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Short-term piano training changes the neural correlates of musical imagery and perception - a longitudinal fMRI study

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ABSTRACT

Short-term instrumental training has the potential to alter auditory cognition, but effects on mental imagery of music are yet unknown. In the present study we investigated the effects of six week of piano training on the behavioral and neuronal correlates of perception and mental imagery of music, in a longitudinal functional magnetic imaging study in healthy young adults. Learning to play familiar simple melodies resulted in increased activity both during listening and imagining of the trained compared to untrained melodies in left dorsal prefrontal cortex and bilateral intraparietal sulcus, a network believed to be important for motor learning and auditory-motor integration. For imagery, we additionally found training-related increases in bilateral cerebellar areas involved in mental imagery of music. The results indicate that the cortical networks for mental imagery and perception of auditory information not only overlap, but are also similarly malleable by short-term musical training.

I. INTRODUCTION

Over periods of many years, musical training influences higher-order processing of auditory information, such as auditory-motor integration (Chen, Penhune, & Zatorre, 2008) and melodic processing (Fujioka, Trainor, Ross, Kakigi, & Pantev, 2004), as seen in differences in behavioral and neuronal correlates of auditory cognition between musicians and nonmusicians.

Previous research has also shown that piano training over shorter periods of weeks to months causes changes in neural correlates of auditory perception and auditory-motor networks (Lahav, Saltzman, & Schlaug, 2007; Lappe, Herholz, Trainor, & Pantev, 2008). Such experimentally controlled musical training studies are indispensable for establishing causal relationships between the training on the one hand and neuronal and behavioral changes on the other hand, and they provide an excellent framework for the investigation of training-related plasticity in the human cortex for various cognitive functions (Münte, Altenmüller, & Jäncke, 2002).

Mental imagery of music is modulated by long-term musical training (Aleman, Nieuwenstein, Bocker, & de Haan, 2000; Herholz, Lappe, Knief, & Pantev, 2008), and mental imagery and perception of music share overlapping cortical networks (Herholz, Halpern, & Zatorre, in press; Zatorre & Halpern, 2005; Zatorre, Halpern, Perry, Meyer, & Evans, 1996). However, to our knowledge the effects of training on musical imagery on a shorter time scale have not been tested. The investigation of training-related changes on neural correlates of mental imagery would not only increase our understanding of functional cortical plasticity, but might also have implications for clinical applications of mental imagery, for example for the control of brain-computer interfaces in paralyzed patients and for neuro-prostheses (Fetz, 2007).

In the present study, we used functional magnetic resonance imaging to investigate whether six weeks of piano training could result in changes in the brain networks for auditory mental imagery and perception.

II. METHODS

A. Participants

Fourteen young adults participated in the experiment. They were recruited via electronic advertisements on the McGill University job posting website and screened for musical experience via an online questionnaire [Montreal Music History Questionnaire, MMHQ, (Coffey, Herholz, Scala, & Zatorre, 2011)]. Participants had less than one year of formal musical training and none had any experience on keyboard instruments. All participants had grown up in an English-speaking environment in Canada or the US and reported familiarity with the melodies used in the study. Participants gave written consent before entering the study and received compensation for their participation. All procedures were approved by the research ethics board of the Montreal Neurological Institute.

B. Design

Participants were scanned at three times separated by six-week intervals. During fMRI scanning they performed a task that involved listening or imagining familiar melodies. The first six week interval between MRI scans 1 and 2 served as a baseline. Immediately after scan 2, participants started six weeks of piano training. MRI scan 3 took place immediately after the last piano training session.

Participants performed the piano training on portable MIDI keyboards with 25 keys (Q25, Alesis, Cumberland, RI, USA) connected to computers running a custom-made piano training program based on the Presentation software suite (Neurobehavioral Systems, Albany, CA, USA). Piano training consisted of 30 min practice sessions 5 days/week for 6 weeks during which participants progressed at their own pace through levels of gradually increasing difficulty in length, rhythm, speed, variation in notes needed, and melodic contour. Participants practiced on their own at home but came to the lab for one of the sessions per week, where the session was supervised by an experimenter to ensure instructions were being followed and to reassure the participant if he or she was becoming frustrated. For home practice sessions, participants were asked to minimize distractions and interruptions. We collected performance data to ensure they were practicing continuously during the training sessions.

