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Music training modulates theta brain oscillations associated with response suppression

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Abstract

There is growing interest in developing training programs to mitigate cognitive decline associated with normal aging. Here, we assessed the effect of 3-month music and visual art training programs on the oscillatory brain activity of older adults using a partially randomized intervention design. High-density electroencephalography (EEG) was measured during the pre- and post-training sessions while participants completed a visual GoNoGo task. Time-frequency representations were calculated in regions of interest encompassing the visual, parietal, and prefrontal cortices. Before training, NoGo trials generated greater theta power than Go trials from 300 to 500 ms post-stimulus in mid-central and frontal brain areas. Theta power indexing response suppression was significantly reduced after music training. There was no significant difference between pre- and post-test for the visual art or the control group. The effect of music training on theta power indexing response suppression was associated with reduced functional connectivity between prefrontal, visual, and auditory regions. These results suggest that theta power indexes executive control mechanisms in older adults. Music training affects theta power and functional connectivity associated with response suppression. These findings contribute to a better understanding of inhibitory control ability in older adults and the neuroplastic effects of music interventions.

KEYWORDS
aging, art training, brain oscillation, brain plasticity, executive functions, music training

INTRODUCTION

In the last 20 years, there has been a surge of research aiming to find ways to mitigate age-related changes in cognition. Research has shown that a healthy diet,[1] engagement in physical activity,[2] bilingualism,[3] volunteering,[4] mindfulness training,[5] "gamified" puzzle training,[6] and playing a music instrument[7,8] or participating in a choir[9] can help older adults maintain their physical and cognitive fitness. Among these various activities, music training shows real promise in mitigating age-

related changes in cognitive functions because playing a musical instrument is a rich and complex activity that engages many brain areas.

Cross-sectional studies showed that older musicians often outperform older nonmusicians on various tasks that require selective attention and cognitive control, such as speech-in-noise perception,[10] and the GoNoGo tasks.[11] Behavioral studies using a longitudinal design provide converging evidence that older adults do benefit from music training programs. For instance, Bugos and colleagues showed 6 months of musical training (e.g., piano lessons) can improve executive

functioning and working memory.[8,12] Seinfeld and colleagues found enhanced inhibition in older adults after months of group piano training.[12] In a recent, randomized controlled trial, 4 months of piano training enhanced verbal fluency in older adults as compared to computer-assisted cognitive training and controls.[13] Music therapy is beneficial in reducing depressive symptoms and improving quality of life in older adults.[14] A study suggests that older adults with subjective cognitive decline show significant improvement in psychological well-being and in sleep quality after 12 weeks of music listening.[15] In addition, singing and listening to music can alleviate depression in patients with dementia.[16] Specifically, singing is beneficial especially in improving working memory, maintaining executive functions, and orientation. Music listening was beneficial in supporting general cognition, working memory, and quality of life.

More recent studies using scalp recording of neuroelectric brain activity have shown that in older adults, 3–6 months engagement in music[17,18] and visual art[18] lessons yield neuroplastic changes in the event-related potentials (ERPs). In Alain et al.,[18] older adults were randomly assigned to music, visual art (active control), or a passive (no intervention) control group. They all completed the GoNoGo task before and after a 3-months training period. Notably, participants from the music intervention program showed greater differences in ERPs elicited by Go and NoGo trials after training than older adults taking part in visual art instruction, or the control group. These changes in ERPs following music training may reflect a more efficient use of attentional resources.

Evidence of neuroplastic changes from ERP research are, however, small and variable between studies.[18,19] This could be partly due to the time-domain analysis of EEG data, which is susceptible to temporal jitter and may miss important information contained in brain activity (e.g., induced nonphase locked activity). Time-frequency analyses, which take into account differences in phase-locked and nonphase locked activity simultaneously, may be better suited for assessing neuroplastic changes associated with training in older adults. The theta (4–7 Hz) and alpha (8–13 Hz) bands are particularly relevant to the GoNoGo paradigm due to their association with cognitive control.[20–24] Prior studies in young adults have revealed increased theta oscillation (4–7 Hz) power over mid-frontal scalp area, associated with withholding the prepotent response in NoGo trials.[22,25]

Cross-sectional studies comparing theta power in young and older adults have yielded mixed results. For instance, one study showed lower performance and reduced mid-frontal theta modulation in older compared to younger adults during a working memory task.[26] However, another study found comparable accuracy in young and older adults when working memory demand was low, but showed enhanced mid-frontal theta oscillations in older compared to younger adults.[27] These findings suggest that age-related differences in theta oscillations may vary due to task demands and could be related to cognitive effort. Although the latter may be amenable to change, training effects on theta power during a GoNoGo task in older adults have yet to be investigated. Evidence suggests that age-related differences in visual-evoked responses may also be associated with changes in functional connectivity between the prefrontal and sensory cortex.[28] Thus,

training-related changes in older adults' ERPs could also be related to alterations in functional connectivity.

