

Brain Processing of Meter and Rhythm in Music

Electrophysiological Evidence of a Common Network

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ABSTRACT: To determine cortical structures involved in “global” meter and “local” rhythm processing, slow brain potentials (DC potentials) were recorded from the scalp of 18 musically trained subjects while listening to pairs of monophonic sequences with both metric structure and rhythmic variations. The second sequence could be either identical to or different from the first one. Differences were either of a metric or a rhythmic nature. The subjects' task was to judge whether the sequences were identical or not. During processing of the auditory tasks, brain activation patterns along with the subjects' performance were assessed using 32-channel DC electroencephalography. Data were statistically analyzed using MANOVA. Processing of both meter and rhythm produced sustained cortical activation over bilateral frontal and temporal brain regions. A shift towards right hemispheric activation was pronounced during presentation of the second stimulus. Processing of rhythmic differences yielded a more centroparietal activation compared to metric processing. These results do not support Lerdhal and Jackendoff's two-component model, predicting a dissociation of left hemispheric rhythm and right hemispheric meter processing. We suggest that the uniform right temporofrontal predominance reflects auditory working memory and a pattern recognition module, which participates in both rhythm and meter processing. More pronounced parietal activation during rhythm processing may be related to switching of task-solving strategies towards mental imagination of the score.

KEYWORDS: rhythm processing; meter processing; musicians; brain activation; local and global processing

INTRODUCTION

In contrast to pitch or melody processing, relatively few neurobiological investigations have been concerned with processing of musical time structures. These studies have yielded contradictory results. Besides the fact that various methods were

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applied and different populations with respect to musical expertise were investigated, inconsistent definitions of “musical time structures” may have contributed to these discrepancies. With respect to temporal structures, for example, three levels of organization may be distinguished: meter, pulse (grouping), and rhythm. Rhythm is defined as the serial relation of durations between different acoustical events in a train of sounds, that is, rhythm represents a serial durational pattern, whereas pulse or grouping is based on gestalt principles and depends, among other physical characteristics, on the relative proximity in time of sound events.¹ Meter, in contrast, involves a temporal invariance in terms of the regular recurrence of pulses marking off equal durational units, which can be organized as measures. Meter, therefore, represents a more complex acoustical gestalt, because its perception and production require information on sound intensity (accented and unaccented events) and on periodicity of rhythmic events, the latter based on integration of information over longer time periods. Perception and creation of meter are a prerequisite of the musician’s ability to make music “swing.”

The cerebral mechanisms underlying the processing of rhythm and meter are largely unknown. In a group of patients with unilateral right- or left-hemispheric brain damage, Peretz² found spared metric judgment in the presence of disrupted rhythmic discrimination, irrespective of whether the right or left hemisphere was lesioned. In a more recent investigation of 65 patients who had undergone unilateral temporal cortectomy for the relief of intractable epilepsy, this dissociation between rhythmic and metric judgment was confirmed.³ For meter processing, a critical involvement of the anterior part of the superior temporal gyrus was found, whereas rhythm processing seemed to rely more on the posterior parts of the right superior temporal gyrus. In a very elegant multimodal auditory and visual paradigm, Penhune *et al.*⁴ demonstrated in chronic epileptic patients a modality-specific dissociation with isolated involvement of the anterior secondary auditory areas in the right temporal lobe during processing of acoustically presented time structures. In an earlier study,⁵ we investigated 20 patients who had had small unilateral cerebrovascular cortical lesions. Using a discrimination paradigm similar to the test published by Peretz,² processing of acoustically presented rhythms and meters was assessed. Detailed analysis of the individual patterns of neuropsychological deficits revealed a hierarchical organization, with an initial right-hemisphere recognition of meter followed by identification of rhythm via left-hemisphere subsystems. In addition, individual aspects of musicality and musical behavior as well as musical knowledge contributed to the formation of neuronal subsystems underlying the perception of musical time structures.