On each training exercise, the participant first listened to a short tone sequence presented by the computer and then tried to play it. The correct key for the first note was indicated on the screen, but otherwise no visual aids were provided in order to focus the training on the auditory and sensorimotor modalities. The computer analyzed the participant's keystrokes after each attempt and provided feedback immediately after each trial as to whether the notes played were correct or incorrect (smiley face or unhappy face), and whether the rhythm was accurate (smiley face), passable (neutral face), or inadequate (unhappy face). An appropriate difficulty level for the rhythm assessment was determined through pilot testing. If the performance on a trial received a poor evaluation (unhappy face) for either notes or rhythm, the trial was repeated up to three times. After three failures, we reshuffled the exercises in the level to limit frustration. Participants progressed to the next level in the curriculum when all of the trials in the level were played correctly at least once.

During the first 20 sessions, which occurred over the first four weeks, participants practiced short unfamiliar melodies to introduce hand position (first right, then left, then both), associate the sounds of the notes with the keys, and practice listening carefully to and then repeating the phrases.

For the last 10 sessions over the final two weeks of training, two randomly assigned subgroups of 7 participants each practiced a set of six familiar melodies starting with a few notes and adding a few notes at a time until they could play the first melodic phrases of each. Participants went through their assigned melodies twice in the course of the curriculum. The criterion to advance to the next level was to play the full melodic phrase correctly at least three times. Although the melodies were transposed so that they would involve both hands to some extent, the right hand had a stronger role in most of the melodies.

After each training session, performance information collected during the training session was automatically output and uploaded to our servers to allow us to monitor training progress remotely.

C. Material and behavioural tasks

Twelve familiar melodies were used as stimuli in the experiment, both during the piano training (two subgroups each practiced six melodies), and during the fMRI task (all subjects heard and imagined all melodies). Melodies were selected for high familiarity in an independent group of participants with comparable background and age range during pilot testing, and the familiarity of each subject in this study with the melodies was confirmed prior to the first scan.

Musical imagery was elicited in the scanner using a task adapted from a previous MEG study (Herholz, et al., 2008) to an fMRI sparse sampling paradigm and with additional control conditions. Figure 1 illustrates the Listen and Imagine conditions. In the Listen condition, subjects were presented with the title of the melody followed by the instruction "LISTEN". The beginning or chorus of the song (whichever was more familiar to most people) was played in grand piano timbre. The subject judged whether the final note presented before the scan was correct or incorrect and indicated their decision by button press. In the Imagine condition, only the initial segment of the melody was presented, and the participant's task was to imagine the continuation of the melody during a silent gap of at least six seconds and to make a judgment on the last tone, which was again presented after the silent gap.

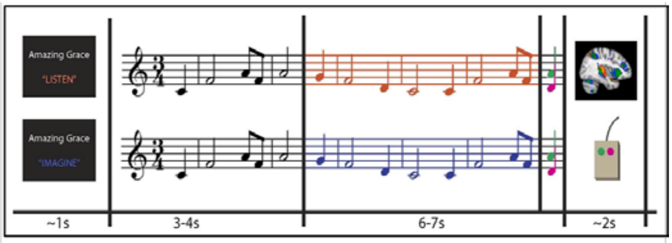

Figure 1: Graphic representation of the two experimental conditions, Listen (red) and Imagine (blue) in the functional scanning protocol. A screen indicated the upcoming melody and the experimental condition. Tones marked blue in the Imagine condition were not physically presented but had to be imagined. Responses were given immediately after the presentation of the last note, during the functional MRI scanning.

The accuracy of the correct/incorrect judgment was calculated for the Listen and Imagine conditions as a measure of how well the participants were able to perform the task. In both conditions, the tone to be evaluated was correct 50% of the time. Incorrect tones were always in key, deviated by different musical intervals (higher/lower tones for half of the melodies, respectively) and were in the tonal range of the melody. These constraints were imposed in order to ensure that participants could not rely on harmonic or other regularities to identify the incorrect tones, but had to correctly imagine the melody during the silent gap.

Two additional conditions served as control conditions for the fMRI task. In the Random condition the participants listened to sequences of random tones that had the same physical parameters and same silent gaps as the stimuli in the Imagine condition, but with scrambled initial notes that did not elicit a memory of a familiar tune. Participants were required to press one of the buttons after the last tone without making any judment. This condition thus served as a control for auditory input and motor response. The Silence condition served as baseline during which no auditory input was presented. In both conditions the initial visual cue screen contained the words "Pause" and "REST" to control for visual input.