The present study reanalyzed the EEG data from Alain et al.[18] to test the hypothesis that training-related changes in older adults' ERPs are related to alteration in oscillatory power and functional connectivity. We focus on theta (4–7 Hz) band, which has been shown to index executive control and response suppression.[22,29,30] Theta synchronization also improves over frontal areas after working memory training[31] and over fronto-parietal areas after mindfulness meditation.[32] Moreover, both Gist reasoning training and learning training have been shown in increase theta synchronization in GoNoGo tasks among older adults with cognitive impairment, suggesting that theta oscillations might index training effects.[33] Here, we test whether music and visual arts training in older adults are differentially associated with similar neuroplastic changes in theta oscillatory activity.

METHOD

Overview

Analyses of the ERPs during the GoNoGo task and behavioral responses associated with this dataset are reported in Alain et al.[18] New time-frequency analyses (applied here) were used to evaluate whether engagement in musical activities yield neuroplastic changes in brain activity or the maintenance of benefits after training ends.

Participants

Sixty healthy older adults were recruited from the Greater Toronto Area. For pre- and post-training phases, five participants were lost to attrition. Two due to technical problems during EEG recording, resulting in 16 participants in the music group (age range 57–80 years, three males), 17 in the visual art group (age range 59–80 years, two males), and 17 in the no-contact control group (age range 57–79 years, three males).

All participants had limited music and visual art training: They had not engaged in any visual art or musical training or activity within the past 5 years and had no more than 6 years of formal visual arts or musical training over their lifespan. The music group had an average of 1.2 years (SD 2.0) of private music lessons and 0.7 year (SD 1.2) of private art lessons, and the art group had an average of 1.3 years (SD 1.8) of private music lessons and 0.2 year (SD 0.7) of private art lessons. The control group had 0.7 year (SD 1.1) of private music lessons and 0.3 year (SD 0.9) of private art lessons.

The groups did not differ in age ($p = 0.92$; music: $M = 67.8$, SD $= 6.0$ years; visual art: $M = 68.5$, SD $= 6.2$ years; control, $M = 68.5$, SD $= 5.9$ years), years of formal education ($p = 0.121$; music: $M = 16.4$, SD $= 2.7$ years; visual art: $M = 17.2$, SD $= 2.4$ years; control: $M = 16.9$, SD $= 2.2$ years). Participants were screened for amusia and other auditory or musical deficits using the Musical Ear Test.[34] All three groups showed similar scores at baseline psychometric assessment (all p values > 0.1).

After 3 months, 13 participants from the music group and 12 participants from the visual art group returned for follow-up testing. These two subgroups remained similar in age ($p = 0.87$), education ($p = 0.94$), and had comparable intelligence on WASI-II FSIQ4 ($p = 0.39$) at pre-test. All participants provided written informed consent in accordance with a protocol approved by the Baycrest Research Ethics Committee.

Study design

This longitudinal study consisted of four phases: pre-training, 3-month training, post-training, and a 3-month follow-up test. Participants did not engage in formal music or visual arts activities during the 3 months between post-training and follow-up. At pre-training, post-training, and follow-up sessions, participants were tested individually and were blind to our hypotheses. After the pre-training, participants were assigned to either music or visual-arts training in a pseudorandom manner to equate pre-training differences between groups on intelligence scores and background demographic measures (gender, age, and years of education). An additional passive control group was recruited to distinguish potential training effects from test-retest effects.

Training curricula

Participants in the music and visual art groups received group classroom instruction and activities in their respective training domain by a professional teacher (i.e., two teachers: a music and a visual art teacher) at the Royal Conservatory of Music in Toronto for 3 months (36 1-h sessions, three times per week). The music group was engaged in music-making using body percussion, voice, and nonpitched musical instruments. They also learned basic music theory and melody and harmony concepts through the singing of simple canons. The visual art group learned basic drawing and painting techniques, analyzed the work of famous artists, and created original paintings of landscape, still-life, and self-portrait. All materials were provided for them (i.e., instruments for the music lesson and all the material for drawing and painting in the visual arts lesson).

Procedure

Testing (EEG and psychometric tests) took place in the laboratory on 2 days and lasted approximately 1.5–2 h per session.

