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Generation of novel motor sequences: The neural correlates of musical improvisation

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While some motor behavior is instinctive and stereotyped or learned and re-executed, much action is a spontaneous response to a novel set of environmental conditions. The neural correlates of both pre-learned and cued motor sequences have been previously studied, but novel motor behavior has thus far not been examined through brain imaging. In this paper, we report a study of musical improvisation in trained pianists with functional magnetic resonance imaging (fMRI), using improvisation as a case study of novel action generation. We demonstrate that both rhythmic (temporal) and melodic (ordinal) motor sequence creation modulate activity in a network of brain regions comprised of the dorsal premotor cortex, the rostral cingulate zone of the anterior cingulate cortex, and the inferior frontal gyrus. These findings are consistent with a role for the dorsal premotor cortex in movement coordination, the rostral cingulate zone in voluntary selection, and the inferior frontal gyrus in sequence generation. Thus, the invention of novel motor sequences in musical improvisation recruits a network of brain regions coordinated to generate possible sequences, select among them, and execute the decided-upon sequence.

Keywords: Motor sequences; Music; Selection; Improvisation; fMRI; Mirror neurons

Introduction

From the everyday movements of locomotion and speech to the adept actions of acrobats and athletes, the neuromuscular system is capable of producing a diverse array of motor sequences. Some motor sequences are executed automatically (e.g., reflexes), while other movements are learned and re-used. Other action sequences, however, must be spontaneously created by combining pre-existing, elemental movements to fit a unique set of environmental circumstances at a given moment in time. Previous neuroimaging work examining motor sequencing has studied the performance of pre-learned sequences (Roland et al., 1982; Catalan et al., 1998; Bengtsson et al., 2004), auditorily-cued sequences (Lewis et al., 2004), and visually-cued sequences (Harrington et al., 2000; Haaland et al., 2004; Bengtsson and Ullen, 2006), as well as sequence learning (Grafton et al., 1995, Müller, 2002; for reviews see Ivry and Helmuth, 2003; Janata and Grafton, 2003). However, to the best of our knowledge, the neurobiological basis of the generation of novel motor sequences has thus far not been studied.

Musical improvisation represents an ideal realm through which to study the neural bases of the invention of action sequences. In musical improvisation, musicians combine a finite collection of notes and rhythms to create a potentially infinite number of musical phrases that correspond to a particular musical idiom (for reviews see Pressing, 1988, 1998). In terms of cognitive processes, improvisation can be defined as the spontaneous generation, selection, and execution of novel auditory–motor sequences. Previous brain imaging studies in music cognition have largely focused on the brain mechanisms underlying music perception and processing (for reviews see Koelsch and Siebel, 2005; Peretz and Zatorre, 2005). The few published studies of musical production have been limited to performance of previously memorized (Parsons et al., 2005) or visually presented music (Sergent et al., 1992; Schön et al., 2002; Stewart, 2005; Bengtsson and Ullen, 2006); true production, that is, the real-time creation of novel music, has not to our knowledge been previously investigated with functional magnetic resonance imaging (fMRI).

We studied the neural activity during improvisation among highly trained pianist subjects in order to examine the neural basis of novel action sequencing. Specifically, we employed a 2×2 factorial design, varying melodic freedom (ordinal freedom, i.e., choice of pitch) and rhythmic freedom (temporal freedom, i.e., choice of duration) both separately and together (Fig. 1; see also

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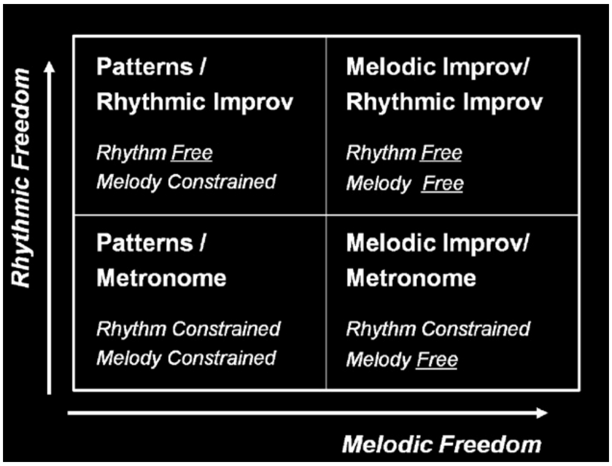

Fig. 1. Task design. Four conditions with varying degrees of rhythmic and melodic freedom.

