEA was administered (Peretz et al., 2003, Li et al., 2014). There were 20 experimental trials, which included 10 “same” trials and 10 “different” trials. Each “same” trial consisted of two identical melodies, whereas in each “different” trial, the durations of two adjacent tones in the second melody were changed from the first one. The rhythmic test also included two practice trials and a catch trial. The procedures and data analysis of the rhythmic test were the same as the interval test.

Music Training Questionnaire

For the first sample of participants, a questionnaire was employed to assess whether

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they had learned to play a musical instrument and the age of onset of music training. The questionnaire contains 2 questions. One is “Have you learned any musical instrument?”, and the other one is “If so, when did you start learning it?” Based on the answers to the two questions, participants were divided into two groups. One was the training group who had instrument-training experience starting before 18 years old (N = 30); the other was the control group who had no experience of playing instrument (N = 185). Because the sample sizes of the training and control groups differed drastically, the between-group difference was tested using permutation tests. Briefly, the labels (training vs. control) of participants were randomly shuffled 5000 times to obtain the null distribution of the group difference. A between-group difference was considered significant if the probability of obtaining the difference under the null distribution is less than 0.05.

Raven’s APM

Raven’s APM was used to measure the general cognitive ability. Raven’s APM contained 48 multiple-choice items of abstract reasoning where participants were asked to identify the missing figure required to complete a larger pattern. Participants were required to answer the questions as accurate and quick as they could. The number of correctly identified figures served as a measure of participants’ general cognitive ability.

Symbol cancellation test

A symbol cancelation test was also administered to control for general cognitive ability. There were 308 symbols in this test, 100 of which were the targets to be canceled (§) and 208 of which were distracters (※, §, ⊙, 〒, and♀). The procedures and data analysis were the same as the language cancellation tests, except that the time limit for this test was 30 seconds.

Image data acquisition

Images were acquired using a 3T Siemens Trio scanner (MAGENTOM Trio, a Tim system) with a 12-channel phase-arrayed coil at BNU Imaging Center for Brain Research, Beijing, China. During the rs-fMRI scan, participants were instructed to close their eyes, keep still, remain awake, and not consciously think about anything.

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The rs-fMRI scan lasted 8 min, consisted of 240 contiguous echo-planar imaging (EPI) volumes (TR = 2000 ms; TE = 30 ms; flip angle = 90º; number of slices = 33; matrix = 64 × 64; FOV = 200 × 200 mm^2; acquisition voxel size = 3.125 × 3.125 × 3.6 mm^3). In addition, high-resolution T1-weighted images were acquired with the magnetization prepared gradient echo sequence (MPRAGE: TR/TE/TI = 2530/3.39/1100 ms; flip angle = 7º; matrix = 256 × 256) for spatial registration. One hundred and twenty-eight contiguous sagittal slices were acquired with in-plane resolution of 1 × 1 mm^2 and a slice thickness of 1.33 mm.

Imaging data analysis

rs-fMRI data preprocessing. The rs-fMRI data were preprocessed using FSL (FMRIB Software Library, http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/). The preprocessing steps included motion correction (by aligning each volume to the middle volume of the image with MCFLIRT), spatial Gaussian smoothing (FWHM = 6 mm), intensity normalization, and the removal of linear trends. Registration of each participant's rs-fMRI images to the structural images was carried out using FLIRT to produce a six degrees-of-freedom affine transformation matrix. Registration of each participant's structural images to a common stereotaxic space (the Montreal Neurological Institute (MNI) 152-brain template with a resolution of 2×2×2 mm^3, MNI152) was accomplished using FLIRT to produce a twelve degrees-of-freedom linear affine matrix (Jenkinson and Smith, 2001, Jenkinson et al., 2002).

For the rsFC analysis, a temporal band-pass filter (0.01 – 0.1 Hz) was applied with FSLMATHS to reduce low-frequency drifts and high-frequency noise. Then, to further eliminate physiological noise, such as fluctuations caused by motion, cardiac and respiratory cycles, nuisance signals from cerebrospinal fluid, white matter, whole brain average, motion correction parameters, and first derivatives of these signals were regressed out using the methods described in previous studies (Fox et al., 2005, Biswal et al., 2010). The 4-D residual time series obtained after removing the nuisance covariates were used for the rsFC analyses.

Analysis of regional fALFF shared by language and music. Following the procedure described by (Zou et al., 2008), the fALFF value of each voxel was calculated for

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each participant. For the time series of each voxel, the sum of the amplitudes within a low frequency range (0.01–0.1 Hz) was extracted. The fALFF was then computed as the fractional sum of the amplitudes within the low frequency range divided by the sum of amplitudes across the entire frequency range (0–0.25 Hz) (Zuo et al., 2010). As a normalized index of ALFF, fALFF is less susceptible to artifactual signals in regions located within the vicinity of vessels and/or significant pulsatile motion (Zou et al., 2008). Because low-frequency fluctuations are sensitive to spontaneous brain activities in gray matter regions (Biswal et al., 1995), additional analyses were conducted in a gray matter mask which was described in detail by Xu et al. (2015).