Psychometric assessment comprised the following tests: (1) Wechsler Abbreviated Scale of Intelligence – Second Edition; (2) Forward and Backward Word Span; (3) Stroop test; (4) Computerized Peabody Picture Vocabulary Test; and (5) Digit symbol (Subtest of the WAIS-R). Details regarding these assays are available in Alain *et al.*[18]

We measured neuroelectric brain activity (EEG) while participants were presented with the oddball auditory paradigm and a visual GoNoGo task. The same stimuli were used at each of the three testing sessions (pre, post, and follow-up), while the order of trials was randomized across participants and sessions. The recordings took place in an acoustically and electrically shielded room. The results from the oddball auditory paradigm are available in Alain *et al.*[18]

During the visual GoNoGo task, participants were presented with white or purple geometric triangles or squares at the center of the screen located at about 1 m from the participant. Before each trial, a white fixation cross appeared on a black background for a variable duration (500–1000 ms), then a geometric shape appeared in the center of the screen for 500 ms. Participants were instructed to press the right mouse button in response to white shapes (80% probability) and to withhold responding to purple shapes (20% probability). The experiment consisted of 200 trials (160 Go and 40 NoGo trials). A practice block of 20 trials was used to familiarize participants with the task. During the task, participants did not receive feedback on their performance. Accuracy rates were recorded for Go and NoGo trials, and reaction times were recorded for Go trials.

EEG recording and data processing

EEG was recorded from 66 scalp electrodes using a BioSemi Active Two acquisition system (BioSemi V.O.F., Amsterdam, The Netherlands). Electrode locations were based on the 10/20 system and included a common mode sense active electrode and driven right leg passive electrode serving as ground. Ten additional electrodes were placed below the hairline (both mastoid, pre-auricular points, outer canthus of each eye, inferior orbit of each eye, two facial electrodes) to monitor eye movements and cover the whole scalp evenly. EEGs were digitized continuously at a rate of 512 Hz with a bandpass of DC-100 Hz and stored for offline analysis. Offline analyses were performed using Brain Electrical Source Analysis software (BESA, version 7.1; MEGIS GmbH, Gräfelfing, Germany).

Continuous EEGs were rereferenced to the average of all electrodes and digitally filtered with 0.53 Hz high-pass (forward, 6 dB/octave) and 170 Hz low-pass filters (zero phase, 24 dB/octave). For each participant, a set of ocular movements was identified from the continuous EEG recording and used to generate spatial components to best account for eye movement artifacts. The spatial topographies were then subtracted from the continuous EEG to correct for lateral and vertical eye movements as well as for eye blinks. The continuous EEG data were segmented into 1500 ms epochs that were time-locked to stimulus onset, including 500 ms of pre-stimulus activity. After ocular correction, traces were then scanned for artifacts and epochs with deflections exceeding $\pm$ 60 μV were marked and excluded from the time-frequency analysis.

As a data reduction method, we used a source montage to extract time-frequency representations at the different source locations. We used a model from BESA software (i.e., Ventral Attention with Noise Sources) that encompassed the visual sensory areas, parietal, frontal, and cingulate cortex (Figure 1). This was chosen based on source activity associated with visual attention[35] and GoNoGo[36] tasks. Time series were extracted from dipoles with a radial orientation relative to the scalp surface. A complex demodulation method with 1 Hz wide frequency bins and 50 ms time resolution in the range
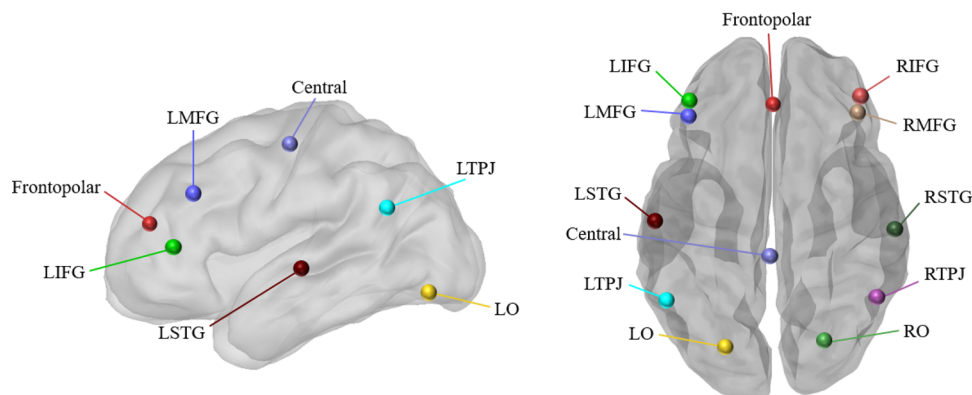
FIGURE 1 Schematic of the source montage use to extract time-frequency representations of temporal spectral evolution. Abbreviations: LIFG, left inferior frontal gyrus; LMFG, left middle frontal gyrus; LO, left occipital; LSTG, left superior temporal gyrus; LTPJ, left temporal parietal junction; RIFG, right inferior frontal gyrus; RMFG, right middle frontal gyrus; RO, right occipital; RSTG, right superior temporal gyrus; RTPJ, right temporal parietal junction