For each condition 48 trials were presented, distributed across two runs of functional MRI scanning of equal length. Imagery, Listen, and Random trials were presented in blocks of 12 trials each, in a balanced order of blocks, interspersed with shorter blocks of four Silence trials. Although our event-related sparse sampling design did not require blocked presentation of trials, this order was deemed advantageous in order to prevent high cognitive load due to frequent task switching.

D. Scanning parameters and data analysis

EPI images covering the whole head (voxel size 3.5mm3, 40 slices, TE 30ms, TR 15 s) were acquired on a Siemens 3T Scanner using a 32-channel head coil. We used a sparse sampling paradigm that was optimized to pick up listen- and imagery-related activity. Scanning took place immediately after the presentation of the test tone.

All functional data analyses were performed using the FEAT package of FSL software (fMRIB, Oxford, UK). In preprocessing functional images were motion-corrected and spatially smoothed with 5mm FWHM. Individual fMRI data were registered to high-resolution T1-weighted anatomical images and then registered to MNI standard space for group analyses. Task-related BOLD images were analyzed using the general linear model. In all analyses the contrasts between conditions were estimated on the first level for each run, and then the two runs for each subject were combined using a fixed effects model on the second level. Group averages and training-related effects over time were assessed on the group level (third level) using a mixed model with subject as random factor for the longitudinal analyses.

We were interested in imagery- and listen-related cortical activity, and especially in the changes related to the piano training. On the first level, the different conditions were modeled as separate explanatory variables, and imagery-related activity was assessed in the contrast [Imagine > Random] and perception-related activity in the contrast [Listen > Silence]. Group averages as well as a conjunction of the resulting activation maps of these contrasts were computed on the third level.

For the analysis across time group-level contrasts of Scans 2 and 1 (baseline) and of Scans 3 and 2 (piano training) were computed on perception and imagery-related activity for all songs as given by the first-level contrasts [Imagine > Random] and [Listen > Silence], respectively, in order to assess general training effects. In order to assess specific training effects, we further separated the Listen and Imagery trials regarding their training status in Trained and Untrained, based on the individual assignment of songs for training for each subject. Third-level contrasts across time [Scan 2 > 1] for baseline and [Scan 3 > 2] for piano training, as above, were computed on the contrasts [Trained melodies > Untrained melodies] for each of the two experimental tasks (Imagine and Listen). We used cluster-level thresholding as implemented in FSL FEAT, with an initial z-value of 2.3 and $p < 0.05$ in all analyses. For illustration of the training effects in the present paper we extracted the signal change in the contrast parameter estimate (COPE) images for each participant, at the peaks of the group level clusters for the training effects (in the contrast between scan 2 and 3) that survived the statistical thresholding in the full brain search on the third level, in order to show how the contrast between trained and untrained melodies changes due to the piano training.

III. RESULTS

E. Behavioral data

All participants learned to play their melodies, but the rate of learning varied widely among individuals, with some individuals completing all of the levels within the first few sessions, and some individuals completing them only on the last session. Participants were able to accurately imagine the songs during scanning as evidenced by above-chance performance on this task (*t*-tests; all $p<0.05$). Performance in the Listen task was near ceiling.

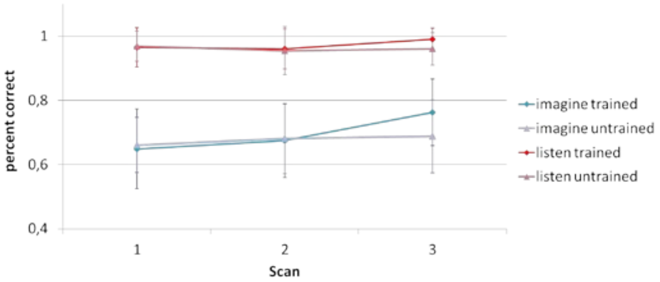

Figure 2. Mean performance on the imagery and perception tasks. Error bars indicate the standard deviation.

Training resulted in improved performance on the imagery task for the trained melodies after the piano training as visible in the increased performance on those melodies (figure 2). However, this trend was not statistically significant in a repeated measures ANOVA with the factors training (untrained/trained) and scan (1, 2, 3).

F. Functional data

In line with our previous study on cortical networks for imagery and perception of music (Herholz, et al., in press), our preliminary analyses of the present data show activity related to imagery and to listening in an extended bilateral cortical network encompassing auditory areas, supplementary motor area, dorsal premotor, inferior frontal and parietal cortices in the group averages on the initial scan. The networks overlapped to a large extent, with the notable exception that the primary auditory cortex was not activated during imagery.

