



저작자표시-비영리-변경금지 2.0 대한민국

이용자는 아래의 조건을 따르는 경우에 한하여 자유롭게

- 이 저작물을 복제, 배포, 전송, 전시, 공연 및 방송할 수 있습니다.

다음과 같은 조건을 따라야 합니다:



저작자표시. 귀하는 원저작자를 표시하여야 합니다.



비영리. 귀하는 이 저작물을 영리 목적으로 이용할 수 없습니다.



변경금지. 귀하는 이 저작물을 개작, 변형 또는 가공할 수 없습니다.

- 귀하는, 이 저작물의 재이용이나 배포의 경우, 이 저작물에 적용된 이용허락조건을 명확하게 나타내어야 합니다.
- 저작권자로부터 별도의 허가를 받으면 이러한 조건들은 적용되지 않습니다.

저작권법에 따른 이용자의 권리는 위의 내용에 의하여 영향을 받지 않습니다.

이것은 [이용허락규약\(Legal Code\)](#)을 이해하기 쉽게 요약한 것입니다.

[Disclaimer](#)

이학박사 학위논문

Expectation in Music

: Electromagnetic studies on Harmony, Melody, and Beat

음악에서의 기대감

: 화성, 선율, 박에 대한 전자기학적 연구

2020년 2월

서울대학교 대학원

협동과정 뇌과학 전공

김 찬 희

Expectation in Music

: Electromagnetic studies on Harmony, Melody, and Beat

지도교수 정 천 기

이 논문을 이학박사 학위논문으로 제출함

2019년 12월

서울대학교 대학원

협동과정 뇌과학 전공

김 찬 희

김찬희의 이학박사 학위논문을 인준함

2019년 12월

위원장 이 석 원 (인)

부위원장 정 천 기 (인)

위원 김 상 정 (인)

위원 최 세 영 (인)

위원 이 경 면 (인)

Expectation in Music

: Electromagnetic studies on Harmony, Melody, and Beat

Chan Hee Kim

Interdisciplinary Program in Neuroscience

The Graduate School

Seoul National University

**A Thesis Submitted to the Faculty of Interdisciplinary Program in
Neuroscience, in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy in Science at the Seoul National
University, Seoul, Korea**

December 2019

Approved by Thesis Committee

Chairman	Suk Won Yi
Vice-chairman	Chun Kee Chung
Member	Sang Jeong Kim
Member	Se-Young Choi
Member	Kyung Myun Lee

ABSTRACT

Expectation in Music

: Electromagnetic studies on Harmony, Melody, and Beat

Chan Hee Kim

Interdisciplinary Program in Neuroscience

The Graduate School

Seoul National University

When listening to music, we can perceive a signal from music, such as harmony, melody, pitch, tonality, rhythm, and beat. The musical signals arouse an expectation. Musical expectation implied in harmony and melody can be usually explained in a hierarchical model based on tonal structure. However, in this doctoral dissertation, I would like to propose a hierarchical model based on not tonal structure but temporal dimension. That is, because musical expectation continuously changes along with “moments” which musical signals are presented, the moments that a musical signal arouses an expectation are synchronized on “beat” of the musical stimuli.

In this doctoral dissertation, magnetoencephalography (MEG) studies focusing on harmonic and melodic expectation and intracranial electroencephalogram (iEEG) study focusing on temporal expectation were analyzed based on the “beats” which

an expectation was aroused. In the MEG studies, connectivity strength for the unexpected signals was higher than for the expected signals. These connectivities involved both superior temporal gyrus involving auditory area and inferior frontal gyrus associated with auditory signals and expectation processes. The iEEG study using beat signal shows that expectation on regularly presented beats elicit ERP in auditory area, and that the sinusoidal signals reflecting beat sense were observed in the brain regions excluding auditory area.

Given the MEG and iEEG studies together, I propose that expectation in music, in the perspective of temporal dimension, would be based on hierarchical model for melody and harmony interrelated with beat, and that can be explained based on “hierarchical model for processing melody, harmony, and beat”.

Keywords: Expectation, Harmony, Melody, Beat, Auditory area, Superior temporal gyrus (STG), Inferior frontal gyrus (IFG), Magnetoencephalography (MEG), intracranial Electroencephalogram (iEEG)

Student number: 2013-30122

CONTENTS

Abstract	i
Contents	iii
List of Abbreviations	iv
List of Figures	v
List of Tables	vi
Chapter 1. Introduction	1
Chapter 2. Harmony	4
STUDY I. Change in left inferior frontal connectivity with less unexpected harmonic cadence by musical expertise	4
STUDY II. Dissociation of connectivity for syntactic irregularity and perceptual ambiguity in musical chord stimuli	32
Chapter 3. Melody	53
STUDY III. Increased fronto-temporal connectivity by modified melody in real music	53
Chapter 4. Beat	68
STUDY IV. Auditory beats evoke coherent widespread brain oscillations	68
Chapter 5. General discussion	84
References	86
Abstract in Korea	97