of 2 and 50 Hz was used for decomposing the single-trial EEG data into time-frequency representations of temporal spectral evolution (TSE, an equivalent measure of event-related synchronization and desynchronization).

Brain networks provide important physiological and psychological information, and the construction of functional connectivity is essential for understanding brain function. Phase-locking values (PLVs) are commonly used for studying functional connectivity and were adopted to capture the nonlinear phase synchronization between paired nodes to network in Go or NoGo trials.[37,38] Processing was performed using Brainstorm software (https://neuroimage.usc.edu/brainstorm/). We computed functional connectivity within the network based on PLVs elicited by Go and NoGo trials, separately. Then, the difference matrix between NoGo and Go trials was obtained by subtraction. A paired *t*-test was performed on the difference matrix before and after the music training program to test for changes in functional connectivity between sessions.

Statistical analyses

Oscillatory activity elicited by Go and NoGo trials from the pre-test session was subjected to nonparametric cluster-based permutation testing using BESA Statistics software (Statistics 2.1, MEGIS GmbH). This analysis comprised all participants and aimed to identify neural correlates of response suppression in our sample of older adults. A preliminary step identified clusters both in time (adjacent time points) and space (adjacent electrodes), where the time-frequency representations differed between the conditions. A Monte-Carlo resampling technique[39] then identified clusters with higher values than 95% of all clusters derived by random permutation of the data. This nonparametric permutation statistic is no longer subject to the multiple comparisons problem; for an in-depth overview of permutation statistics as implemented in BESA Statistics, see Ref. 39. A time interval was set from stimulus onset (0 ms) to 1000 ms post-stimulus. This interval

was chosen because it encompasses the time window of interest for sensory-evoked responses and response suppression associated with NoGo trials. An alpha level of 0.01 was used for cluster building, and the number of permutations was set at 3000.

The clustered-based statistic was followed by a mixed model analysis of variance (ANOVA) with group as the between-subject factor and session as the within-subject factor. This analysis focused on the frequency and time-interval that best captured the differences between Go and NoGo trials at pre-test. An alpha value of 0.05 was used throughout, and the effect size was measured with partial eta-squared (η_p^2).

RESULTS

Behavioral data

Results from the GoNoGo task are reported in Alain *et al.*[18] Briefly, all three groups showed ceiling performance on Go trials with few (if any) false positives on NoGo trials. There was no difference between the groups nor between the pre- and post-test sessions. The group x session interaction was not significant for accuracy or response time measures.

Pre-training: brain oscillations indexing response suppression

We first compared oscillatory brain activity elicited by the Go and NoGo trials among all participants. Clustered-based permutation statistic revealed greater theta power for NoGo versus Go trials over mid-central and frontal regions (clusters 1–3, Table 1). Compared to the Go trials, NoGo trials were also associated with enhanced beta power at mid-central sites from 100 to 800 ms.

TABLE 1 Summary of clustered-based statistics comparing oscillatory brain activity elicited by the Go and NoGo trials before training (pooling all participants)

Cluster # and brain source	Cluster range ms/Hz	Cluster maximum ms/Hz	p Value
1 Mid central	100–750 ms; 18–25 Hz	400 ms, 24 Hz	< 0.001
2 Mid central	100–450 ms; 2–10 Hz	250 ms, 4 Hz	< 0.001
3 Mid frontal	150–450 ms; 2–8 Hz	300 ms, 4 Hz	< 0.001
4 Left occipital	400–800 ms; 9–13 Hz	650 ms, 10 Hz	0.004
5 Right occipital	550–700 ms; 12–19 Hz	650 ms, 18 Hz	0.017

Note: Thresholds for cluster building were set at $p = 0.01$.