To explore regional fALFF shared by semantic processing and melodic analysis, we used the regions where the fALFF correlated to semantic processing measured by animal-word cancelation test in the same group of participants in our previous study (Xu et al., 2015) as the regions of interest (ROIs), including the bilateral precentral gyrus (PCG) and superior temporal plane (STP). Note that the two ROIs defined from resting-state data partly overlapped with the regions showing a higher response to sentences than to pseudo-sentences in a task-based fMRI experiment (Xu, et al., 2015), verifying their functional involvement in language processing during task state. The two ROIs were projected to the brain of each participant and taken as the ROIs for each participant. Then, we performed correlation analyses between the mean fALFF value of each ROI and the accuracy in the interval test. In addition, partial correlation analyses were performed to rule out the confounding effects of general cognitive ability measured by Raven's APM and the symbol cancelation test. Because the first sample of participants who were divided into musical training and non-training groups did not participate in fMRI scan, and the second sample of participants who participated in the fMRI scan did not receive the music training questionnaire, the group difference analysis or ANCOVA models were not applicable to the analyses of regional fALFF or rsFC.

Analysis of rsFC shared by language and music. First, we defined a 3-mm-radius sphere in each of the four ROIs as seeds, and calculated Pearson's correlation coefficients between the mean time course of each seed and that of each voxel across

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the whole brain for each participant, to generate a participant-level rsFC map with each seed. The participant-level rsFC maps were transformed to Z-score maps using Fisher's r-to-z transformation and then registered to MNI152 space. Then, to explore the rsFC related to semantic processing, Pearson's correlation between rsFC of each voxel and the Q score of the animal-word cancelation test was calculated with a GLM tool implemented in FSL, where semantic Q score was set as an independent variable and rsFC as the dependent variable. Multiple comparison correction was performed on the statistical map using the 3dClustSim program implemented in AFNI (version May 2016, http://afni.nimh.nih.gov). A threshold of cluster-level $p < 0.05$ and voxel-level $p < 0.01$ (cluster size > 100 voxels) was set based on Monte Carlo simulations across the whole brain. To maximize the sensitivity to detect the rsFC related to semantic processing, from which the rsFC shared by semantic processing and melodic analysis would be uncovered, a relatively liberal threshold was used. The correlation coefficients were transformed to z-score using Fisher's r-to-z transformation. Finally, to examine whether the rsFC related to semantic processing also contributes to melodic analysis, we computed the rsFC between the significant clusters identified in the rsFC-semantic correlation analysis and their corresponding seed regions, and correlated the rsFC with the accuracies in the interval test. Note that the rsFC was selected on the basis of its correlation with semantic processing, which did not predict whether the rsFC-melodic correlation would be significant in the subsequent analysis.

Participant exclusion

First, for all behavioral tests, Tukey's outlier filter (Hoaglin et al., 1983) was used to identify outlier participants with low hit rate (three times the interquartile range below the first quartile) and/or high false alarm rate (three times the interquartile range above the third quartile). In the first dataset, three participants (1 female) in the onset cancelation test and two participants (1 female) in the word-animal cancelation test were excluded. In the second dataset, two male participants in the onset cancelation test, two participants (1female) in the word-animal cancelation test, and two participants (1 female) in the symbol cancelation test were excluded. No participants

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met this criterion in the music tests.

Second, participants who made a wrong response for the catch trial in the music tests would be excluded. In the first dataset, two participants (1 female) in the interval test and three participants (females) in the rhythmic test were excluded. In the second dataset, one male in the melodic test and three participants (2 females) in the rhythmic test were excluded.

Third, Participants whose head motion was greater than 3.0° in rotation or 3.0 mm in translation throughout the fMRI scan were excluded from further analyses. For the rs-fMRI, five participants (1 female) who met this criterion were excluded.

Therefore, for the first sample of 225 participants, 215 participants (112 females) were included. For the second sample of 306 participants, 296 participants (177 females) were included. Among them, 256 participants (156 females) agreed to participate in the fMRI scan and their images were included in the fMRI analysis.

Results

Individuals with music training experiences showed higher semantic ability

To systematically investigate the relationship between music and language, we measured two musical components (i.e., melodic and rhythmic analysis) and two language components (i.e., semantic and phonemic processing) respectively. We reasoned that if musical and linguistic abilities share common cognitive mechanisms, individuals who had music training experiences would show higher linguistic ability. To test this hypothesis, we classified the first sample of participants into two groups based on a music training questionnaire, a music training group who had instrument training experiences starting before 18 years old ($N = 30$) and a control group who had no experience of playing instrument ($N = 185$), and examined the differences on linguistic ability between the two groups. As expected, the training group showed significantly higher accuracy in both the interval test ($p < .001$, permutation tests, Figure 1A) and the rhythmic test ($p = .01$, permutation tests, Figure 1B) than the control group, confirming that music training before 18 years old improved participants' abilities of melodic and rhythmic analysis. Importantly, we found that the training group performed significantly better than the control group in the

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animal-word cancelation test ($p = .01$, permutation tests, Figure 1C). In contrast, no difference was found for the onset cancelation test ($p > .05$, permutation tests, Figure 1D). These results indicated that music training improved the linguistic ability of semantic processing, but not that of phonological processing. Further, because previous studies have found that music training can improve general cognitive abilities which may then influence linguistic ability (e.g., Schellenberg, 2004; Moreno et al., 2011), we controlled participants' general cognitive abilities assessed by Raven's APM and a symbol cancelation test. We found that the difference on semantic processing between the training group and control group remained significant ($p = .03$, Figure 1E), indicating that the training effect could not be accounted for by general cognitive abilities. In short, these results suggested that music ability was related to the semantic component of language. Yet, given that training of playing instruments improved musical ability generally, it remained unclear which specific components of music ability was associated with the improvement of semantic processing ability.

