Short-term Music Training Enhances Complex, Distributed Neural Communication during Music and Linguistic Tasks

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Abstract

■ Musical training is frequently associated with benefits to linguistic abilities, and recent focus has been placed on possible benefits of bilingualism to lifelong executive functions; however, the neural mechanisms for such effects are unclear. The aim of this study was to gain better understanding of the whole-brain functional effects of music and second-language training that could support such previously observed cognitive transfer effects. We conducted a 28-day longitudinal study of monolingual English-speaking 4- to 6-year-old children randomly selected to receive daily music or French language training, excluding weekends. Children completed passive EEG music note and French vowel auditory oddball detection tasks before and after training. Brain signal complexity was measured on source waveforms at multiple temporal scales as an index of neural information processing and network communication load. Comparing pretraining with posttraining, musical training was associated with increased EEG complexity at coarse temporal scales during the music and French vowel tasks in widely distributed cortical regions. Conversely, very minimal decreases in complexity at fine scales and trends toward coarse-scale increases were displayed after French training during the tasks. Spectral analysis failed to distinguish between training types and found overall theta (3.5–7.5 Hz) power increases after all training forms, with spatially fewer decreases in power at higher frequencies (>10 Hz). These findings demonstrate that musical training increased diversity of brain network states to support domain-specific music skill acquisition and music-to-language transfer effects. ■

INTRODUCTION

Cognitive transfer occurs when experience in one area of study leads to improvements in seemingly unrelated domains. Few areas of training have shown evidence of this kind of skill transfer (Owen et al., 2010; Olesen, Westerberg, & Klingberg, 2004), with music training and bilingualism standing out as positive exceptions (Moreno & Bidelman, 2014; Bialystok, Craik, Green, & Gollan, 2009; Chan, Ho, & Cheung, 1998). Although some investigations of music training transfer effects have produced mixed results (Schellenberg, 2012; Rauscher, Shaw, & Ky, 1993), a small number of longitudinal studies over the past decade have begun to clarify the issue. Schellenberg (2004) observed increased full-scale IQ in children who received music lessons, as compared with those receiving drama lessons. Other experiments comparing music and visual art training in young children found that music training was associated with enhanced verbal intelligence and executive/inhibitory control (Moreno et al., 2011). Bilingualism has been consistently associated with similar benefits to executive control processes in lifelong bilingual children (Carlson & Meltzoff, 2008) and adults (Costa, Hernández, & Sebastián-Gallés, 2008) and has gained recent interest for possible

dementia protective effects in older adults (Bialystok, Craik, & Freedman, 2007).

Recent longitudinal studies have observed structural (Hyde et al., 2009) and functional (Seither-Preisler, Parncutt, & Schneider, 2014; Trainor, Lee, & Bosnyak, 2011) music-induced neuroplasticity that corroborates correlational differences between adult musicians and nonmusicians (for reviews, see Herholz & Zatorre, 2012; Münte, Altenmüller, & Jäncke, 2002). Multiple studies have suggested that the neural basis of the reported music-to-other-cognition transfer effects involves enhancement of neural resources shared with general executive cognition; however, they acknowledge that the methods failed to capture sufficient cortical dynamics to describe a more specific mechanism (Moreno et al., 2011; Jentschke & Koelsch, 2009; Patel, 2003). Bilingualism has been suggested to impact executive control through a similar "shared-resource" hypothesis, but the type of neural activity that could support such transfer effects remains to be described (Abutalebi & Green, 2008).

We conducted a longitudinal study to examine changes in cortical activity associated with music and language training as well as domain general training effects. Non-musician, monolingual English-speaking children (aged 4–6 years) were randomly assigned to receive 20 days of music or French language training. Both groups completed music and language tasks during EEG recording

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before and after training. The effects of cognitive training should manifest as a change in the information processing capacity of the brain. Increased cortical information processing and superior cognitive performance are associated with higher brain signal complexity (Raja Beharelle, Kovačević, McIntosh, & Levine, 2012; Deco, Jirsa, & McIntosh, 2011; Ghosh, Rho, McIntosh, Kötter, & Jirsa, 2008; McIntosh, Kovačević, & Itier, 2008). Therefore, increased EEG complexity was expected after both training regimes, during domain of training-specific tasks, and was further expected during the French language task in musically trained children, as a potential mechanism of previously reported music-to-language transfer.