Effects of training on theta power

The effect of training on theta power (4–7 Hz) from the central source near the anterior cingulate was examined for the 300–500 ms interval using *a priori* planned contrasts within the repeated measured ANOVA with the visual art group as our reference category and session as the within-subject variable (Figure 2). Our primary hypothesis was that the effect of treatment will differ between the experimental group (i.e., music) and the active control group (i.e., visual art). The secondary hypothesis was that the active control group would differ from the passive control group. The ANOVA yielded a main effect of session ($F(1,47) = 6.747$, $p = 0.013$, $\eta_p^2 = 0.1266$), with the GoNoGo difference in theta power being smaller in the post- than in the pre-training session. More importantly, the planned contrast between experimental group and active control group yielded a significant group × session interaction, ($F(1,47) = 4.314$, $p = 0.043$, $\eta_p^2 = 0.084$). The contrast between active and passive control group also yielded a group × session interaction, ($F(1,47) = 4.100$, $p = 0.049$, $\eta_p^2 = 0.080$). Pairwise comparisons revealed a smaller difference between Go and NoGo trials in theta power at post-test in those who received musical training ($p = 0.003$). There was no significant difference between pre-test and post-test in older adults who took part into the visual art training ($p = 0.150$) or those from the control group ($p = 0.870$) (Figure 3).
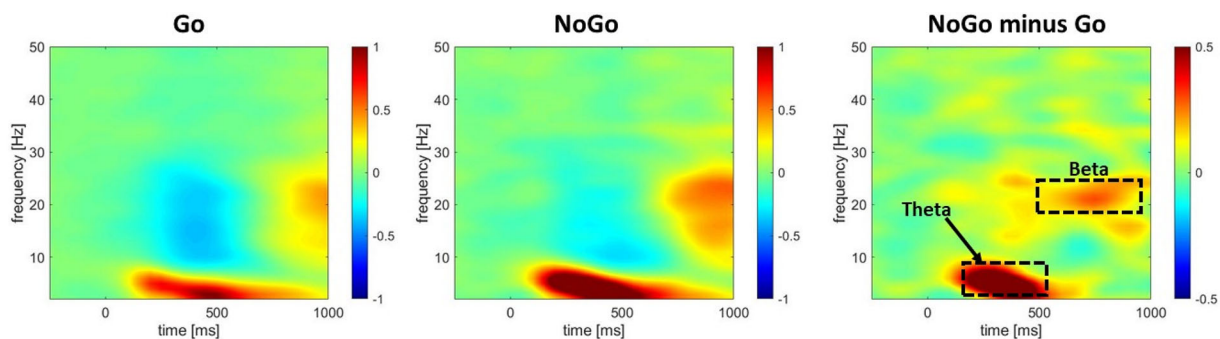
To better understand the effects of music training on the GoNoGo modulation, we compared the mean theta power for the Go and NoGo trials between the pre- and post-training session. The analysis revealed a significant interaction between condition and session, $F(1,15) = 6.811$, $p = 0.020$, $\eta_p^2 = 0.312$), which was due to a greater difference in theta power between pre- and post-training sessions for the NoGo than Go trials. Pairwise comparison revealed a significant difference between pre- and post-training for the NoGo trials ($p = 0.040$). There was no difference in theta power between sessions for the Go trials ($p = 0.683$).

Effects of training on beta power

The main effect of session on beta power was not significant ($F(1,47) = 2.887$, $= p = 0.096$, $\eta_p^2 = 0.058$) nor was the main effect of group ($F < 1$) or the group × session interaction ($F < 1$).

Follow up

A subset of participants from the music ($n = 13$) and visual art ($n = 12$) training groups took part in a 3-month post-training follow-up. Here, we carried out exploratory analyses to test whether the smaller difference between Go and NoGo trials in theta power at post-test in the music group was long lasting. The analysis revealed comparable theta power at pre-test and follow-up, and a significantly smaller difference between Go and NoGo at post-test ($p < 0.05$ in both cases). In the visual art group, the difference between Go and NoGo trials was comparable across all three sessions (Figure 4).

Functional connectivity

We tested whether the impact of music training on theta power indexing response suppression was linked to changes in functional connectivity within the attentional network by comparing PLV elicited by Go and NoGo trials, before and after training. Differences in theta power between NoGo and Go trials at pre-test in the music group were observed in three connections: LOcc-LTPJ ($p < 0.001$, $t = -4.44$), central-ROcc ($p = 0.048$, $t = 2.15$), and RMFG-ROcc ($p = 0.023$, $t = 2.49$) (Figure 5A). Differences in theta power between NoGo and Go trials at post-test in the music group showed seven significant connections: LIFG-frontopolar ($p = 0.041$, $t = 2.23$), LIFG-RSTG ($p = 0.023$,