With respect to the functional anatomy of rhythm processing in normal subjects, new studies exist. Patel *et al.*⁶ investigated brain activation with the PET technique during regularly and irregularly presented series of tones. They found a pronounced involvement of the left frontal Broca region and concluded that language processing and rhythm processing might be closely related to each other. Contradictory results emerged from a PET study by Penhune *et al.*,⁷ testing the perception and reproduction of regular isochronous or complex novel time structures in both the auditory and the visual modality. Auditory perception of rhythm produced an activation of the right planum temporale. Because the design of the study additionally required production of rhythms, activation of the somatosensory cortices and of the cerebellar hemispheres was demonstrated. In an fMRI work, processing of simple (1:2, 1:3,

1:4) and complex (1:2.5, 1:3.5) time relationships was compared.⁸ Simple rhythmic relationships yielded activation of left prefrontal and parietal brain areas, whereas complex relationships were processed in right prefrontal, premotor, and parietal regions. Although not discussed by the investigators, the results can be interpreted in the light of Lerdhal and Jackendoff's two-component model.⁹ According to their model, rhythm and meter sense rely on two different cognitive operations, which may be processed in different hemispheres: processing of rhythm requires a left-hemispheric "local"-level, serial cognitive operation; processing of meter a right-hemispheric "global"-level, holistic strategy linked to grouping or chunking mechanisms. Applied to the fMRI experiment, simple rhythmic relationships can be understood as "local tasks," because they are accessible for analytic and sequential "counting" strategies. By contrast, this processing mode is not accessible for perception of the complex stimuli, which therefore had to be analyzed in a holistic way as auditory gestalt.

Summarizing the results of lesion and brain imaging studies, a puzzling and in many instances contradictory variety of findings emerged. The present study attempts to contribute to the clarification of the neuronal substrates of the processing of musical time structures. To assess cortical activation patterns during processing of musical time structures, the topographic distribution of sustained surface negative DC-potential shifts was recorded using scalp electrodes. Because these DC potentials reflect activation of the underlying cortex,¹⁰ their local distribution reveals task-specific patterns that correspond to the brain structures specifically involved in the processing of the respective task.

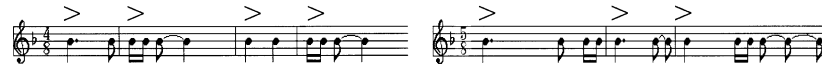
METHODS

Subjects and Stimuli

With respect to findings indicating that cortical activation patterns during music processing may be influenced by musical expertise,¹¹ only trained musicians were included in the present study: 18 experienced right-handed musicians (10 males, 8 females) with at least 5 years of formal musical training were included. They either played a melodic instrument (violin, viola, violoncello, and clarinet), piano, or sang in a semiprofessional choir. None of the participants played percussion. Subjects were between 21 and 39 years of age (mean 25.5).

In a same-different paradigm, subjects had to rate whether two subsequent acoustic time sequences of 4 seconds' duration each, were same or different. Each stimulus pair consisted of two monophonic sequences, sampled as MIDI piano sounds and played at the pitch of one-line b flat (for an example, see FIG. 1). Stimuli were structured in time and in intensity of the beats. They consisted of sequences of notes with "regular" temporal intervals. The temporal sequences of subsequent notes were composed of 1:2, 2:1, 1:3, 3:1, 1:4, 4:1 ratios, or, expressed in musical terms, of classical time values of notes such as crochets, quavers, triplets, and semiquavers. Intensity variations were interspersed at regular time intervals to produce the perception of an underlying regular (metric) pulsation. The second stimulus was either identical to the first or differed with respect to its rhythmic or metric structure. In the meter condition, the occurrence of the marked notes was shifted to a different meter,

Stimuli



Meter

changed



Rhythm

changed

FIGURE 1. Examples of pairs of stimuli used for the “meter” (*upper row*) and the “rhythm” (*lower row*) condition.

changing for example a 4/8 meter into a 5/8 meter (see example in FIG. 1, upper row). In the rhythm condition, single notes were changed in value without affecting the underlying metric structure (see example in FIG. 1, lower row).

Tasks and Procedures

Subjects were seated comfortably in a dimly lit and acoustically shielded room. Stimuli were delivered via stereo speakers 1.5 m in front of the subjects, set at a comfortable sound level of 72 dBA measured at the listener’s position. To minimize artifacts in the EEG recordings, subjects were requested to fix their gaze on a fixation point displayed on a 14-inch monitor in front of them and to avoid body movements or vocalizations while performing the tasks.

Subjects began each trial by pressing a button on a keyboard as soon as they felt ready. After a randomized time interval of 1,000–1,500 ms, the first stimulus was delivered, followed by a 2-second break and the subsequent second stimulus. Two seconds after presentation of both stimuli, subjects had to press one of two keys on the keyboard, indicating either a “same” or a “different” judgment of the stimuli delivered previously. Button presses were randomly balanced executed with the right/left hand. A total of 160 pairs of stimuli were presented. In the rhythm condition, 40 stimulus pairs were identical and 40 were different, and in the meter condition accordingly 40 pairs were identical and 40 were different. After the experiment (total duration about 2 hours), subjects filled in a questionnaire concerning eventual task-solving strategies (verbal, e.g., “counting” vs holistic, nonverbal strategies).

