Examining Rhythm and Melody Processing in Young Children Using fMRI

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ABSTRACT: While it is often reported that musical experience can have positive effects on cognitive development in young children, the neural basis of such potential effects remains relatively unexplored. Employing functional magnetic resonance imaging (fMRI) for such research presents as many challenges as possibilities, not least of which is the fact that young children can find it difficult to remain still and attentive for long periods of time. Here we describe an fMRI scanning protocol designed specifically for young children using short scanning runs, a sparse temporal sampling data acquisition technique, simple rhythmic and melodic discrimination tasks with a button-press response, and a child-oriented preparation session. Children were recruited as part of a large-scale longitudinal study examining the effects of musical training on cognitive development and the structure and function of the growing brain. Results from an initial analysis of 33 children and from the first five children to be re-scanned after musical training indicate that our scanning protocol is successful and that activation differences can be detected both between conditions and over time.

KEYWORDS: music; fMRI; children; rhythm; melody; brain imaging

INTRODUCTION

Music plays an important part in the lives of young children. Traditional lullabies, nursery rhymes, singing games, and playground songs are perhaps increasingly being replaced by Disney musicals, TV theme songs, and pop music, but to no less enthusiastic response and indeed with great commercial success. This natural engagement with, and enjoyment of, music by children gives it enormous potential as an educational and therapeutic tool, particularly considering both the range of claimed benefits of music making (including enhanced language skills, motor skills, communication skills, and self esteem)[1–4] and the evidence suggesting that musical training may affect both brain function and brain structure.[5–10]

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In order to employ such potential benefits of music effectively, we must identify the specific mechanisms by which music can engage and develop specific perceptual, cognitive, motor, and personal skills. Some attempts at hypothesis development in this area have been made; for example, it has been proposed that temporal processing is a key mechanism underlying the potential of music lessons to support the language and literacy skills of dyslexic children,[11,12] while a range of studies have attempted to define the conditions and mechanisms under which listening to music can enhance spatial–temporal reasoning ability, usually in adults.[13–16] To date, however, there remains little understanding of the neural basis of such cognitive transfer effects, or indeed of the neural basis of music processing in young children. Such understanding of the parent domain of music processing remains crucial to an understanding of cross-domain transfer to other areas of learning.

In a large-scale, longitudinal study currently in progress,[17] the effects of musical instrument training are being monitored on the functional and structural brain development of children aged 5 to 7, along with a range of behavioral measures, including tests of language, mathematics, music, and motor skills. The use of functional magnetic resonance imaging (fMRI) in this study provides a powerful tool with which to examine potential changes in the localization of music processing after musical training, as well as any potential correlations with cognitive or structural development. However, the technique also presents a number of methodological challenges since it requires full concentration and an absence of physical movement in a noisy and potentially intimidating scanning environment.

Here we present the child-appropriate methods we have developed in order to address such challenges, which we have found to be successful. We also discuss preliminary data from the first five children to be retested after one year of musical training.

STIMULI AND TASK DESIGN

In order for neuroimaging data to be interpretable and useful, it is essential that participants be fully engaged in the behavioral tasks during scanning. This presents a particular challenge when working with young children since this population (1) can find it difficult to engage in a task unless they find it interesting, (2) can be easily distracted, and (3) generally take longer than adults to fully comprehend a task and perform it fluently. Thus, our aim was to design musical stimuli and a task paradigm that were as simple, quick to learn, and engaging as possible for children with or without musical training and on which performance would reflect a response to musical training.

The decision to focus on rhythm and melody skills was based on a number of factors. First, rhythm and melody are the two fundamental organizing principles of music[18] and are thus worthy of special attention. Second, most children, regardless of musical training, are familiar with the simple rhythms and melodies of children's songs. Third, rhythm and melody skills have often been found to be disassociated in tests of musical ability[19–21] and have also been found to show different hemispheric lateralization in nonmusicians, with melody tending toward a right-hemispheric dominance[22] and rhythm tending toward a left-hemispheric dominance.[23] While this effect appears to depend to some extent on the task paradigm, it is nevertheless worthy of examination in the developing brain. Fourth, it has sometimes been suggested that trained musicians show a reverse tendency for melody processing: a leftward dominance.[24–27] This indicates that musical training may have a particularly strong effect on the neural organization for melody-processing skills. Fifth, it has been hypothesized that rhythm skills play a key role in the transfer of musical abilities to other areas of cognitive ability,[12] making the neural basis of rhythm processing a particularly interesting area of study.