FIGURE 2 Grand average time-frequency representation at pre-test (pooling all participants). Midline central source
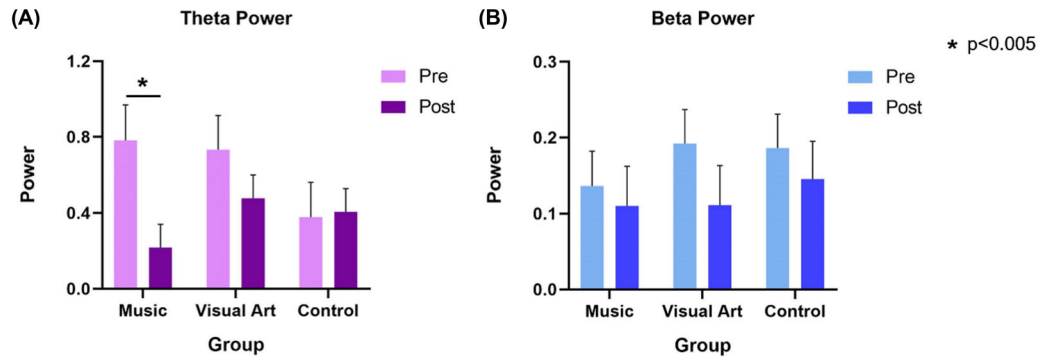
FIGURE 3 (A) Group mean difference in theta power between Go and NoGo trials at pre- and post-tests. The measurements reflect the mean theta power (4–7 Hz) between 300 and 500 post-stimulus from the midline central source. (B) Group mean difference in beta power between Go and NoGo trials at pre- and post-tests. The measurements reflect the mean beta power (18–25 Hz) between 400 and 800 post-stimulus from the midline central source.
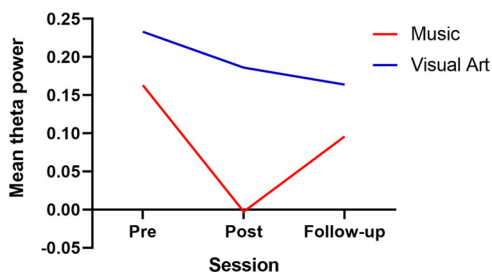

FIGURE 4 Mean theta power (difference between Go and NoGo) at pre, post, and follow-up sessions

$t = -2.56$), frontopolar-ROcc ($p = 0.028$, $t = -2.43$), RMFG-LOcc ($p = 0.007$, $t = -3.11$), ROcc-LOcc ($p = 0.008$, $t = -3.08$), ROcc-RTPJ ($p = 0.039$, $t = -2.26$), and central-RTPJ ($p = 0.009$, $t = -3.02$) (Figure 5B). There were also five significant connections within the attentional network between pre- and post-test in LIFG-RSTG ($p = 0.014$, $t = -2.79$), frontopolar-RO ($p = 0.023$, $t = -2.53$), RMFG-RO ($p = 0.039$, $t = -2.27$), RMFG-LO ($p = 0.047$, $t = -2.16$), and central-RTPJ ($p = 0.021$, $t = -2.58$) (Figure 5C). After excluding participants lost of follow-up, we calculated the difference in theta power between NoGo and Go trials in the music group at follow-up. There was one significant connection: central-RIFG ($p = 0.032$, $t = 2.42$) (Figure 5D).
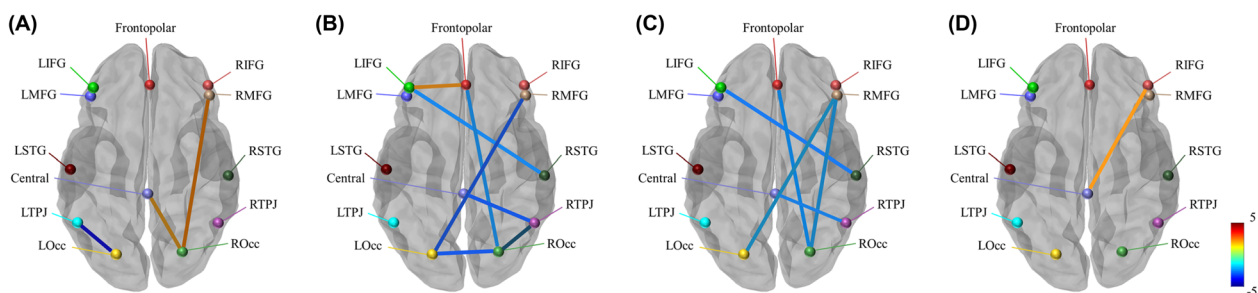
DISCUSSION

Before music and visual art training, we observed a significant increase in theta and beta power elicited during the NoGo trials compared to the Go trials. This enhanced theta and beta power during the NoGo trials is consistent with prior studies in young adults[22,40,41] and likely reflects the engagement of executive control mechanisms that withhold response execution (i.e., button press). Stronger theta and beta oscillations in NoGo trials may also reflect conflict detection and resolution, respectively. The infrequent NoGo trials conflict with the general task context, requiring pressing a button on most trials.