Insert Figure 1 here

Association between melodic analysis and semantic processing

Next, to gain a more specific picture of the association between music and language, we examined the correlations between the two components of musical ability and those of linguistic ability. The descriptive statistics for all behavioral measurements are shown in Table 1. We found that the performance in the animal-word cancelation test was positively correlated with the accuracies in the interval test ($r = .22$, $p = .001$, Figure 2A), but not with the rhythmic test ($r = .10$, $p = .14$, Figure 2C), indicating that semantic processing was associated with melodic analysis, but not with rhythmic analysis, of musical ability. On the other hand, the performance in the onset cancelation test was weakly correlated with the rhythmic test ($r = .15$, $p = .03$, Figure 2D), but not with the interval test ($r = .10$, $p = .13$, Figure 2B), and thus, there appeared to be an association between phonological processing and rhythmic analysis.

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However, as the performances in the two music tests correlated with each other ($r = .42$, $p < .001$), and so did the two language tests ($r = .22$, $p < .001$), it was possible that these associations were contaminated by the effects of related components. Therefore, we performed partial correlation analyses between one music test and one language test when controlling for the other music test and language test. We found that the animal-word cancelation test was still correlated with the interval test when controlling for the onset cancelation test and the rhythmic test (partial $r = .19$, $p = .006$), while the partial correlation between the onset cancelation test and the rhythmic test was no longer significant when controlling for the animal-word cancelation test and the interval test (partial $r = .11$, $p= .10$). These correlation results, consistent with the training results, indicated a specific link between melodic analysis of music and semantic processing of language.

Insert Table 1 and Figure 2 here

In addition, to examine whether the association between melodic analysis and semantic processing was accounted for by the confounding effect of general cognitive abilities, we performed partial correlation analyses controlling for Revan's APM and the symbol cancelation test. Results showed that the correlation between semantic analysis and melodic processing was still significant (partial $r = 0.17$, $p < .01$), even when additionally controlling for the phonological and rhythmic tests (partial $r = 0.16$ $p = .02$). These results indicated that the correlation between semantic analysis and melodic processing could not be ascribed to general cognitive abilities, but rather due to some shared mechanisms underlying linguistic and musical abilities per se.

Finally, to examine the reliability of these results, an independent sample of participants ($N = 296$) were tested. The above correlation results were replicated in the second sample. That is, we found significant correlation between semantic analysis and melodic processing ($r =.29$, $p < .001$), even when controlling for phonological and rhythmic performances (partial $r =.23$, $p < .001$) or general cognitive abilities (partial $r = 0.22$, $p < .001$). In contrast, the correlation between

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semantic processing and rhythmic analysis was not significant when controlling for phonological and melodic performances (partial r = .06, p = .30). In addition, there was no correlation between phonological processing and melodic (r = .09, p = .12) or rhythmic analysis (r = .07, p = .20). The replication of the correlation results in two large samples of participants indicated a reliable association between melodic analysis and semantic processing. Taken together, the training effect of musical on linguistic ability and the correlation results consistently suggested shared mechanisms between music and language which may lie in the link between melodic analysis and semantic processing. Next, we explored shared neural basis between language and music by focusing on the relationship between melodic analysis and semantic processing.

Shared neural basis of melodic analysis and semantic processing

Semantic-related regional spontaneous activities contributing to melodic analysis

We used rs-fMRI to investigate neural overlap between melodic analysis and semantic processing on both regional and network levels in the second sample. First, we explored shared regional spontaneous activities between music and language by examining whether the regional fALFF related to semantic processing also contributed to melodic analysis. We took the bilateral PCG and STP where the mean fALFF correlated with sematic processing measured by the animal-word cancelation test in a previous study (Xu, et al., 2015) as the ROIs (Figure 3A). As expected, the mean fALFF of these ROIs were also correlated with semantic processing in the current study (lPCG: r = .26, p < .001; rPCG: r = .25, p < .001; lSTP: r = .23, p < .001; rSTP: r = .26, p < .001), even when controlling for general cognitive abilities (lPCG: partial r = .23, p < .001; rPCG: partial r = 0.22, p < .001; lSTP: partial r = .19, p = .003; rSTP: partial r = .20, p = .001). Importantly, the mean fALFF of these ROIs were positively correlated with accuracy in the interval test (Figure 3B), even when controlling for general cognitive abilities (lPCG: partial r = .17, p = .007; rPCG: partial r = 0.13, p = .03; lSTP: partial r = .13, p = .04; rSTP: partial r = .17, p = .006). These results indicated that the fALFF in the bilateral STP and PCG that contributed to semantic processing of language were also related to melodic analysis, demonstrating shared regional spontaneous neural activities supporting both language

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and music.

Insert Figure 3 here

Semantic-related rsFC contributing to melodic analysis

Next, we went on to investigate whether the neural basis of these two abilities also overlapped on the network level by examining whether the rsFC related to semantic processing also contributed to melodic analysis. To identify the rsFC related to sematic processing, we performed voxel-wise seed-based rsFC analyses with the four semantic-related ROIs as the seeds, and the rsFC of each voxel across the brain with each seed was correlated with the Q scores of the animal-word cancellation test. We found several clusters whose rsFC with bilateral PCG and the left STP positively correlated with the semantic Q scores (*ps* < .01, corrected; Figure 4A, Table 2), even when general cognitive abilities were controlled for (*ps* < .05, Bonferroni corrected; Table 2). Then, to examine whether the semantic-related rsFC also contributed to melodic analysis, we computed the rsFC between the identified clusters and their corresponding seed regions, and correlated the rsFC with the accuracies in the interval test. We found that the rsFC between the lPCG and the left supramarginal gyrus (lSMG) was positively correlated with melodic analysis ($r = .17$, $p = .005$, Figure 4B), even when general cognitive abilities were controlled for ($r = .16$, $p = .012$). Additionally, the rsFC between the lPCG and the left STG (lSTG) was also positively correlated with melodic performance ($r = .14$, $p= .024$, Figure 4B), even when general cognitive abilities were controlled for ($r = .14$, $p =. 023$). No other correlations were found. The results indicated that the rsFC of lPCG-lSMG and lPCG-lSTG contributed to both semantic processing of language and melodic analysis of music, revealing shared neural basis of language and music on the network level.