Data Acquisition and Data Analysis

DC potentials were recorded from 32 electrodes positioned according to the modified 10/20 system over left and right frontal, central, temporal, parietal, and occipital brain regions. Linked mastoid electrodes served as a reference. Impedance was reduced to less than 1 kOhm. To control artifacts arising from eye movements, the electrooculogram (EOG) was obtained. The frequency band of amplification ranged from DC to 100 Hz. Sampling rate was 200 Hz (SynAmps-Amplifier).

Each data-sampling epoch lasted 12 seconds. Baseline correction was performed offline, and trials contaminated by artifacts were excluded from further analysis. For each of the two conditions, about 30 artifact-free trials were averaged per subject. Based on the individual averages, grand averages across all subjects were derived. For selected time intervals, mean amplitudes of DC shifts referenced to baseline were calculated. Analyses of brain activation during processing of the first and the second stimulus were performed on the mean amplitude of DC-EEG evoked between the 2,000 and 4,000 ms after beginning of the stimulus. The first second of either stimulus presentation was excluded from analysis, because unspecific EEG components related to arousal and orientation occur in this time interval.

Data were subjected to MANOVA using the software packet "Statistica." A within-subjects factor Task (2 levels: rhythm vs meter) was tested. For correction of violations of the sphericity assumption, the Huynh-Feldt epsilon was used. Only those variables that after correction showed significant ($P < 0.01$) main effects or significant interaction terms were further analyzed using the appropriate T test. Because this procedure applies multiple T tests, the P values were Bonferroni adjusted. To further analyze the spatial origin of significance between means of the two conditions, electrodes were grouped according to regions of interests and contrasted against each other.

RESULTS

Behavioral Results and General Course of DC Potentials

On average, 69% of the tasks were answered correctly. There was no significant difference in the responses to metric (71% correct) or rhythmic (68% correct) variations. Differences between both types of tasks are therefore not attributable to different levels of difficulty.

The general course of the DC potential shifts is shown in FIGURE 2. A characteristic biphasic negative-going plateau-like shift reflects the presentation of the two stimuli. Maximal amplitudes can be detected over anterior frontotemporal and central electrode positions.

In FIGURE 3, the values of DC potential amplitudes are visualized topographically. In both stimulus conditions, maximal activation occurred over frontotemporal brain regions. The mean amplitudes during the second period are displayed in FIGURE 4. The second stimulus yielded an additional increase in amplitude in all electrode positions and a more pronounced lateralization towards the right frontotemporal brain areas.

DC-EEG

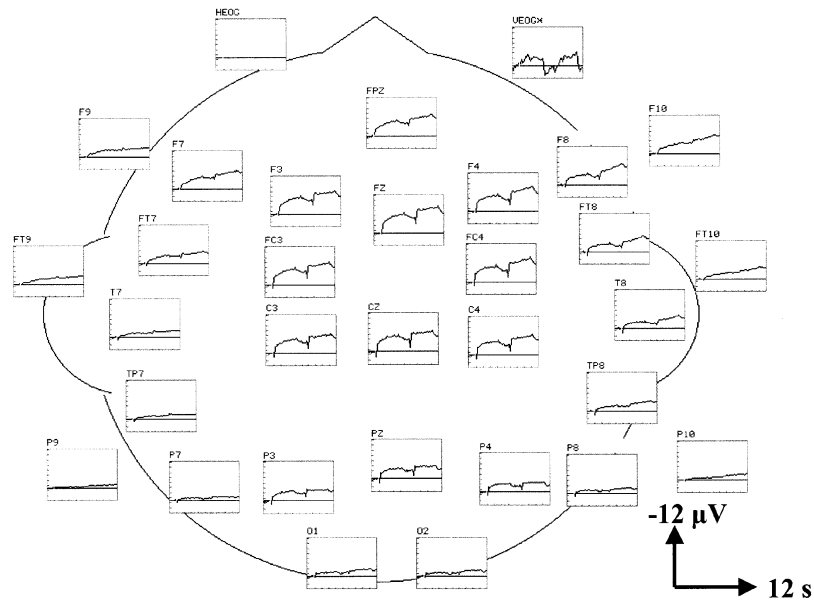


FIGURE 2. Grand average of all subjects during the “rhythm” condition displayed topographically. Each of the small rectangular insets represents DC potential shifts in one electrode position. Shown are slow potential shifts during 12 seconds, including 1-second baseline, 4-second presentation of the first stimulus, 2-second pause, and subsequent 4-second presentation of the second stimulus and 1-second postperiod. Averages obtained from electrodes over the left hemispheres are on the left side, those from the right hemisphere on the right side. Stimulation produces a widespread biphasic increase in surface-negative DC potential shift, with maximal amplitudes over bilateral frontocentral brain regions.