Notably, 3 months of music training reduced the difference in theta power between Go and NoGo trials. The difference in theta power between Go and NoGo trials, thought to index response suppression, was little affected by visual art training. In controls, the difference in theta power between Go and NoGo trials was comparable for both test sessions. The analysis of Go and NoGo trials in the music group revealed an effect of training only on the NoGo trials. Specifically, theta oscillations during NoGo trials were reduced after training. Therefore, this is a potential indicator that short-term music intervention, unlike the other training regimes, can improve conflict detection and inhibitory control ability of older adults.

The GoNoGo paradigm is often used to study response activation and inhibition processes.[41,42] Studies suggest theta oscillations play

FIGURE 5 Functional connectivity (difference between Go and NoGo) within the attentional network based on PLV in the music group. (A) Differences at pre-test ($p < 0.05$). (B) Differences at post-test ($p < 0.05$). (C) Differences before and after the music training program ($p < 0.05$). (D) Differences at follow-up ($p < 0.05$). Participants lost in follow-up tests were excluded and the number of participants in D is 13.

an important role in young adults performing the GoNoGo task. Theta activity increases in NoGo trials, which is associated with withholding the prepotent response.[22,25,43] Specifically, theta oscillations in the fronto-central area serve as a marker for action monitoring and conflict detection processes, and nonphase-locked theta power is a better predictor of conflict conditions than conventional time-domain phase-locked EEG components.[24] Theta activity associated with response inhibition has been observed to increase in persons who meditate[44] and decline in those suffering from alcoholism.[45] ERP studies found that N2 and P3 components were related to response conflict and inhibition of overt responses, respectively.[42,46] A previous study provided evidence that theta band activity is associated with N2 and P3 ERP component activity by using time-frequency analysis.[47] Collectively, these studies reveal that theta oscillations play an essential role in increased cognitive control demands, such as performance monitoring, and serve as a marker of conflict detection in young adults. In addition, the timing of theta power in the aforementioned studies is consistent with the time course observed here (~400 ms post stimulus). Our data show that theta power in mid-frontal cortex is dominant at pre-test of all older participants. This is consistent with previous studies showing increased theta oscillations in frontal areas.[21,48-50] Meanwhile, the greater theta oscillations also occurred around 400 ms after stimulation. Thus, these results provide support for the role of theta power in conflict detection and response suppression and further extend the current gap in research on theta oscillations in the GoNoGo task for older adults. Additionally, greater beta oscillations were also observed in NoGo trials. Previous studies have found that motor tasks typically generate electrophysiological responses in the beta frequency band.[51,52] There is usually an increase in amplitude above baseline with movement interruption.[53,54] At the same time, prefrontal areas have been proposed to play an important role in top-down control over urges, which is thought to involve inhibitory control.[55,56] Therefore, enhanced beta oscillations in fronto-central regions in our older adults seem to reveal the mechanism underly response suppression in NoGo trials, elucidating the role of beta activity in inhibitory control processes.

Many kinds of training affect theta activity, such as intensive mental training,[57] neurofeedback training,[58] and GoNoGo training.[43] Therefore, our theta findings caused by music training may be helpful in exploring positive interventions for aging. Previous studies suggested that music training can affect brain functions of older adults. For example, older musicians show better ability of inhibitory control,[11,18,59] and executive functioning was improved after short-term musical training.[7,8] In the present study, differences in theta oscillations related to inhibitory control were reduced following a 3-month music training program, which was mainly due to decreased theta power elicited during the NoGo trials. Previous studies found that frequent responding and rare inhibition in the GoNoGo task makes the participants susceptible to impulsive errors/false alarms.[60-62] Therefore, these unexpected signals may also contribute to theta oscillations. Studies suggest that frontal theta oscillations likely reflect the coding of a "surprise signal,"[24,63] which leads to stronger theta oscillations when error-prone response inhibition occurs. Therefore, weakened theta oscillations after the music training program might reflect that music training reduces the occurrence of error-prone response inhibition, that is, the reduction of "surprise." In the present study, the theta power elicited by the NoGo stimulus was reduced after music training. This finding is consistent with the hypothesis that the intensity of theta oscillations reflects the strength of executive control ability. The reduced theta power after music training may, therefore, reflect increased efficiency of executive control mechanisms.