Insert Table 2 and Figure 4 here

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Discussion

In the current study, we characterized the relationships between particular components of linguistic and musical abilities and explored their shared neural basis. Behaviorally, we found that individuals with music training experiences were better at semantic processing, but not at phonological processing, than those without training. Further correlation analyses showed that semantic processing of language was correlated with melodic, but not rhythmic, analysis of music. Neurally, we found that performances in both semantic processing of language and melodic analysis of music were positively correlated with the fALFF in the bilateral PCG and STP at the regional level, and with the rsFC of lPCG-lSMG and lPCG-lSTG at the network level. Together, our study revealed the shared spontaneous neural basis of music and language which relied on the association between semantic processing and melodic analysis.

Our finding that adults with experience of music training showed higher linguistic ability is in agreement with previous findings, especially those from longitudinal studies, indicating that music training can improve linguistic ability in children (e.g., Moreno and Besson, 2006; Patel and Iversen, 2007; Lorenzo, et al., 2014, for a review, see Tierney and Kraus, 2013). In addition, the association between music and language components is broadly consistent with extensive evidence that music capacity is related to linguistic ability in normal children (Lamb and Gregory, 1993, Anvari et al., 2002) and children with dyslexia (Atterbury, 1985, Overy, 2003), and importantly, extended these relations to normal adults. More specifically, our result that adults who had music training performed better in semantic processing, but not phonological processing, is in line with previous findings that musical ability is prediction of linguistic performances besides phonological processing (Lamb and Gregory, 1993) and even when variances of phonological processing is removed (Anvari et al., 2002). Further, in the semantic processing task, semantic information is extracted by analyzing and organizing orthographic forms and phonological units (Koelsch and Siebel, 2005, Koelsch, 2011). Thus, it is possible that while phonological processing, the essential and most studied language component connected to music in children, may be critical for new readers during reading

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acquisition (e.g., Loui et al., 2011; Moritz et al., 2013), the more complex component of semantic processing is more prominently connected to music in language performance of adults. Consistently, a recent study has shown that music training facilitates semantic language processing in adults (Dittinger et al., 2016). Moreover, the specific correlation between melodic analysis and semantic processing observed here fits nicely with an apparent more consistent link of linguistic ability with melodic analysis than with rhythmic analysis in literature (Atterbury, 1985, Anvari et al., 2002, Forgeard et al., 2008). In short, our study revealed that the association between music and language in adults may lie in the specific link between melodic analysis of music and semantic processing of language.

Based on the behavioral results, we further revealed the possible shared mechanism underlying this link with fMRI results. We found that spontaneous brain activity (i.e., the fALFF) in the bilateral PCG and STP was associated with both melody analysis and semantic processing. This result is in line with previous findings that the PCG and STP were typically involved in processing of language (Vigneau et al., 2006, Vigneau et al., 2011) and music (Doeller et al., 2003, Brown and Martinez, 2007, Hyde et al., 2008, Foster and Zatorre, 2010, Klein and Zatorre, 2011, Wehrum et al., 2011). The ROI in the PCG consisted of the precentral gyrus, postcentral gyrus, and pars opercularis (i.e., part of the Broca's area in the inferior frontal gyrus), and the ROI in the STP consisted of the PT, HG, and STG. Previous studies on language have indicated that the PCG is involved in motor processing of language production (Price, 2012) and also activated during silent word-reading tasks (Chen et al., 2002, Longcamp et al., 2005, Jobard et al., 2011), and the PT is involved in phonological processing of both speech (Price, 2012) and reading (Vigneau et al., 2006). Together, the PCG and STP are the core regions of the auditory-motor system subserving auditory-motor integration (Friederici, 2011). Likewise, for music processing, the PCG and STP were activated during pitch discrimination and interval analysis regardless of whether participants were asked to pay attention to the musical stimuli or not (Doeller et al., 2003, Brown and Martinez, 2007, Hyde et al., 2008, Foster and Zatorre, 2010, Klein and Zatorre, 2011, Wehrum et al., 2011). Moreover, researchers

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found widespread interactions between the linguistic and musical dimensions within the network including the STG and IFG when listening to sung words (Schön et al., 2010), suggesting a common network involved in lexical and melodic processing. Therefore, spontaneous activity in the PCG and STP might serve as a framework for evoked brain activity for auditory-motor integration that is recruited automatically by semantic and melodic processing.