Methods). Subjects either continuously invented and performed novel 5-note melodies on a 5-key piano-like keyboard (Melodic Improvisation) or played extremely simple pre-learned 5-note patterns in a random order (Patterns). In both Melodic Improvisation and Patterns conditions, subjects performed the task while either generating novel rhythms (Rhythmic Improvisation) or playing isochronously, with one note per beat synchronized with a metronome click every 500 ms (Metronome). These four conditions (see Methods for additional details) allowed for examination of melodic and rhythmic freedom separately, as well as the combined effect of freedom in both parameters. We were particularly interested in observing which areas were commonly activated by both rhythmic and melodic freedom, since such overlapping areas would ostensibly be involved in generation, selection, and execution of novel motor sequences most generally.

Methods

Subjects

We recruited 13 classically trained undergraduate pianists from the Dartmouth College Music Department (8 female, mean age = 21.9, mean musical training = 13 years piano experience). One subject's data were excluded due to excessive head movement, leaving a total of twelve participants in the final analyses.

Task

Prior to functional scanning, each subject was familiarized with the 5-key piano keyboard and the four tasks were explained. Subjects were told that they would see two types of task instructions, either "Make up melodies" or "Play patterns." For "Make up melodies," subjects were told to make up as many unique 5-note melodies as they could in each block. For "Play patterns," seven simple pattern sequences were demonstrated to each subject: five sequential presses of any key (CCCCC, DDDDD, etc.), a 5-note ascending scale (CDEFG), and a 5-note descending scale (GFEDC). Subjects were told that they could play the patterns in any random order of their choosing during "Play patterns" conditions. All subjects were able to immediately recall and demonstrate these patterns before scanning, suggesting that the simplicity of these patterns created no significant memory load. Subjects were told that in both conditions, they may or may not hear a metronome click. If the click was present, subjects were told to play one note of their patterns or made-up melodies with each click. If there was no click present, subjects were told that they should make up their own rhythms for the patterns or made-up melodies. Subjects were instructed to carefully follow only whether a click sound came through the headphones, and to ignore any regular clicking or beeping sounds made by the scanner.

During scanning, subjects performed the four different tasks with the right hand on a five-key piano-like keyboard (notes: C, D, E, F, G), and heard what they were playing through headphones in real time. In order to study the effects of different types of freedom on novel motor sequence generation, we varied constraints on note choice and rhythm across the four tasks (see Fig. 1): (1) *Patterns/Metronome* (note choice and rhythm both constrained): Subjects played any of the seven simple, pre-instructed 5-note patterns described above in any order of their choosing. Subjects played one note per beat coordinated with a 2-beats-per-second metronome click. (2) *Melodic Improvisation/Metronome* (note choice free, rhythm constrained): Subjects spontaneously invented and performed 5-note melodies with the metronome click. (3) *Patterns/Rhythmic Improvisation* (note choice constrained, rhythm free): Subjects played the 5-note patterns in (1) without metronome, continually making up novel rhythms for the patterns. (4) *Melodic Improvisation/Rhythmic Improvisation* (both note choice and rhythm free): Subjects improvised 5-note melodies as in (2), but with no metronome, allowing for rhythmic improvisation as well as melodic improvisation.

Design

A block design was used, and each subject performed 5 runs in which each of the 4 tasks was presented once. In each run, subjects performed each task once for 40 s with 30 s of rest between tasks. Task instructions ("Play patterns" and "Make up melodies") were presented onto a screen positioned for viewing in the scanner, and responses (notes) and metronome were heard through headphones. Response data was collected using e-Prime software (Psychological Software Tools, Pittsburgh, PA), recording each key press and the inter-press duration.

Stimulus delivery

Subjects performed the task on a 5-note response box resembling a five-key piano keyboard. Each key triggered the playing of a wave file of the given note by e-Prime software. We used the following five sequential notes: C (262 Hz; "middle C"), D (294 Hz), E (330 Hz), F (349 Hz), and G (392 Hz). The sounds were synthesized with an "acoustic piano sound" on Finale for Macintosh (MakeMusic, Inc., Eden Prairie, MN). These sounds were then delivered to the subject in real time at the moment of key press through MR-safe headphones. In metronome conditions, the metronome click was also presented through the headphones at 120 beats per minute, or one beat every 500 ms.

Imaging parameters

Functional and structural images were acquired in a 3T Phillips Intera Allegra whole-body MRI scanner using an 8-Channel Phillips Sense head-coil. A gradient echo-planar imaging T2*-sequence sensitive to blood-oxygenation level-dependent (BOLD) contrast was used to acquire functional images. Functional images