Previous studies assessing conflict detection and response suppression using the GoNoGo task have focussed primarily on ERPs measured at the scalp.[11,18,43] The current work extends prior research by using source montage, which allows us to draw some conclusion regarding the possible brain regions involved in theta power associated with GoNoGo task. In the source analysis, the PLV results suggest that the underlying mechanism of the weakened theta oscillations is due to the changes of connections between prefrontal and perceptual areas. Connection strength after subtraction of Go trials from NoGo trials decreases after the music training program, which suggests that the prefrontal lobe regulates executive control functions in older adults through connections with audiovisual brain areas. Evidence also suggests that the prefrontal cortex exerts modulatory control over sensory processing.[28,65] Taken collectively, the causal training in our results contributes to the underlying hypothesis that music training affects inhibitory control. Our data further suggest that these changes might be due to rapid plasticity in neural connectivity caused by training.

Furthermore, in our previous ERP study, we found that music training enhanced auditory-evoked responses to piano tones in older adults and modulated visual processing, which indicates the training effect on the elderly.[18] However, we note the short-lived extent of our music training effects. We found that music training effects on the GoNoGo task were relatively short-lived and disappeared by the follow-up test in ERP study. The results of these new time-frequency analysis of the follow-up data show that 3 months after the end of music training, the difference between NoGo and Go in theta oscillations is enhanced, indicating that the music training effect did not persist. Further, PLV connectivity analysis on the follow-up data showed that the difference in connectivity between NoGo and Go after training disappeared during the follow-up test, which is consistent with our previous ERP work and affirms the short-lived nature of neural effects from our music intervention. Our data suggest that maintained participation in music training programs is necessary to demonstrate changes in PLV, and older adults may need ongoing training (i.e., periodic "doses") to maintain the long-term benefits of musical training. Indeed, there is some evidence (at least in young adults) that the neuroplastic effects of music begin manifesting only after ~1–2 years of training.[66]

Limitations and future directions

The current study uses a relatively short (3 months) training program. It is very likely that increasing the duration of the training regimen would yield greater difference in brain activity. Besides, only music

and visual art training were included in this experiment, other training regimes, such as intensive cognitive training and/or neurofeedback training, may also affect inhibitory control functions. Meanwhile, our music training group program was designed for nonmusicians and focused on basic aspects of music. Since we observed some benefits from this training, individualized training programs should also be considered. Furthermore, the current findings provide evidence for training-related differences in neural activity underlying inhibition, but these differences were not strong enough to elicit behavioral differences in our response inhibition task. We cannot rule out that with more practice, we would have observed some behavioral benefit (e.g., faster response time for the Go trials). However, performance was near ceiling leaving little room for changes in response time and error rate. Therefore, future studies should also investigate the behavioral effects of training on inhibitory control using more complex tasks that allow a wide range of performance with no ceiling effects, which may contribute to understand the effect of music training on people's everyday life.

CONCLUSION

Our work found that theta oscillatory activity in the frontal region dominated the pre-training of all adult participants. This result supports the hypothesis that theta oscillations correlate with executive control in older adults. Increased activity in frontal regions was observed in the NoGo trial compared to the Go trial in the pre-training. Our findings are consistent with previous research, indicating that theta oscillation may serve as a marker for conflict detection. Our results provide evidence that differences in theta oscillations between NoGo and Go in older adults may serve as an EEG indicator of inhibitory control ability. The findings also suggest that theta oscillations are influenced by training and that music training significantly reduced the difference in theta oscillations between NoGo and Go trials, while visual arts training remained unchanged. Results of PLVs connectivity revealed the same trend, that is, differences in connectivity between NoGo and Go trials were significantly reduced after the music training program. These connections are mainly concentrated in the prefrontal and sensory areas, which reflects the critical role of prefrontal areas in the music-regulated inhibitory control and reveals the underlying brain mechanisms of this process. Furthermore, we found that the effects of the music training program were not long-lasting and were associated with differences in connectivity between the NoGo and Go trials. In general terms, our results suggest the uniqueness of music training in terms of its effect on inhibitory control decline in older adults. Thus, this may be one potential indicator of the effect of music training intervention on brain aging in older adults.

AUTHOR CONTRIBUTIONS

C.A. and S.M. designed the experiments. Y.L., A.M., and G.M.B. performed the experiments and collected data. C.A., C.S., J.B., S.G., and J.L. analyzed the data. C.A., A.M., G.M.B., Y.L., S.M., C.S., J.B., J.L., and D.Y. interpreted the results of experiments. J.L. and C.A. drafted the manuscript. All authors edited, revised, and approved the final version of the manuscript.

COMPETING INTERESTS

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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