Further, we found that the rsFC between the lPCG and two regions, the lSTG and lSMG, could predict performances in both the melodic and semantic tests. First, previous studies have shown that the lSTG was activated by semantic contrasts based on written words, such as words versus pseudo-words or pseudo-fonts (Fiez et al., 1999, Moore and Price, 1999, Fiebach et al., 2002), and categorization of written words (Perani et al., 1999, Chee et al., 2000, Grossman et al., 2002). Researchers proposed that this area may convert orthographic units into syllable sounds which are then maintained in phonological working memory and made accessible for further syntactic or conceptual processing (Vigneau et al., 2006). Second, the lSMG is a core region in phonological working memory loop (Vigneau et al., 2006), and its fiber connection with the ventral premotor cortex (i.e. the lateral part of the PCG) subserves articulatory processing as demonstrated by dysarthria elicited by stimulation (Maldonado et al., 2011). Together, the connectivity of lPCG-lSTG and lPCG-lSMG may further support auditory-motor integration at the network level, which possibly serves as the common mechanism contributing to both semantic processing and melodic analysis.

Combined with the neural evidence, one possible account for the musical training effect on semantic processing is that semantic processing may benefit from music training through improved auditory-motor integration. On one hand, playing an instrument is a multidimensional task that requires efficient integration of auditory information with information from other modalities, and long-term music training improves multiple auditory perceptual and cognitive functions (e.g., George and Coch, 2011; Moreno et al., 2011; Strait et al., 2015, Wang et al., 2015). On the other hand, semantic processing also recruits auditory integration in which phonological

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information is effectively accessed and integrated with orthographic information to extract semantic information. It is therefore possible that the auditory-motor integration ability improved in music training facilitates semantic processing.

Although our results are consistent with a number of fMRI studies indicating shared neural basis for music and language processing (Koelsch et al., 2002, Levitin and Menon, 2003; Schön et al., 2010), several fMRI studies suggest that distinct brain regions are involved in language and music processing (Fedorenko et al., 2011, Rogalsky et al., 2011). Indeed, these apparently contradictory results are highly expectable, given that both language and music involve multiple cognitive components. That is, while the neural circuits underlying language and music are dissociable across the brain, some specific components of them may share common neural substrates. Notably, both of the two studies (Fedorenko et al., 2011, Rogalsky et al., 2011) have reported overlapping activation between language and music in some regions. Moreover, these studies have treated language and music as single entities without breaking down to their specific components (e.g., sentence vs. nonwords for language processing; intact music vs. scrambled music for music processing), which may be insensitive to detect shared neural basis between specific components of language and music as revealed in our study.

In conclusion, the present study reveals shared spontaneous neural basis of music and language based on a specific link between melodic analysis and semantic processing. Our study also raised several important issues for future research. First, rs-fMRI is a promising tool that evaluates spontaneous brain activity in both regional and network level. By using rs-fMRI, our study may provide easy-to-access neural markers to screen participants previously excluded from traditional task-based fMRI, such as young children and patients with cognitive impairments. However, rs-fMRI cannot directly measure task-evoked activity, and thus, future studies using task-based fMRI with fine experimental design are needed to directly investigate shared brain activity when participants are performing music and language tasks. Second, our study roughly divided participants into musical training and non-training groups and examined the group differences between them. Future studies are needed to collect

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more information about music training such as average number of training hours, the type of musical instrument, and the level of musical expertise, and further investigate whether language ability changes linearly with music training experiences. Third, the current study is cross-sectional and correlational, and future studies using a longitudinal approach that compares the semantic processing ability of non-musicians before and after music training are needed to further elucidate the causal effect of music training on semantic processing. Fourth, all participants in the current study were native Chinese Mandarin speakers and the stimuli we used were in Mandarin. Considering the phonological differences between dialects (e.g., Mandarin, Cantonese, see Wang and Peng, 2014), future studies can adopt participants from different regions and stimuli in different dialects to investigate the possible role of dialect in the relations between the neural basis of music and language. Finally, the language tests used in our study only tapped specific aspects of semantic and phonological processing (i.e., categorization and phoneme processing), respectively. Future studies should adopt more comprehensive tests of semantic and phonological processing, as well as other components of music and language, to further elucidate shared neural basis between language and music.

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Figure legends

Figure 1. Participants with music training experiences showed higher semantic ability. Performances of the musical training group and control group in (A) melodic analysis, (B) rhythmic analysis, (C) semantic processing, (D) phonological processing, and (E) residual of semantic processing regressing out the variance of Raven's APM and the symbol cancelation test. ***, $p < .001$; **, $p < .01$; *, $p< .05$; n.s., not significant.

Figure 2. Behavioral correlations of the language and music components. Scatter plots depicting correlation between (A) the Q score of semantic processing and the accuracy of melodic analysis, (B) the Q score of phonological processing and the accuracy of melodic analysis, (C) the Q score of semantic processing and the accuracy of rhythmic analysis, (D) the Q score of phonological processing and the accuracy of rhythmic analysis.

Figure 3. Regional fALFF related to semantic processing was correlated with melodic analysis. (A) The ROIs of bilateral precentral gyrus (PCG) and superior temporal plane (STP) used in our study. (B) Scatter plots depicting correlations between the mean fALFF in each ROI and the accuracy of melodic analysis.

Figure 4. Functional connectivity shared by semantic processing and melodic analysis. (A) The seed lPCG and the clusters where the rsFC with the lPCG correlated with semantic processing were displayed on an inflated cortical surface of MNI standard template. (B) Scatter plots depicting correlations between the rsFC of lPCG-lSMG and semantic processing (left) and melodic analysis (right). (C) Scatter plots depicting correlations between the rsFC of lPCG-lSTG and semantic processing (left) and melodic analysis (right). lSMG: left supramarginal gyrus; lSTG: left superior temporal gyrus.