The choice of task paradigm was influenced by the fact that children of this age group (5–7) are particularly attuned to the concept of same/different. We thus presented pairs of rhythms or melodies to the children and asked them to determine whether the phrases in the pair were the "same" or "different." The phrases were composed using the first five notes of the C major scale (264, 297, 330, 352, and 396 Hz), since these lie in the natural vocal range for children and thus allow for comfortable and familiar listening. In order to avoid the potential experience bias of a real musical instrument sound, such as a piano or violin, a neutral, "marimba-like" sound was used (Cubase Universal Sound Module no. 13). The musical phrases were long enough to be musically interesting, but short enough to be memorable: each phrase was presented at 120 bpm, lasted for 5 beats, and consisted of 5 notes. Within the melody pairs, the pitches varied from *c* to *g*, while the durations remained constant at 500 ms;[a] within the rhythm pairs the durations varied from 125 ms to 1500

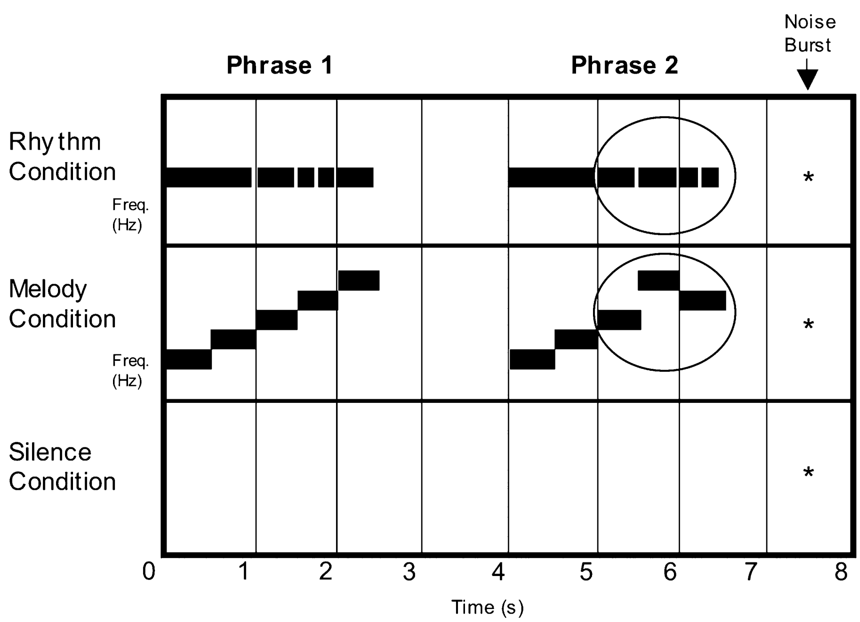

FIGURE 1. Task design. Diagram shows the three task conditions: rhythm discrimination, melody discrimination, and silence.

[a]We recognize that a melody usually includes both pitch and timing variation. Here, we use the term in its more limited sense of pitch variation.

ms, while the pitches remained constant (for both phrases) but were varied *between* trials using the same range of pitches from *c* to *g*. Thus, across all trials, the two experimental conditions were well matched acoustically, each with the same overall pitch content and number of notes.

The children gave their response using a button press (left button for same, with a soft-toy puppy held under the left arm as a reminder), allowing us to keep track of both their engagement with, and performance on, the task throughout the scanner session. The button press was cued by a short noise burst after the pair of musical phrases, thus limiting any motor activation to a specific temporal window after the cognitive discrimination had taken place. Similarly, the temporal window for potential cognitive discrimination was kept constant across trials: any difference between the two musical phrases occurred between beats 3 and 5 of the second phrase. Finally, a baseline condition of silence was included, in which the children simply heard a short noise burst cue and performed a bilateral button press (see FIG. 1).

SCANNING PROTOCOL

The high-volume noise of the fMRI scanner presents a number of potential difficulties for auditory studies, including masking of the auditory stimuli and causing unwanted auditory activation. Such noise might also be intimidating and distracting for young children. We overcame these potential difficulties with a sparse temporal sampling data acquisition technique that takes advantage of the natural delay in the cerebrovascular response to neural activity. Using this technique, single whole-brain images are acquired *after* each discrimination trial, thereby eliminating the possibility of either masking or distracting from the auditory stimuli, while considerably re-