METHODS

Participants

The data from this study have been previously described in detail (Moreno, Lee, Janus, & Bialystok, 2015). Thirty-six English-speaking children (4–6 years old) with no prior French language or musical training were recruited from the Greater Toronto Area. The study used a three-phase longitudinal design: pretest, training, and posttest. After the pretest, children were pseudorandomly assigned to French language or music training to ensure no pretraining differences between groups in age, English vocabulary scores, nonverbal intelligence, and socioeconomic status based on parents' education.

Training

Training consisted of computer-based programs conducted in groups in a classroom setting for two 1-hr sessions each day for 4 weeks, excluding weekends (20 days total; Moreno et al., 2011, 2015). The music (Moreno, 2012) and French curriculum were designed to share the same learning goals, graphics and design, duration, number of breaks, and number of teaching staff, thereby differing only in content. The music training program was based on a combination of motor, perceptual, and cognitive tasks and included training on rhythm, pitch, melody, voice, and basic musical concepts. The French language curriculum included vocabulary learning (e.g., days of the week, body parts, animals) and communication schemes (e.g., interacting with a character in the projected game). Both programs involved activity or discussion with the teacher or with other children in the class.

EEG Tasks

The EEG experiment had two passive oddball detection conditions, which were tested in separate blocks: vowel and note. The vowel condition presented the French vowels /u/ [u] and /ou/ [y], and the note condition used piano tones A (440 Hz) and A# (466.164 Hz) as the standards and deviants. The standard and deviant stimuli were randomized across all children and alternated between pretesting and posttesting. To maintain naturalistic acoustics, the durations of each vowel and note were 280 and 1000 msec, respectively. The sound onset asynchrony was 1500 msec in both conditions, and there were 300 trials (15% deviants) in each condition. After training, French vowels should be familiar to children in the French group, and piano tones should sound more relevant to those in the music group.

During EEG recording, the children sat in a comfortable chair while a silent movie of their choice was displayed on a computer screen. They were instructed to attend to the movie and ignore the sounds, as they would be asked about the contents of the movie. The sounds were played through two loudspeakers. After the experiment, the research assistant asked questions to ensure that children had attended to the movie.

EEG Recording and Preprocessing

EEG was recorded using a 70-channel Biosemi (Amsterdam, The Netherlands) ActiveTwo system (512-Hz sampling rate) with electrodes placed around the scalp according to standard 10–20 locations (Oostenveld & Praamstra, 2001). Continuous EEG recordings were bandpass filtered at 0.5–30 Hz. Data were segmented into 1000-msec epochs and baseline corrected based on a 200-msec prestimulus interval. Trials with excessive signal amplitude were rejected. Ocular and muscle artifact removal was performed on the remaining concatenated trials using independent component analysis implemented in EEGLAB (Delorme & Makeig, 2004). The average number of trials for all participants and conditions after data processing was completed was 42 (SD = 1.3) deviant trials and 241 (SD = 7.3) standard trials.

We performed source estimation at 72 ROIs defined in Talairach space (Diaconescu, Alain, & McIntosh, 2011) using sLORETTA (Pascual-Marqui, 2002), as implemented in Brainstorm (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011). Brainstorm is documented and freely available for download under the GNU general public license (neuroimage.usc.edu/brainstorm). Source reconstruction was constrained to the cortical mantle of the brain template MNI/Colin27 defined by the Montreal Neurological Institute. Current density for one source orientation (X component) was mapped at 72 brain ROIs adapting the regional map coarse parcellation scheme of the cerebral cortex developed in Kötter and Wanke (2005). Multiscale entropy (MSE) was calculated on the source waveform at each ROI for each participant as a measure of brain signal complexity.

MSE

MSE calculates sample entropy (Richman & Moorman, 2000) at multiple timescales (Costa, Goldberger, & Peng, 2002, 2005) and has been previously validated as a

measure of brain signal complexity (Catarino, Churches, Baron-Cohen, Andrade, & Ring, 2011; Mišić, Mills, Taylor, & McIntosh, 2010; McIntosh et al., 2008). We calculated MSE in two steps using the algorithm available at www.physionet.org/physiotools/mse. First, the EEG signal was progressively down-sampled into multiple coarse-grained timescales where, for scale t, the time series is constructed by averaging the data points with nonoverlapping windows of length t. The number of scales is determined by a function of the number of data points in the signal, and the data in this study supported 12 timescales [sampling rate (512 Hz) × epoch (1200 msec)/ 50 time points per epoch = maximum of 12 scales]. To convert timescale into milliseconds, divide the timescale by the EEG sampling rate (512 Hz).