Figure1

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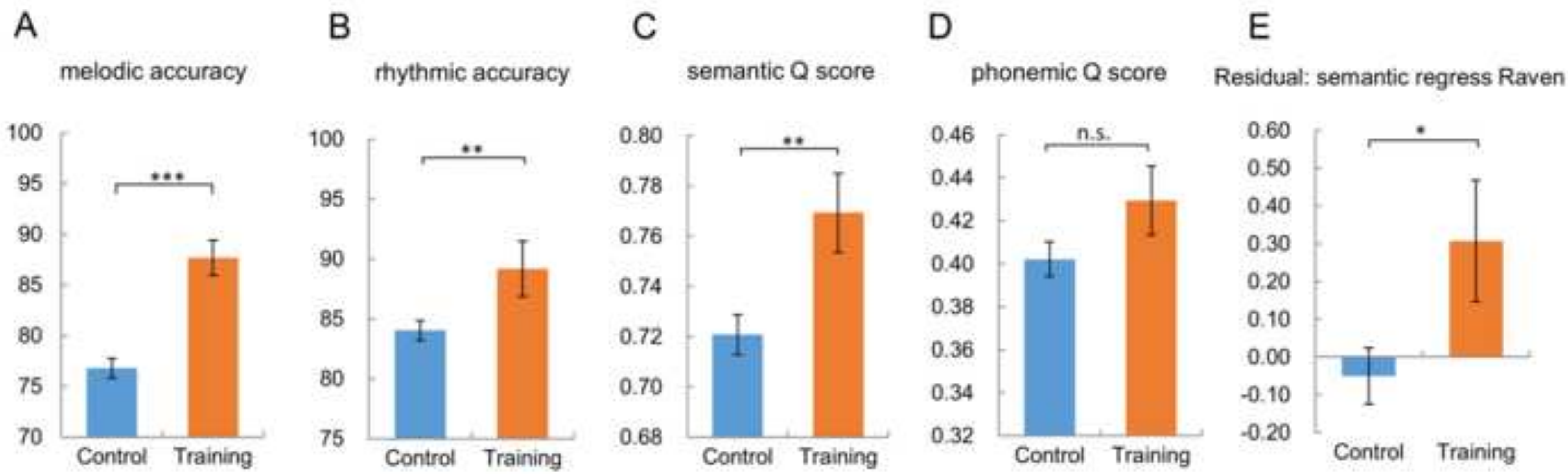

Figure2

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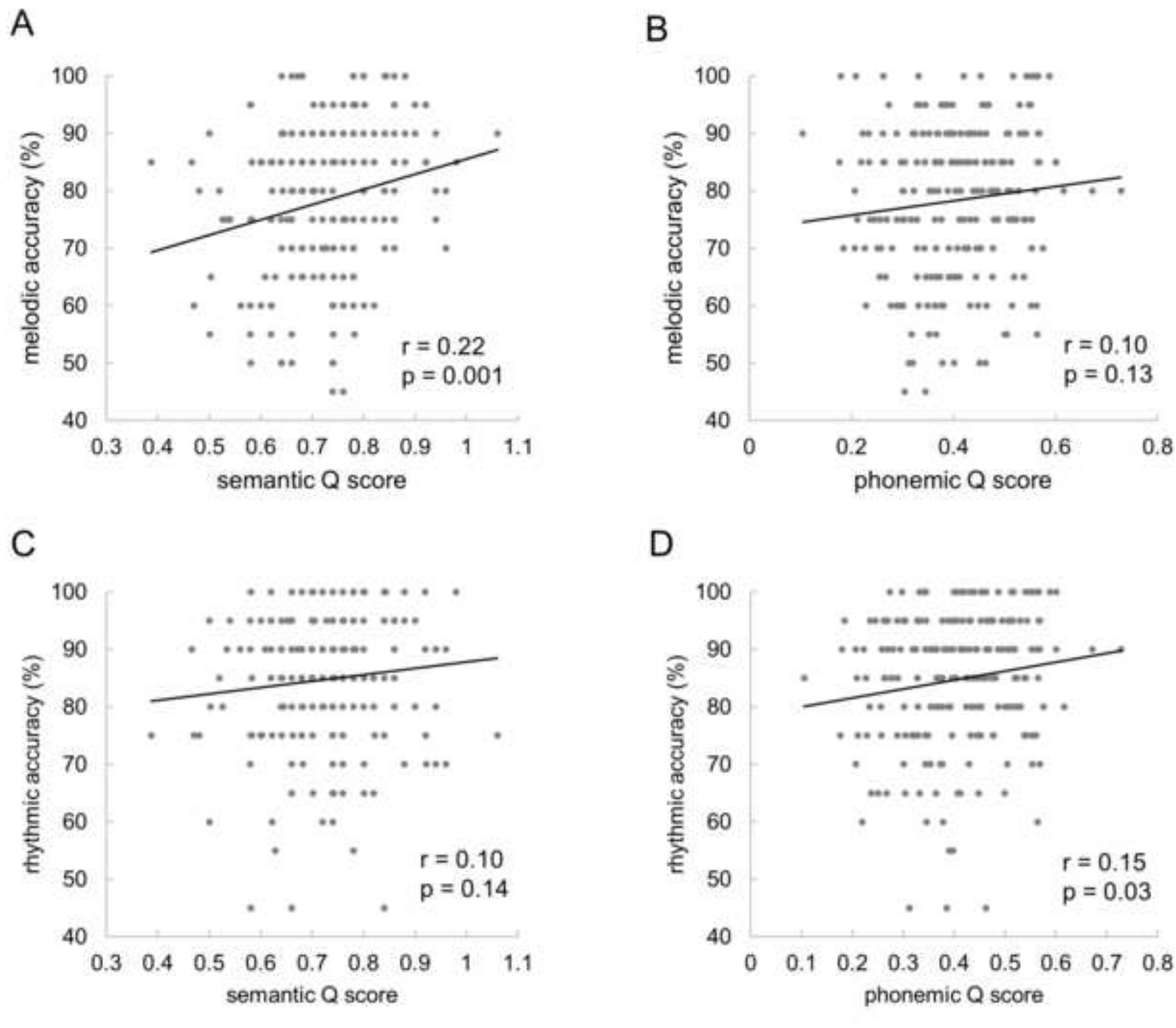