Results of Statistical Testing

Since the main factor Task was highly significant ($P < 0.01$), testing was continued using contrast analysis. Contrast analysis revealed that both rhythm and meter processing produced increased activation over the right frontotemporal regions (electrodes F4, F8, Fc4, F10, FT10, FT8, T8, $P = 0.001$). When contrasting rhythm versus meter processing, the first stimulus presentation did not reveal any differences, because stimuli were identical in nature. However, during the second presentation of paired stimuli, rhythmic alterations produced a more pronounced activation over centroparietal brain regions (Cz, Pz, C4, C3, P4, P3, TP7, TP8, P7, P8, $P < 0.001$), as shown in the difference plots displayed in FIGURE 5.

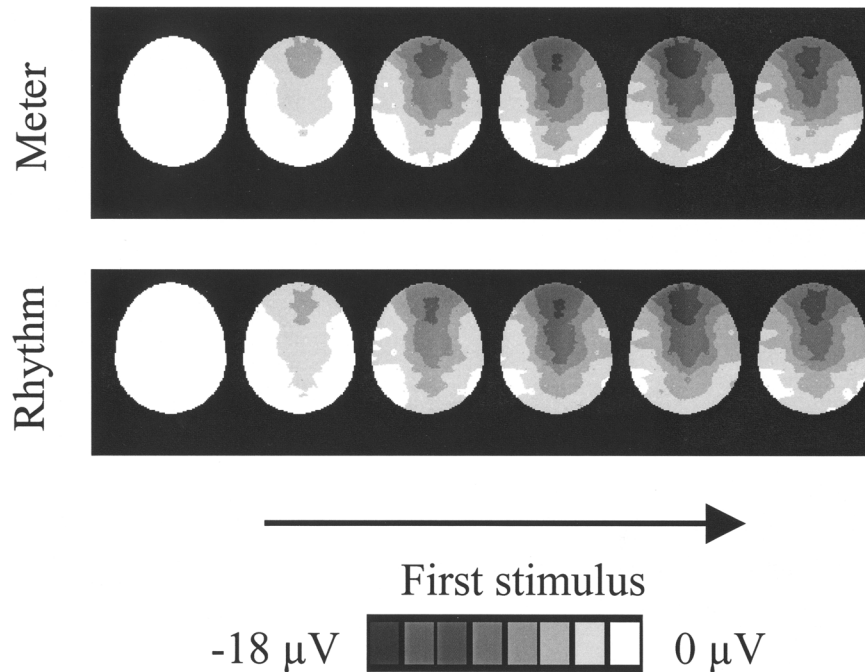


FIGURE 3. Brain maps representing meter (*upper row*) and rhythm (*lower row*) processing during the first stimulus presentation. Grand averages over all subjects are displayed topographically. Each diagram represents mean activation during 1 second, beginning with the baseline period. The subsequent four diagrams represent the 4 seconds of stimulus presentation. Activation is dark, inhibition is white (see microvolt scale). Brain diagrams are displayed as *top views*, frontal regions *up*, left hemisphere on the *left*, and right hemisphere on the *right*. As can be recognized, both meter and rhythm processing produce a prefrontal, frontal, and bilateral temporal activation pattern with only subtle lateralisation towards the right hemisphere.

DISCUSSION

To our knowledge, this is the first systematic study directly comparing cortical activation patterns during processing of local and global acoustically presented time structures. As local processing, we consider the auditory tracing of a single event in time in contrast to global processing, which in the present paradigm relies on the integration and detection of accents over a longer time span. The main results can be summarized as follows:

Processing of musical time structures produces sustained cortical activation, especially over frontotemporal brain regions with right hemispheric preponderance.

Processing of rhythmic differences yields more centroparietal activation compared to metric processing.