Second, the algorithm calculates the sample entropy for each coarse-grained time series. Sample entropy quantifies the predictability of a time series by calculating the conditional probability that any two sequences of m consecutive data points that are similar to each other within a certain criterion (r) will remain similar at the next point ($m + 1$) in the data set (N), where N is the length of the time series (Richman & Moorman, 2000). In this study, MSE was calculated with pattern length set to $m = 5$, and similarity criterion was to $r = 1$. The value r is defined as a proportion of the standard deviation of the original data (Costa, Goldberger, & Peng, 2004; Richman & Moorman, 2000). MSE estimates were obtained for each participant as a mean across single-trial entropy measures for each timescale.

Spectral Analysis

Studies have found that MSE and power spectrum density (PSD) provide complimentary information on neural signals (Mišić et al., 2014; McIntosh et al., 2008). To determine the extent to which training- and task-based differences in MSE are related to spectral density, we computed PSD for all single-trial time series. Single-trial power spectra were computed using the fast Fourier transform. To capture the relative contribution from each frequency band, all time series were first normalized to mean = 0 and $SD = 1$. Given the sampling rate of 512 Hz and 614 data points per trial, the frequency resolution was effectively 0.834 Hz, and the analysis was constrained to the 0.834- to 30-Hz range.

Partial Least Squares Analysis

Task partial least squares (PLS) analysis was used to assess training- and task-related effects in MSE and PSD. Task PLS is a multivariate statistical technique that employs singular value decomposition to extract latent variables (LVs) that capture the maximum covariance between the task design and neural activity. The data matrix containing participants in each training group by MSE values across the 72 brain regions and sampling scales

was mean-centered with respect to the column grand average. Singular value decomposition was then applied to the matrix to generate mutually orthogonal LVs, with descending order of magnitude of covariance accounted for. Each LV consisted of (1) a singular vector of design scores, (2) a singular vector showing the distribution across brain regions and sampling scales, and (3) a singular value (s) representing the covariance between the design scores and the singular image (McIntosh & Lobaugh, 2004; McIntosh, Bookstein, Haxby, & Grady, 1996).

The statistical significance of each LV was determined using permutation tests (McIntosh & Lobaugh, 2004). An LV was considered significant if a singular value equal to or greater than that of the LV was present less than 5% of the time in random permutations (i.e., $p < .05$). The reliability of each statistical effect is assessed through bootstrap estimation of standard error confidence intervals of the singular vector weights in each LV (Efron & Tibshirani, 1986). In this study, this process allowed for the assessment of the relative contribution of brain regions and timescales to each LV. Brain regions with a singular vector weight over standard error ratio > 3.0 correspond to a 99% confidence interval and were considered to be reliable (Sampson, Streissguth, Barr, & Bookstein, 1989). In addition, the dot product of an individual participant's raw MSE data and the singular image from the LV produces a brain score. The brain score is similar to a factor score that indicates how strongly an individual participant expresses the patterns on the LV and allowed us to estimate 95% confidence intervals for the effects in each group and task condition.

RESULTS

No pretraining differences between the music and French groups were detected in MSE ($p = .45$) or PSD ($p = .26$). We also found no significant differences between the standard and deviant trials, which was consistent with evidence that MSE is unaffected by evoked neurophysiological responses (Mišić et al., 2010), so these trials were combined into one condition for all further analyses. This left four conditions in each training group (pretraining vowel task, pretraining note task, posttraining vowel task, and posttraining note task).

Two data-driven significant statistical effects were identified by task PLS when MSE for all groups and conditions were entered into the analysis. The first captured an increase in MSE from premusical to postmusical training during the vowel and note tasks, which was not observed after French training ($p = .030$, singular value (s) = .353, corresponding to 31% of the cross-block covariance; Figure 1). Spatial patterns presented in Figure 1B show that this increase was robustly expressed at coarse timescales (range = 13.7–23.4 msec) in right-hemisphere primary auditory cortex, superior temporal cortex, anterior IC, OFC, secondary somatosensory cortex, subgenual ACC, and right claustrum (CL) as well as left-hemisphere precuneus and superior

parietal cortex. Brain score confidence intervals (Figure 1A) revealed that this training effect was similar for both the vowel and note tasks.

The second significant effect identified a decrease in MSE only after French training during both task types ($p = .040$, $s = .335$, 29% of cross-block covariance; Figure 2). However, examination of the spatial patterns showed that this contrast was only reliably expressed at a single timescale in the left CL, indicating that French

training was associated with very limited changes in MSE.