Figure3

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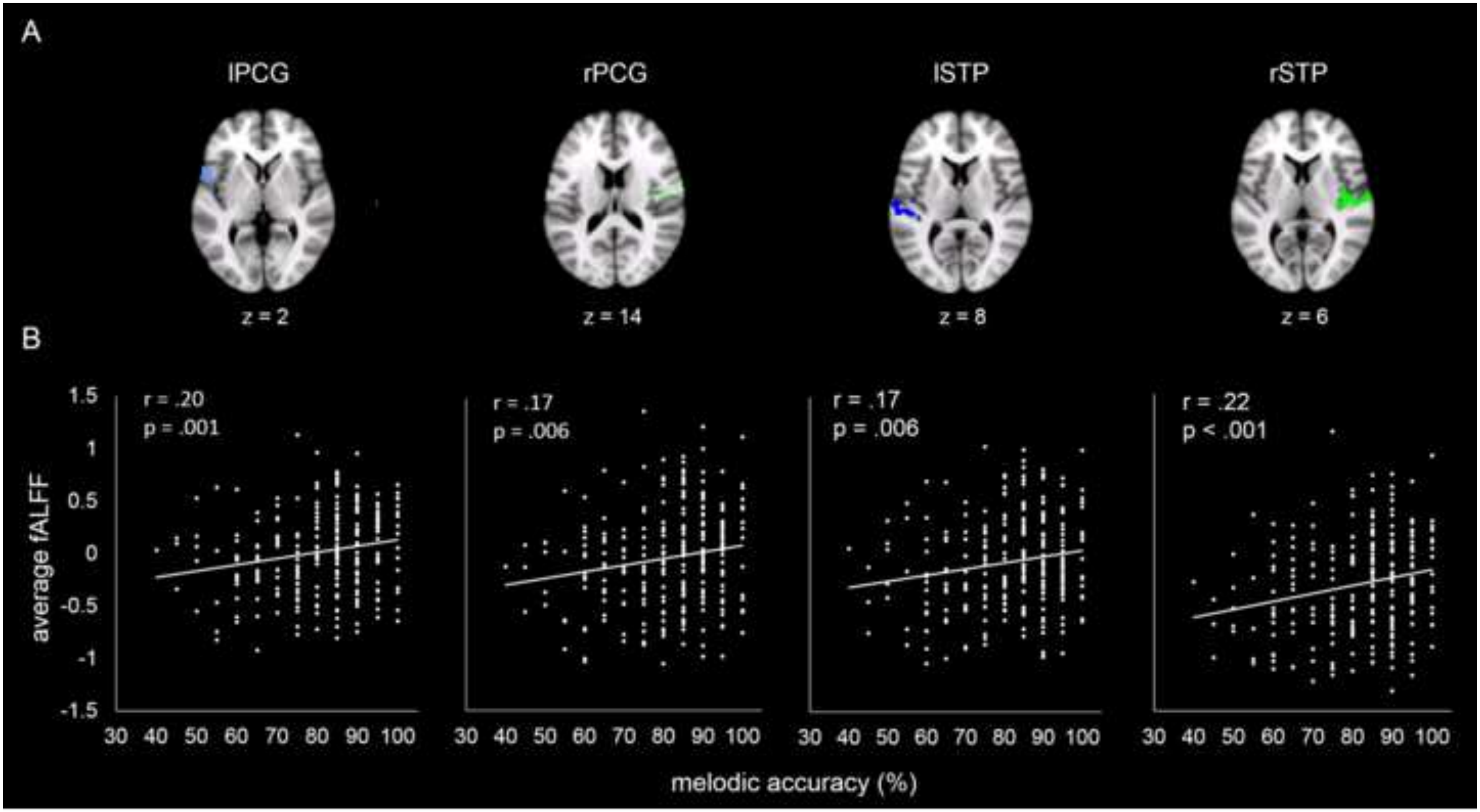