Piano training between scans 2 and 3 resulted in increased activity in the dorsal premotor cortex of the left hemisphere both for imagery- and listen-related activity. No significant changes in auditory areas, and no significant changes during the baseline period were observed.

In the contrasts of trained and untrained melodies we found similar changes in the left dorsal premotor cortex and in left-hemispheric parietal areas (intraparietal sulcus, IPS), extending to right parietal areas, due to piano training for activity during mental imagery and during listening. During imagining, we found additional increases in lobule VI of the cerebellum, with a peak in the left hemisphere, but extending bilaterally. Figure 3 illustrates the percent signal changes of the contrast parameter estimates (COPE) in the peak voxels of the significant clusters found in our preliminary analysis of the training effects.

These increases in activation after training were stronger for melodies that had been trained than for melodies that were familiar, but untrained. No significant changes were observed over the baseline period (Scan 2 > Scan 1) for either of the two experimental conditions, imagining or listening.

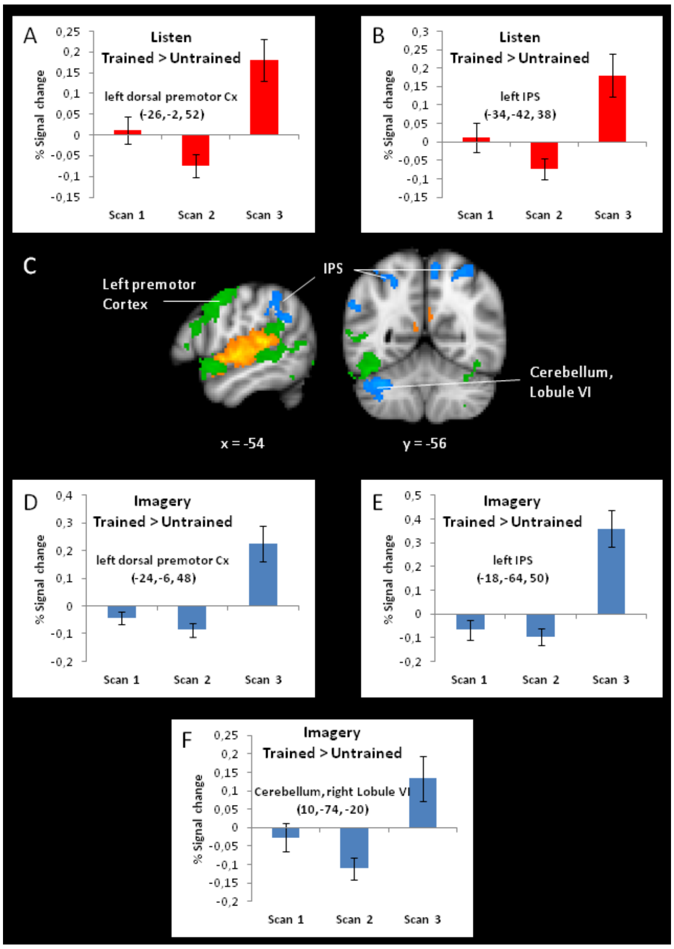

Figure 3. Specific changes for trained compared to untrained melodies during listening (A, B) and imagery (D, E, F) related to six weeks of piano training. Group averages of percent signal changes for trained compared to untrained melodies in each of the scans are given for the peak coordinates of all clusters that survived statistical thresholding in a full brain search on the group level. These brain areas showed specific training effects between scans 3 and 2, whereas no changes were found in any brain areas during baseline (between scans 2 and 1). Error bars indicate the standard error; all coordinates are given in mm in MNI standard space. The cortical networks for mental imagery and listening of music adapted from Herholz et al. (in press) are given in C to illustrate the commonly activated regions (green) and areas that are stronger activated in imagery (blue) and listening (red). These areas overlap with all of the areas found to be modulated by piano training in the present study.

IV. DISCUSSION

In the present study we investigated the effects of six weeks of piano training on behavioural and neural correlates of higher-order music cognition, namely melody perception and mental imagery of melodies.

G. Imagery and perception of music

The cortical networks encompassing auditory, premotor, inferior frontal, parietal cortex and cerebellum that we find active during perception and imagery of music in general are in agreement with previous findings (Herholz, et al., in press; Zatorre & Halpern, 2005). This replication of results is important insofar as it allows us to establish a basis on which to evaluate the training effects. Also, the behavioural data show that participants were performing the imagery task. Although the imagery periods were slightly longer than in the previous study, the overall performance was similar for nonmusicians (Herholz, et al., 2008). In the present study, we had the added perceptual task that only involved listening to the melodies and evaluating the last tone, in which participants essentially showed ceiling performance. While this might not be surprising given the relatively easy task, it nevertheless demonstrates that the difficulties of the nonmusicians on the imagery task are not purely related to deficits in discrimination of pitches for familiar melodies in general.