Spectral analysis revealed a significant effect of training during both tasks in both training groups ($p = .002$, $s = .080$, 37% of cross-block covariance; Figure 3). Training was associated with increased theta band (3.5–7.5 Hz) power in posterior cingulated cortex, left centrolateral pFC, frontal polar, pulvinar, inferior temporal, secondary visual (V2), right CL, dorsolateral pFC, parahippocampal,
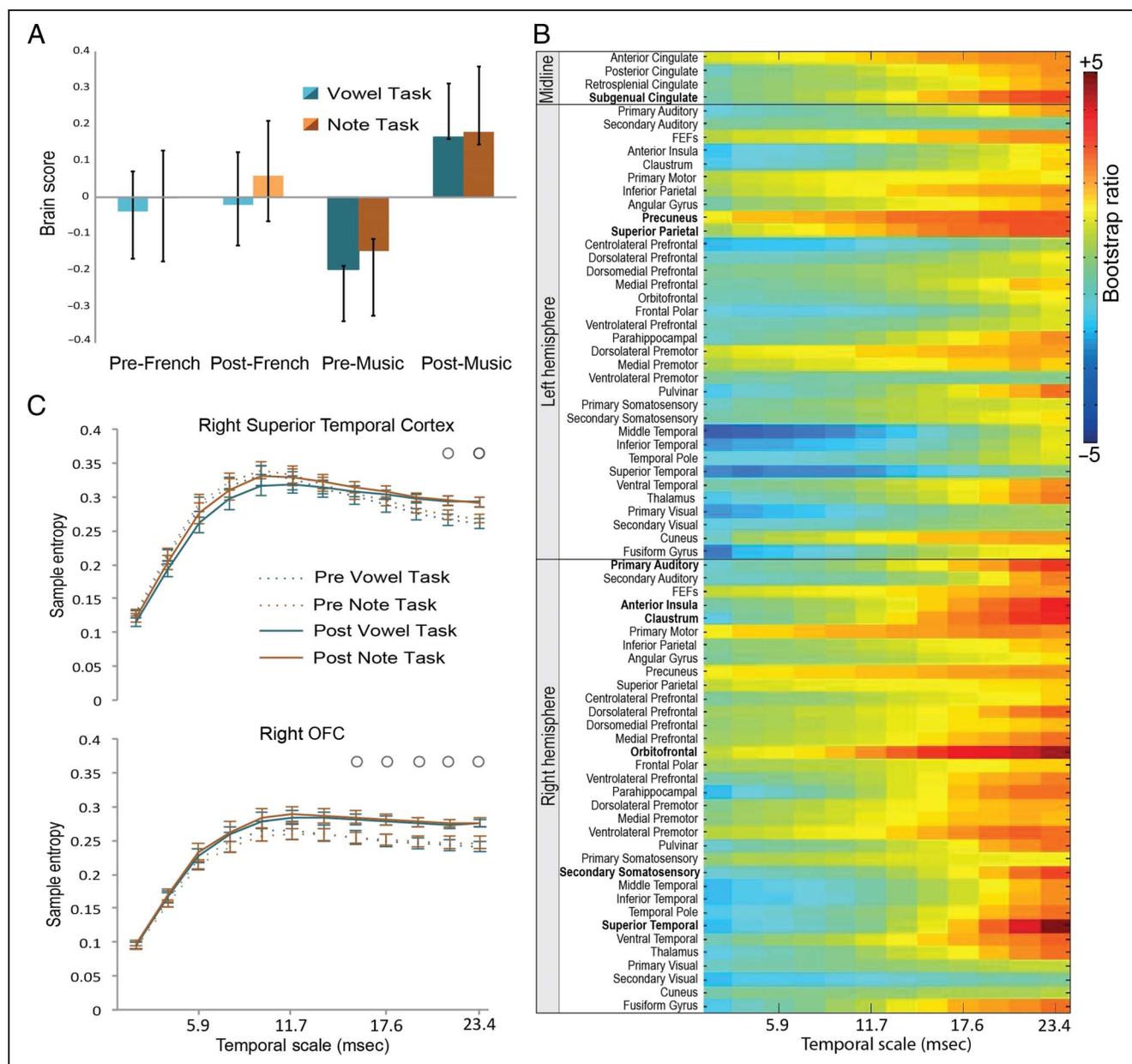