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Figure4

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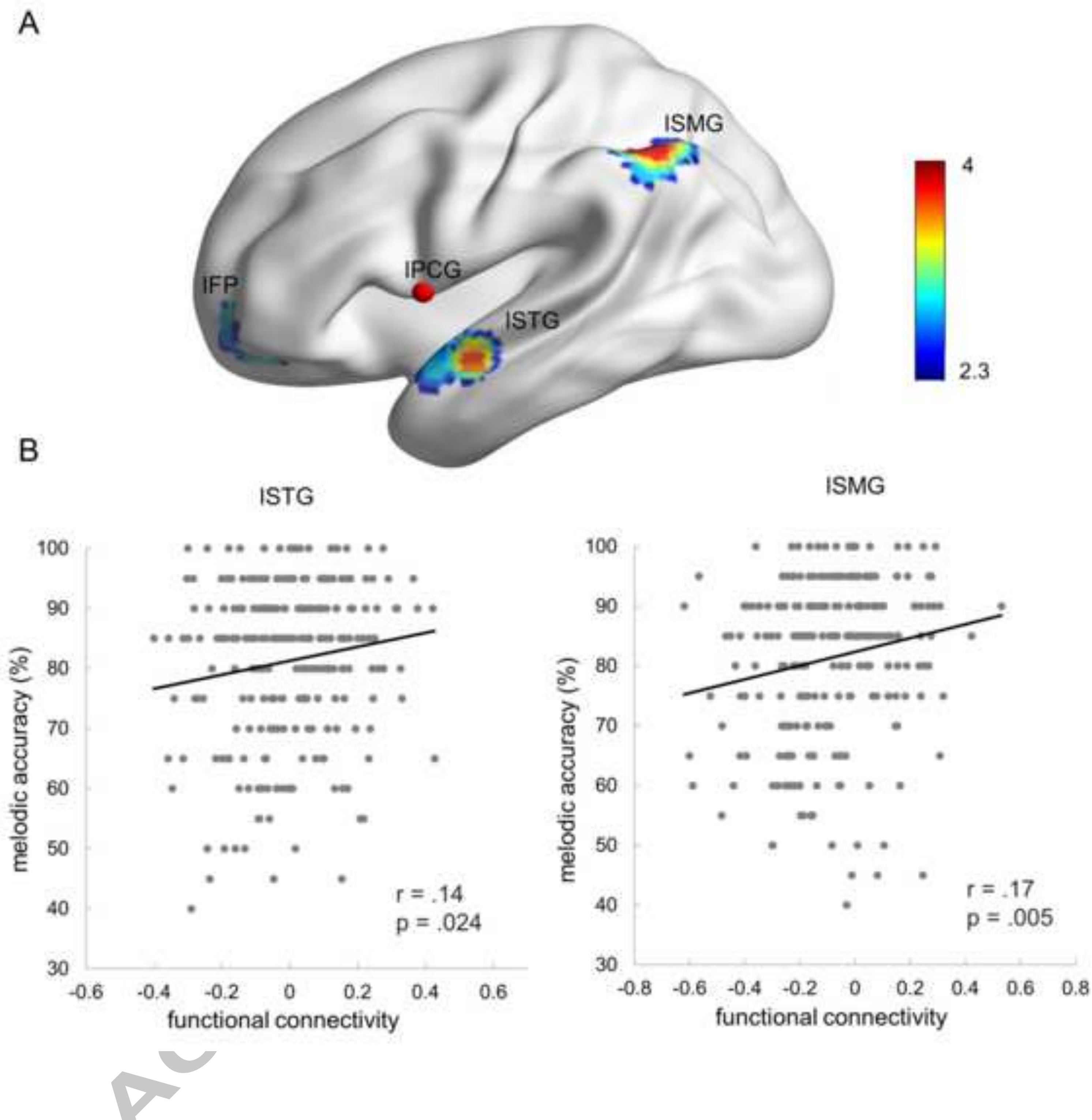

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Table 1. Descriptive statistics of behavior tests for both samples

	Mean	SD	Rang
Sample 1 (N=215)			
Animal-word cancelation test (Q score)	0.73	0.11	0.39-1.06
Onset cancelation test (Q score)	0.41	0.11	0.10-0.73
Interval test (Accuracy)	0.78	0.13	0.45-1
Rhythm test (Accuracy)	0.85	0.12	0.45-1
Raven's APM	36.85	4.75	19-47
Symbol cancelation test (Q score)	1.44	0.21	0.96-2.23
Sample 2 (N=296)			
Animal-word cancelation test (Q score)	0.74	0.11	0.38-1.12
Onset cancelation test (Q score)	0.42	0.12	0.12-0.79
Interval test (Accuracy)	0.81	0.13	0.4-1
Rhythm test (Accuracy)	0.84	0.11	0.5-1
Raven's APM	37.10	4.29	17-47
Symbol cancelation test (Q score)	1.49	0.22	0.77-2.13

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Table 2. Clusters where the rsFC with the seed regions correlated with semantic processing

Seed	RSFC-semantic area	Cluster size	Peak Z	peak (MNI) X	Y	Z	Partial correlation (*p*)
L PCG	L SMG	382	4	-48	-48	56	.24(<.001)
	L FP	126	3.34	-24	52	-4	.19(=.003)
	L STG	101	3.72	-52	-6	-10	.26(<.001)
R PCG	L PoCG	267	3.23	-62	-12	18	.18(=.005)
	R SMG	254	3.56	54	-38	10	.25(<.001)
	R PoCG	247	3.36	58	-12	36	.18(=.005)
	R SPL(BA7a)	211	3.3	40	-58	56	.25(<.001)
	R SPL(BA7p)	164	3.36	28	-70	38	.24(<.001)
	R Ins	101	3.98	36	-8	8	.19(=.003)
L STP	L SMG	382	4	-48	-48	56	.16(=.012)

L, left; R, right; PCG, precentral gyrus; STP, superior temporal plane; SMG, supramarginal gyrus; FP, front pole; STG, superior temporal gyrus, PoCG, postcentral gyrus; SPL, superior pariatal lobule; Ins, insular.

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Highlights

Individuals with music training experiences were better at semantic processing.

Semantic processing of language was related to melodic analysis of music.

The regional spontaneous activities in the PCG and STP contributed to both semantic processing and melodic analysis.

The resting-state FC of the left PCG with the left SMG and STG were related to both semantic processing and melodic analysis.

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