A big issue in all functional imaging studies of mental auditory imagery is the concern to pick up auditory activity related to the physical auditory input of cue tones, other auditory stimuli or even the MRI scanner noise itself. In our case, the silent gap in the Imagine condition was always of at least six second duration, and thus the auditory BOLD response from the initial tones was expected to have returned to baseline and the response to the last test tone was expected to be not yet detectable at the time of volume acquisition (Zatorre & Belin, 2001). However, by using the Random tone condition with comparable physical auditory input we were also able to control for this directly.

H. Effects of musical training on auditory cognition

Previous studies using MEG had shown that similar short-term training paradigms result in functional changes during melody perception in auditory cortices and in improved auditory discrimination performance (Lappe, et al., 2008; Lappe, Trainor, Herholz, & Pantev, 2011). Regarding mental imagery of music, long-term musical training was shown to alter behavioural performance (Aleman, et al., 2000) and processing in auditory cortex related to musical imagery (Herholz, et al., 2008). In the present study, we show for the first time that short-term multimodal musical training results in changes in the cortical activity during mental imagery, and that these changes parallel the changes observed for the listening condition. On average, for all melodies, we see training-related increase of activity in the dorsal premotor cortex bordering on the hand M1 area in the left hemisphere, both during listening and imagining. Furthermore, we show that listening to and imagining of melodies that were specifically trained results in additional recruitment of slightly more frontal left premotor areas, and bilateral parietal areas. Again, the training-related changes for imagery- and listening-related activity show a high correspondence. This suggests that the two cortical networks not only overlap in general, as demonstrated by previous studies (Halpern & Zatorre, 1999; Herholz, et al., in press; Zatorre, et al., 1996), but that they also respond to training to a similar degree and show a similar potential for functional plastic reorganization.

It might seem somewhat surprising that the observed changes are not found in auditory areas but in the motor network and parietal association areas. However, the finding of increased co-activation of motor areas during listening and imagining in the contrasts for all melodies in general is in line with previous studies on co-activation of motor and auditory areas related to training (Bangert & Altenmüller, 2003; Lahav, et al., 2007) and the close functional connection of these two systems, especially for music, is well established (Zatorre, Chen, & Penhune, 2007). While previous studies only investigated training-related changes in auditory-motor co-activation during actual listening, our results show that motor co-activation during imagery is comparable and comparably malleable by training.

The IPS which showed up bilaterally in response to piano training both for imagery and perception has previously been implicated both in cross-modal auditory-motor integration (Lahav, et al., 2007), but also in mental imagery of music (Herholz, et al., in press) and mental manipulation of auditory information (Foster & Zatorre, 2010). Its role in the present study might involve all of these functions since they all pertain to music processing and the multimodal piano training. Interestingly, one area that specifically showed training-related effects only for the imagery task was the cerebellum. This lines up with our previous findings of increased cerebellar activity during imagery of music (Herholz, et al., in press), possibly related to subvocalization of the tunes (Kleber, Birbaumer, Veit, Trevorrow, & Lotze, 2007) or in the context of the present study motor preparation during imagery of playing the trained melodies.

While these results shed more light on the mechanisms underlying training-related plasticity, especially regarding auditory-motor interactions, they also pertain to clinical applications, where changes of neuronal in cortical networks due to short-term training could be of interest. Musical training is increasingly recognized as a valuable tool for motor rehabilitation after brain lesions and for promoting healthy aging (Wan & Schlaug, 2010). Applications of mental imagery in the clinical context also include neurological rehabilitation after brain lesions (Lotze & Cohen, 2006), and the control of brain-computer interfaces (Fetz, 2007; Kubler, et al., 1999), where auditory imagery is a useful cognitive task to modulate brain activity to control the interface (Curran, et al., 2004).

V. CONCLUSION

The results of this longitudinal auditor-motor training study reveal plastic changes in areas related to motor preparation and cross-modal auditory-motor integration. We demonstrate for the first time that within six weeks similar changes occur within the cortical networks for perception and for mental imagery due to experimentally controlled piano practice, which has implications for our understanding of training-related brain plasticity in the auditory-motor network, and for the use of music training in neurological rehabilitation.

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