Figure 1. First significant PLS result for the comparison of within-group effects of training on MSE. (A) The bar graph depicts the data-driven contrast highlighting changes in MSE between pretraining and posttraining task conditions in the music group significantly expressed across the entire data set, as determined by permutation tests ($p = .0299$). (B) Cortical regions and temporal scales at which the contrast was most stable as determined by bootstrapping. Values represent the ratio of the parameter estimate for the source divided by the bootstrap-derived standard error (roughly z scores). (C) Condition mean MSE estimates for the music training group across temporal scales for the right superior temporal ROI (top) and the right orbitofrontal ROI (bottom), together with corresponding standard errors. Circles above the curves indicate the time points with reliable confidence intervals.
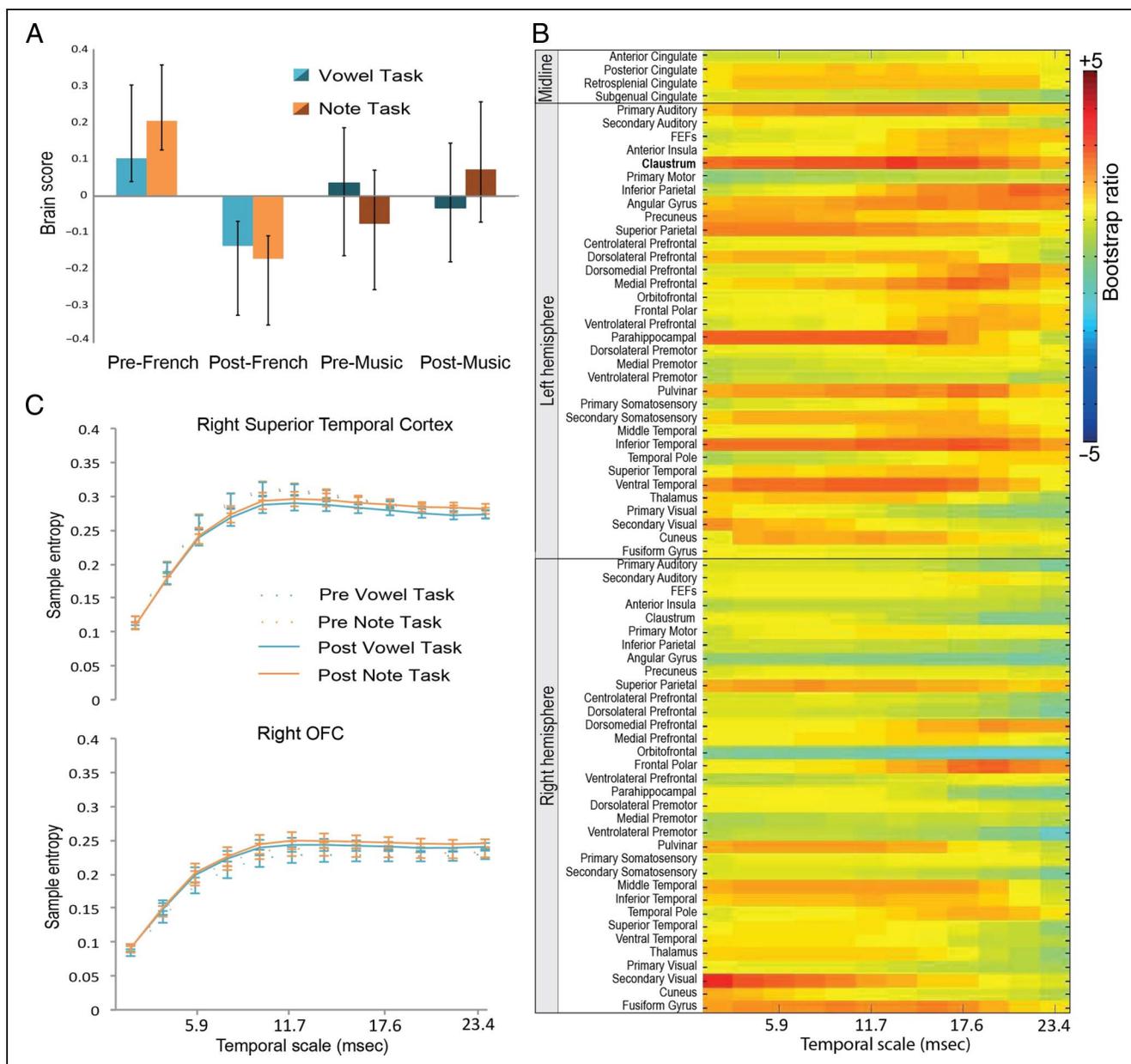
Figure 2. Second significant PLS result for the comparison of within-group effects of training on MSE. (A) The bar graph depicts the data-driven contrast highlighting changes in MSE between pretraining and posttraining task conditions in the French group significantly expressed across the entire data set, as determined by permutation tests ($p = .0399$). (B) Brain regions (left CL only) and temporal scales at which the contrast was most stable as determined by bootstrapping. Values represent the ratio of the parameter estimate for the source divided by the bootstrap-derived standard error (roughly z scores). (C) Condition mean MSE estimates for the French training group across temporal scales for the right superior temporal ROI (top) and the right orbitofrontal ROI (bottom), together with corresponding standard errors. Unlike music training-related changes in MSE, French training had little effect on MSE in these areas.