During processing of both metric and rhythmic stimuli, predominant right frontotemporal activation occurred. This lateralization effect was less pronounced during

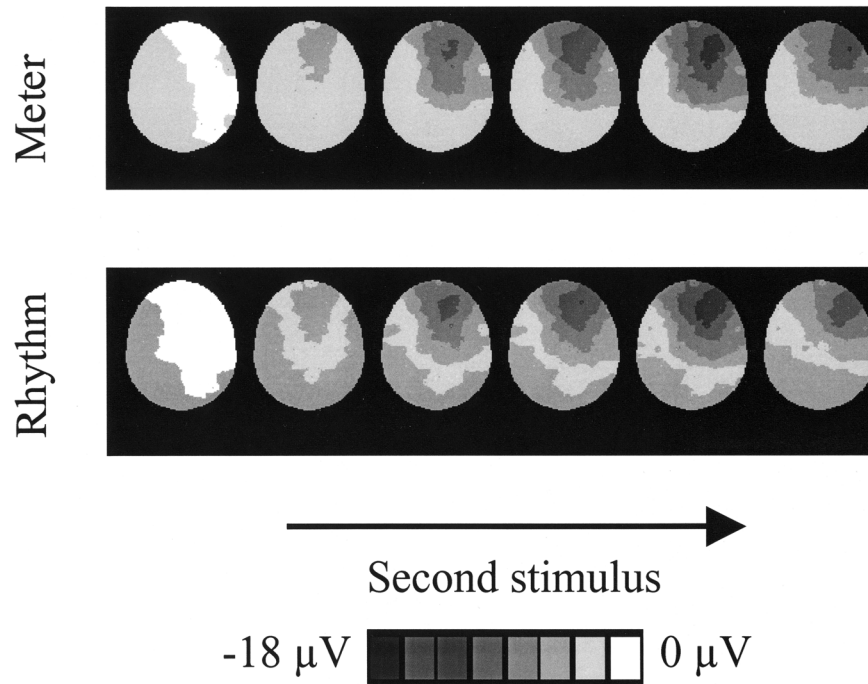


FIGURE 4. Brain maps representing meter (*upper row*) and rhythm (*lower row*) processing during the second stimulus presentation. Same conventions as in FIGURE 3. Compared to FIGURE 3, demonstrating brain activity during the encoding of the first stimulus, retrieval and comparison of the second stimulus produce even more electronegativity, with right-hemispheric lateralization. Rhythm processing produces a more pronounced activation over posterior parietal regions.

the encoding phase, when subjects listened to the first stimulus, and more pronounced during recall and comparison when subjects were exposed to the second stimulus. This result does not fit into Lerdhal and Jackendoff's two-component model,¹ predicting a dissociation of left-hemispheric rhythm and right-hemispheric meter processing. It should be mentioned in this context that up to now lesion studies investigating separately rhythm or meter processing equally failed to clearly demonstrate such a dichotomy.^{3,4,6}

In contrast to the pronounced local/global dichotomies observed in the visual modality (for a review see Ref. 12), auditory perception seems to be organized in a more complex manner. According to Zatorre and Belin,¹³ the left hemisphere auditory cortex is specialized for rapid temporal processing, whereas the right temporal lobe is specialized for spectral processing. These differences may be related to anatomic asymmetries in myelination and spacing of cortical columns in both hemispheres. In the present study, processing of time structures was more characterized by integration over time and pattern recognition than by rapid temporal processing (e.g., as it is required in language comprehension). We therefore suggest that the

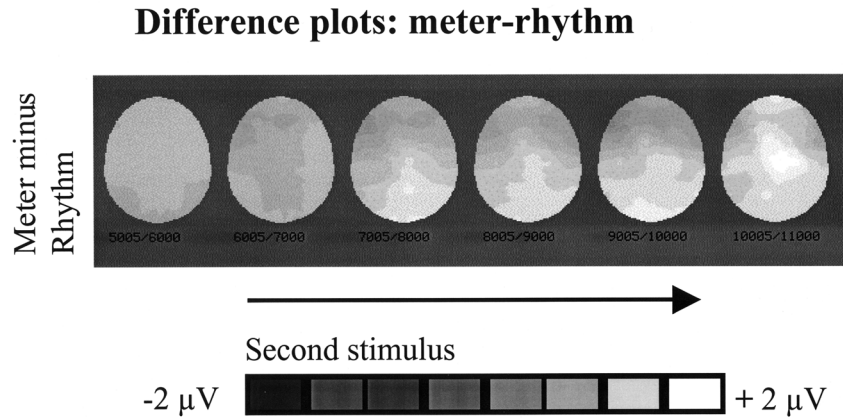


FIGURE 5. Difference plots, obtained after subtracting activation during rhythm processing from activation during meter processing. Only minor differences can be recognized. The *bright area* over posterior regions corresponds to relatively higher activation during rhythm processing in parietal brain areas.

right temporofrontal predominance reflects auditory working memory and a pattern recognition module, which is participating in both rhythm and meter processing.