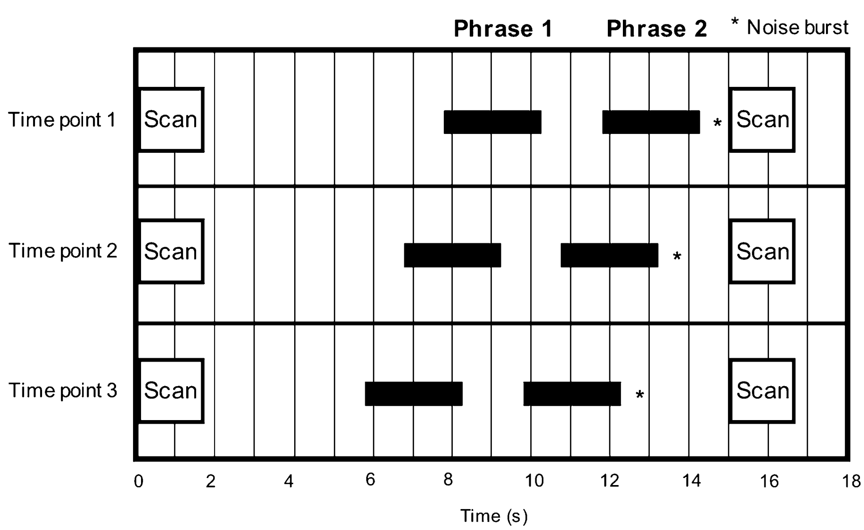

FIGURE 2. Sparse temporal sampling. Diagram shows the data acquisition method, with scans at three different time points relative to the stimuli, TR = 15.

ducing the amount of scanner noise during the test session. By "jittering" the relative position of the auditory stimuli to these scans between three different time points, we were also able to allow for differences in the cerebrovascular peak between brain regions and between individuals (see FIG. 2).

Two further considerations were the length of the scanning runs and the presentation order of the tasks. Since young children generally find it difficult to remain perfectly still and concentrate for long periods of time, we kept the scanning runs very short (3 min each), allowing the children some limited wiggling between runs. We also included only one experimental condition per run, with eight discrimination trials and four silence trials. This design avoided the potential confusion of switching tasks within a run and also created a clear, comprehensive structure of simple alternation between "rhythm" runs and "melody" runs.

PREPARATION SESSION

In order to help the children feel comfortable and confident during the fMRI scanning session, and in turn increase the chances of obtaining useful neuroimaging data, we included a practice session approximately one week before the scanning session, both to train the children on the rhythm and melody discrimination tasks and to familiarize them with the procedure of the scanning session.

Training on the discrimination tasks was a carefully staged process. Initially, the investigator asked the children to "be a listening detective" and determine whether pairs of sung melodies were the same or different. Next the children learned to press the correct buttons for *same*, *different*, and *silence* while keeping their eyes closed. The stimuli were then presented via computer, and the children learned to wait for the noise burst cue before giving their button press response. Last, the children heard recordings of the scanner noises after each trial and practiced keeping very still while listening and responding. Performance scores from the training session were monitored to compare with performance during the scanner session.

In addition to training on the task during the practice session, the children looked at a cartoon story about a boy having an MRI scan, were introduced to two soft-toy puppies, and were invited to choose the puppy they would take into the scanner with them. Finally, the children were shown examples of structural brain images of one of the investigators so that they would be familiar with some anatomical landmarks (e.g., eyes and teeth) when they saw their own "brain pictures" after the scanning session. All children and parents had previously given informed, written consent to take part in the study, which was formally approved by the Internal Review Board of the Beth Israel Deaconess Medical Center.

DATA ACQUISITION

Images were acquired on a 3T General Electric magnetic resonance imaging scanner. Prior to functional acquisition, a high resolution, strongly T1-weighted MR scan was performed, followed by a one-minute phase-encoded reference scan. Functional images were then acquired using a gradient-echo EPI sequence with an echo time of 25 ms and a 64×64 mm matrix. Using a mid-sagittal scout image, 26 slices were acquired over 1.75 s with a voxel size of $3.8 \times 3.8 \times 4$ mm. One volume set was acquired after each discrimination trial, taking advantage of the inherent delay in cerebrovascular response to neural activity. Scanning repetition time (TR) was kept constant at 15 s, while the musical stimuli were jittered between three different time points, such that the onset of the first axial slice varied between 1.25 and 3.25 s after the end of the musical stimuli.

DATA PROCESSING AND ANALYSIS

Preprocessing and analysis were conducted using SPM99 (Wellcome Dept. of Cognitive Neurology, London, UK; <www.fil.ion.ucl.ac.uk/spm>). Spatial normalization to a standard atlas was conducted by matching the T1-weighted images to a pediatric template created from 28 children's anatomical images. The identical transformation was applied to the functional data after realignment. Smoothing was applied with an 8-mm FWHM kernel. Condition effects were estimated according to the general linear model at each voxel in brain space.[28] The effect of global differences in scan intensity was removed by scaling each scan in proportion to its global intensity. Low-frequency drifts were removed using a temporal high-pass filter with a cutoff of 200 s, and no low-pass filter was applied. The data were not convolved with the hemodynamic response function (HRF), a box-car function was applied with an epoch length of 1 to the fMRI time series (12 acquisitions within each run), and no temporal derivatives were applied.[29]

Functional data from the three different time points (jitters) were combined for statistical analysis, thereby allowing for differences in the cerebrovascular peak between brain regions and between individuals.[30] Fixed effects analyses were conducted by combining the group data from all children and then contrasting the images from each condition using whole-brain, voxel-by-voxel *t* test comparisons.