ventral temporal, and bilateral thalamus. Decreases in beta frequency (12.5–30 Hz) power were also observed after training in left centrolateral pFC, frontal polar, inferior temporal, and right V2.

DISCUSSION

Music Training MSE

Kindergarten-aged children performed passive musical note and French vowel oddball tasks during EEG record-

ing before and after 20 days of music training. Compared with pre-music-training, posttraining brain signal complexity was increased during both tasks in right-hemisphere primary auditory cortex, superior temporal cortex, OFC, secondary somatosensory cortex, subgenual ACC, right CL, and anterior IC as well as left-hemisphere precuneus and superior parietal cortex. This potential music-to-language neural transfer is consistent with previous evidence of the superior linguistic abilities of trained musicians (Moreno & Bidelman, 2014; Corrigall & Trainor, 2011;
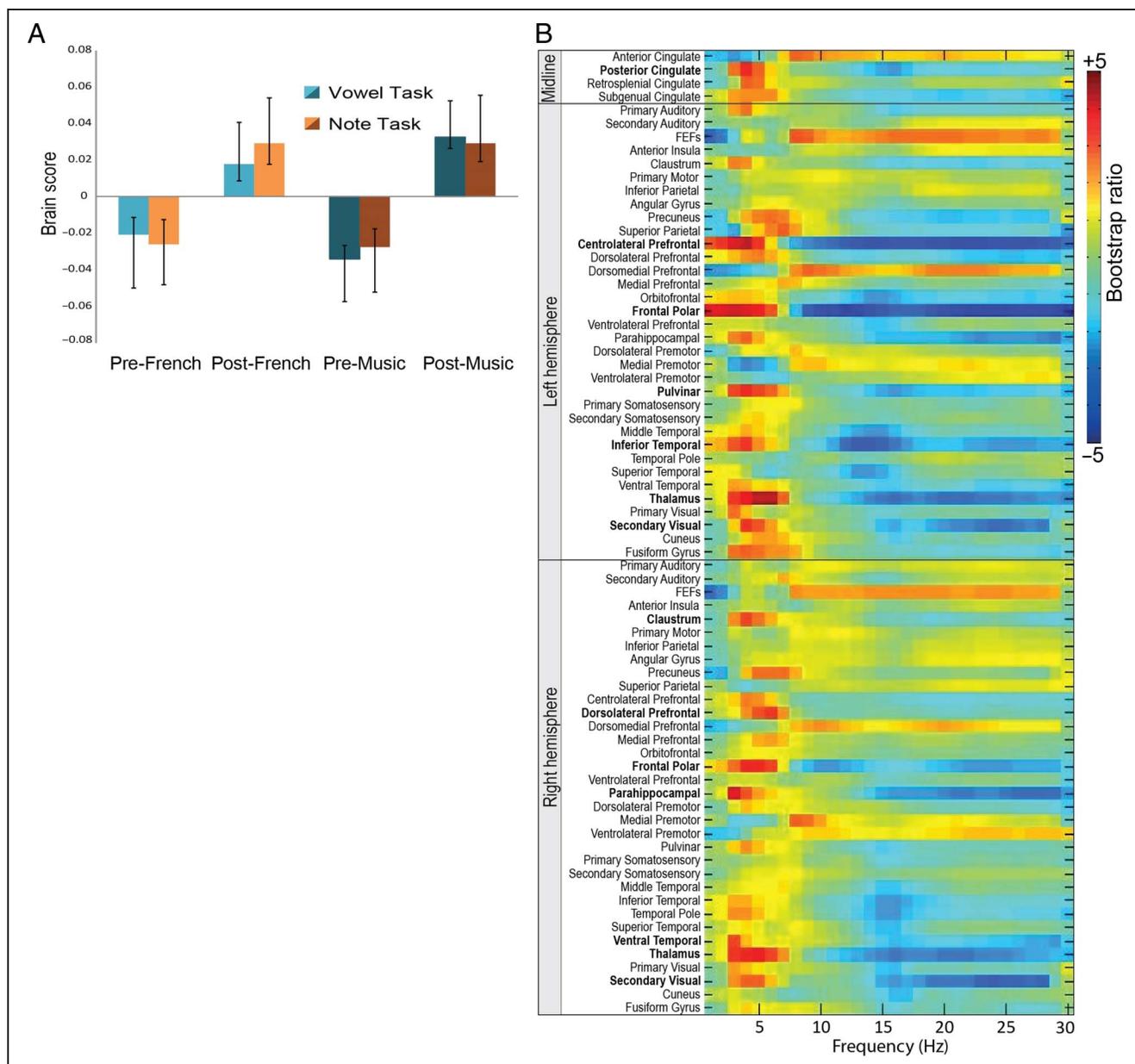
Figure 3. PLS result for the comparison of within-group effects of training on spectral power (PSD). (A) The bar graph depicts the data-driven contrast highlighting changes in PSD between pretraining and posttraining tasks for both the music and French training groups significantly expressed across the entire data set, as determined by permutation tests ($p = .0080$). (B) Brain regions and frequencies at which the contrast was most stable as determined by bootstrapping.