A surprising finding was the more pronounced parietal activation during rhythm processing. Although several brain imaging studies have demonstrated activity in the parietal lobe during temporal processing of music,^{9,14} this finding was never commented in detail. From studies investigating musical auditory imagery,^{15,16} it is known that mental imagery of a musical score produces a similar parietal activity. We could speculate that during the rhythm condition subjects switched their task-solving strategy and relied to a greater extent on their inner eye and their mental imagination of the score. However, as a posthoc speculation, not reflected in the questionnaires filled in by our subjects, this finding remains to be verified in a prospective study designed to control this variable.

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REFERENCES

1. DRAKE, C. 1998. Psychological processes involved in the temporal organization of complex auditory sequences: universal and acquired processes. *Music Percept.* **16**: 11–26.
2. PERETZ, I. 1990. Processing of local and global musical information by unilateral brain-damaged patients. *Brain* **113**: 1185–1205.

3. LIÉGEOIS-CHAUVEL, C., I. PERETZ, M. BABAI, *et al.* 1998. Contribution of different cortical areas in the temporal lobes to music processing. *Brain* **121**: 1853–1867.
4. PENHUNE, V.B., R.J. ZATORRE & W.H. FEINDEL. 1999. The role of auditory cortex in retention of rhythmic patterns as studied in patients with temporal lobe removals including Heschl's gyrus. *Neuropsychologia* **137**: 315–331.
5. SCHUPPERT, M., T.F. MÜNTE, B.M. WIERINGA, *et al.* 2000. Receptive amusia: evidence for cross-hemispheric neural networks underlying music processing strategies. *Brain* **123**: 546–559.
6. PATEL, H., C. PRICE, J.C. BARON, *et al.* 1997. The structural components of music perception. A functional anatomical study. *Brain* **120**: 229–243.
7. PENHUNE, V.B., R.J. ZATORRE & A.C. EVANS. 1998. Cerebellar contributions to motor timing: a PET study of auditory and visual rhythm reproduction. *J. Cognit. Neurosci.* **10**: 752–765.
8. SAKAI, K., O. HIKOSAKA, S. MIYAUCHI, *et al.* 1999. Neural representation of rhythm depends on its interval ratio. *J. Neurosci.* **19**: 10074–10081.
9. LERDAHL, F. & R. JACKENDOFF. 1983. *A Generative Theory of Tonal Music*. MIT Press. Cambridge.
10. ALTENMÜLLER, E. & C. GERLOFF. 1998. Psychophysiology and EEG. *In* *Electroencephalography*. E. Niedermeyer & F. Lopes da Silva, Eds. :637–655. Williams & Wilkins. Baltimore.
11. SCHLAUG, G. 2001. The brain of musicians: a model for functional and structural adaptation. *In* *The Biological Foundations of Music*. R.J. Zatorre & I. Peretz, Eds. Ann. N.Y. Acad. Sci. **930**: 281–299.
12. IVRY, R.B. & L.C. ROBERTSON. 1998. *The Two Sides of Perception*. MIT Press. Cambridge, MA.
13. ZATORRE, R.J. & P. BELIN. 2001. Spectral and temporal processing in human auditory cortex. *Cereb. Cortex* **11**: 946–953.
14. BROCHARD, R., A. DUFOUR, C. DRAKE, *et al.* 2000. Functional brain imaging of rhythm perception. *In* *ICMPC6 Proceedings*. C. Woods, G. Luck, R. Brochard, *et al.*, Eds. Keele University. UK.
15. BEISTEINER, R., E. ALTENMÜLLER, W. LANG, *et al.* 1994. Musicians processing music: measurement of brain potentials with EEG. *Eur. J. Cognit. Psychol.* **6**: 311–327.
16. NAKADA, T., Y. FUJII, K. SUZUKI, *et al.* 1998. “Musical brain,” revealed by high-field (3 Tesla) functional MRI. *Neuroreport* **9**: 3853–3856.