PRELIMINARY RESULTS AND DISCUSSION

In an initial group analysis with 33 right-handed children,[30] mean performance scores were found to be approximately the same during the practice and scanner sessions (57% and 60%,[b] respectively; ns), demonstrating that the scanner environment did not have an adverse effect on performance. When images from each musical condition were contrasted with images from the silence condition, strong bilateral activation of the superior temporal gyrus (STG) was revealed during both melody and rhythm processing. No significant differences were found in direct contrasts between the rhythm and melody conditions, but in a region of interest analysis using the bilateral STG for a small volume correction, a small region in the right STG, slightly anterior and inferior to the primary auditory cortex, was found to show significantly higher activation for melody processing than rhythm processing (FWE, $P < .05$). Interestingly, this location has been identified as active during melodic tasks in several fMRI studies with adults.[32–34]

[b]The *different*/*same* ratio of the 8 phrase pairs per run was weighted so that a child detecting no differences and indicating *same* for every trial would score only 3/8 = 38%.

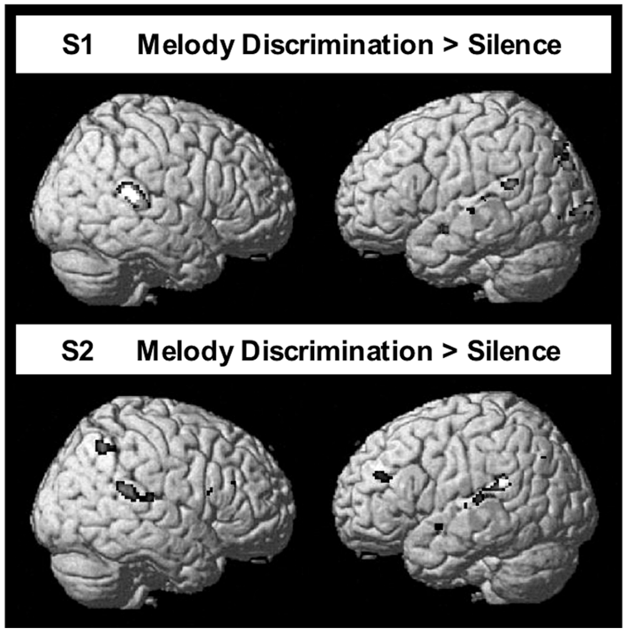

FIGURE 3. Example of images acquired during melody discrimination in scan 1 and scan 2 in one child; $P < .001$, uncorrected.

Preliminary data from the first five children to be rescanned after a year of musical training revealed that the children had improved considerably on the musical discrimination tasks (from a mean of 69% in scan 1 to a mean of 77% in scan 2, ns). Differences in neural activation between the two time points could also be identified, predominantly in the temporal lobes. No voxel-by-voxel statistical analyses were conducted with this small group, and thus no interpretation or conclusions can be made from these preliminary data. However, the results do indicate that our scanning protocol is effective: children were willing to return for a second scan, performance on the musical tasks improved, and differences in neural activation were revealed between scanning time points. For a visual example of the melody discrimination data acquired from one child at each time point, see FIGURE 3.

CONCLUSIONS

Our specially designed fMRI scanning protocol for examining music processing in young children proved extremely effective. The children were comfortable with the stimuli, understood the tasks, and did not become bored during the scanning session. A button press response was successfully used to monitor performance during scanning, and scores indicated that the MRI environment did not have an adverse effect on performance. The children particularly enjoyed certain aspects of the experience, such as the soft-toy puppies and receiving a CD-ROM with pictures of their own brain. The acquired fMRI data showed clear auditory activations and some evidence of differential specialization for melody and rhythm processing, while preliminary results from five children suggest that differences in neural activation patterns after a year of musical training can be revealed. Future analyses with larger numbers of both musically trained and untrained children will give the opportunity to differentiate normal developmental changes from those due to the effects of musical training.

In summary, we have described and demonstrated a useful methodology for examining the neural basis of musical processing in young children. It is hoped that these ideas and techniques will contribute toward providing a powerful tool with which to explore the enormous potential of music as an educational and therapeutic experience.

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[Competing interest: The authors declare that they have no competing financial interests.]

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