Kraus & Chandrasekaran, 2010; Moreno, 2009; Milovanov, Huotilainen, Välimäki, Esquef, & Tervaniemi, 2008; Magne, Schön, & Besson, 2006). This result suggests that music training increased information processing capacities by increasing the functional repertoire of brain regions implicated in musical and language processing (Price, 2010; Zatorre, Belin, & Penhune, 2002; for a discussion, see Hutka, Bidelman, & Moreno, 2013) as well as in domain-general associative cortex that is crucial for global information integration (Hagmann et al., 2008).

It has been suggested that cognition in the human brain is achieved by integration of activity from functionally distinct neural populations (Tononi, Sporns, & Edelman, 1994) across multiple timescales (Honey, Kötter, Breakspear, & Sporns, 2007). These rapidly emerging and dissolving functional networks (Bressler & Kelso, 2001) are associated with highly variable and complex brain signals that reflect an increased number of underlying metastable activity states and an overall greater information processing capacity of the system (Deco et al., 2011; Ghosh et al., 2008; McIntosh et al., 2008). Accordingly, high brain signal complexity has been positively associated with superior cognitive task performance (Raja Beharelle et al., 2012; McIntosh et al., 2008) and greater knowledge representation (Mišić et al., 2010). Musical experiences require integration of a rich perceptual environment with internal representations

(e.g., auditory, motor, visual, emotional, cognitive). We propose that musical training in this study increased diversity of brain network states to support domain-specific music skill acquisition and music-to-language transfer effects. The complexity induced by music training was most reliably displayed at coarse temporal scales previously shown to be frequently associated with global brain communication distributed between regions, compared with the fine scales representation of local dynamics within smaller neural regions (Vakorin, Lippé, & McIntosh, 2011; Nunez, Wingeier, & Silberstein, 2001). Thus, our results suggest that musical training may be associated with increased long-range network integration and global information processing. This increase in the range of flexible brain network configurations prepares the musician brain to coordinate communication between diverse neural populations and allows musicians to flexibly respond to a wide range of potential input more effectively than nonmusicians (Winkler, Denham, & Nelken, 2009).

Brain signal complexity was increased after music training in right temporal regions involved in music and language perceptual processes (Price, 2010; Zatorre et al., 2002). Pitch perception was a primary component of both the note and vowel tasks, and there is evidence that right-hemisphere, compared with left, temporal regions are specialized for spectral auditory processing (Schneider et al., 2005; Zatorre et al., 2002; Zatorre, 2001). Therefore, it is possible that right-hemisphere lateralization is not the exclusive effect of training but was potentially partially driven by the specific task demands. The recorded changes in temporal cortex activity suggest that musical training increased the information processing capacity of auditory regions to improve music and linguistic pitch perception.

Musical training was also associated with increased EEG complexity at coarse timescales in multimodal regions such as the parietal and cingulate cortices, IC, and OFC. Activity changes in these regions have been observed during complex music processing, likely reflecting the use of domain-general resources, rather than music- or language-specific activation (Foster & Zatorre, 2010; Zarate, Wood, & Zatorre, 2010; Zatorre, Evans, & Meyer, 1994). The structural network organization of these regions makes them perfectly suited for the "executive" roles that are traditionally ascribed to them. These regions are densely connected to neighboring regions and have long-range interconnections, enabling efficient global communication and integration of information necessary for healthy cognitive function (van den Heuvel & Sporns, 2011; Zamora-López, Zhou, & Kurths, 2010; Hagmann et al., 2008). The increased brain signal complexity observed after musical training in these regions suggests that musical training is associated with an increased capacity for integrated, interregional cortical communication that may be beneficial for nonmusical cognition.

It should be highlighted that our link between verbal skills and the observed increase in complexity after mu-

sical training is grounded in previous evidence of associations between musical training and verbal abilities (for reviews, see Moreno & Bidelman, 2014; Kraus & Chandrasekaran, 2010) as well as brain signal complexity and cognitive performance (Ghosh et al., 2008; McIntosh et al., 2008). Empirically, the correlation between complexity and cognition follows similar spatiotemporal patterns to the effects observed in this study (Heisz, Shedden, & McIntosh, 2012; Raja Beharelle et al., 2012; Mišić et al., 2010). Thus, future experiments that explicitly address brain and behavior measurements are required to confirm a direct association between these phenomena.

French Training MSE

French training in this study was associated with minimal reduced brain signal complexity at fine timescales. Such a decrease in local processing could reflect a trade-off between global and local processing, where the occurrence of more local processing is disadvantageous and may lead to unstable behavior (Raja Beharelle et al., 2012; McIntosh et al., 2008). Observed decreases in local complexity may reflect a training-induced beneficial shift in the balance between local and distributed neural processing. This effect had limited spatial reliability; however, a non-significant trend toward this shift was observed in many regions, leading to the possibility that learning a second language may follow a slower time course of neuroplasticity than musical training. A longer duration of French language training than that used in this study may produce significant changes in brain signal complexity.

In addition, there is initial evidence that cortical speech processing may be dichotomized between faster and slower temporal scales: higher-frequency phonetic discrimination in left-hemisphere gamma oscillations (30–70 Hz) and slower integration in right-hemisphere theta (Giraud & Poeppel, 2012; Morillon, Liégeois-Chauvel, Arnal, Bénar, & Giraud, 2012; Poeppel, 2003). Our observed trend for decrease in fine-scale complexity and significant increases in theta power after French training suggest a possibility for future inquiry that second-language acquisition is associated with a decrease in reliance on fine-scale phonetic perception, in favor of more efficient syllabic level processing. Our 30-Hz low-pass filter in this study prevented us from examining any potential effects related to the higher-frequency elements of speech processing.

The age group of the children participants is a dynamic time for all neural development, including qualitative changes in the cortical correlates of primary language (Szaflarski et al., 2006), and it is unclear if a second language is associated with quantitative changes within native-language cortical networks (Perani & Abutalebi, 2005) or qualitative changes in neural activation (Archila-Suerte, Zevin, Ramos, & Hernandez, 2013). The precise course of second-language acquisition continues to be explored.

PSD

All training was associated with increased theta power in frontal and temporal regions as well as more spatially constrained decreases in power at higher frequencies (>10 Hz). Theta-band EEG activity has been repeatedly implicated in a range of cognitive, memory (Klimesch, 1999), and emotional processes (Aftanas & Golocheikine, 2001). After a series of experiments, Von Stein and Sarnthein (2000) concluded that long-range network interaction in theta band was associated with higher-level cognition and memory, whereas higher-frequency activity tended to be more frequently observed at spatially local sites in connection with immediate sensory events. The present results suggest that music and French training are associated with a change in the balance between immediate sensory and higher-level cognitive processing.

It is important to note that the PSD results were different from the MSE results, both in contrast and spatial distribution. Standard spectral analysis revealed an overall main effect of training, and MSE additionally captured aspects of neural information processing that differed between music and French training. This is likely because MSE is sensitive to both spectral power distribution and the interdependencies between frequencies (McIntosh et al., 2008).

Conclusions

Children who received musical training displayed increased information processing capacities of auditory and associative cortices during music note and French vowel tasks, as assessed by increased EEG signal complexity after training. This neural activity could underlie previously reported cognitive benefits of musical training to untrained tasks. French training was associated with minimal decreases in fine temporal scale complexity, suggesting an effect of a beneficial change in balance between segregated local and integrated global neural processing. A longer duration of training may clarify French-training-induced neural changes and any possible benefits of such brain activity to cognitive transfer. Both types of training coincided with increases in theta relative to higher-frequency power, further capturing the increasing involvement of distributed memory processes relative to immediate auditory sensation.

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