LIST OF ABBREVIATIONS

- ANOVA, analysis of variance**
- CR, correct rate**
- ECD, equivalent current dipole**
- EOG, electrooculograms**
- ELAN, early left anterior negativity**
- ERAN, early right anterior negativity**
- ERANm, magnetic counterpart of ERAN**
- ERP, event related potential**
- GOF, goodness of fit**
- HG, Heschl's gyrus**
- iEEG, intracranial electroencephalogram**
- IFG-LTDMI, LTDMI values from the right to the left IFG**
- IFG, inferior frontal gyrus**
- LTDMI, linearized time delayed mutual information**
- MEG, magnetoencephalography**
- MI, mutual information**
- P2m, magnetic counterpart of P2**
- PDC, partial directed coherence**
- SM, submediant**
- sPDC, summation of PDC values**
- sPDC_i, inflows to each area**
- sPDC_o, outflows from each area**
- ST, supertonic**
- STG-LTDMI, LTDMI values from the right to the left STG**
- STG, superior temporal gyrus**
- T, tonic**
- VMM, variations with modified melody**
- VOM, variations with original melody**

LIST OF FIGURES

Figure 1-1. Hierarchical model on musical expectation based on key structural dimension.....	1
Figure 2-1-1. Musical stimuli.....	7
Figure 2-1-2. The grand mean dipole source for music-majors and non-music-majors.....	11
Figure 2-1-3. Group difference in the correct rate.....	15
Figure 2-1-4. Group difference in the PDC.....	22
Figure 2-1-5. Hemisphere difference and Condition difference in the PDC....	23
Figure 2-1-6. Flow difference in the PDC.....	27
Figure 2-2-1. Musical stimuli and experimental paradigm.....	36
Figure 2-2-2. Mean dipole source locations of all participants in the bilateral IFGs and STGs, and the time window.....	43
Figure 2-2-3. Difference in the LTDMI values for the three conditions.....	46
Figure 2-2-4. Correlation between CR and STG-LTDMI/IFG-LTDMI.....	48
Figure 3-1. Musical stimuli.....	56
Figure 3-2. Difference in effective connectivity from the left IFG to the right HG for the modified and original melodies.....	62
Figure 4-1. Auditory stimuli.....	70
Figure 4-2. Oscillations by auditory beats.....	72
Figure 4-3. Difference waveforms for 9 patients.....	73
Figure 4-4. MMNs in Strong-omission and Weak-omission for 5 patients.....	77
Figure 4-5. Sinusoidal signals for 8 patients.....	78
Figure 5-1. Hierarchical model on musical expectation based on temporal dimension.....	85

LIST OF TABLES

Table 2-1-1. Four-way repeated measures ANOVA for the factors of Condition, Group, Site and Hemisphere	19
Table 2-1-2. <i>Post hoc</i> for Group factor in four-way repeated measures ANOVA	20
Table 2-1-3. <i>Post hoc</i> for Hemisphere factor in four-way repeated measures ANOVA.....	21
Table 2-1-4. <i>Post hoc</i> for Condition factor in four-way repeated measures ANOVA.....	24
Table 2-1-5. Three-way repeated measures ANOVAs for the factors of Condition, Group, and Flow, and <i>post hoc</i> results	25
Table 2-2-1. <i>Post hoc</i> one-way repeated measures ANOVAs results of the LTDMI for the Condition factor in 12 connections	45
Table 3-1. LTDMI difference between the conditions with the modified or original melodies	63
Table 4-1. Areas responded to MMN and 2Hz oscillation based on Figure 4-3	80

CHAPTER 1. INTRODUCTION

The term expectation in music has a history going back to Lenard B. Meyer's "Emotion and meaning in music" (Meyer, 1956) describing the relation between musical expectation and emotional responses, published in 1956. In 1986, Mireille Besson found that congruous and incongruous terminal notes in well-known French melody elicit distinctive event related potentials (ERPs) in the human brain (Besson and Macar, 1987). Aniruddh Patel, in 1998, suggested that the ERP of P600 is modulated by target chords of same, nearby, and distance keys in harmonic sequence, based on the circle of fifth (Patel, 1998). Stafan Koelsch, in 2000, addressed that incongruent cadence in terms of harmonic syntax, evokes early right anterior negativity (ERAN) (Koelsch et al., 2000), which is comparable to early left anterior negativity (ELAN) reflecting language syntactic error. Musical expectation across these studies would be explained based on "hierarchical model for processing melody, harmony, and key", proposed by Willian F. Thompson (Thompson, 1993) (Figure 1-1). In this model, expectation in melody and harmony is interrelated with key structure.

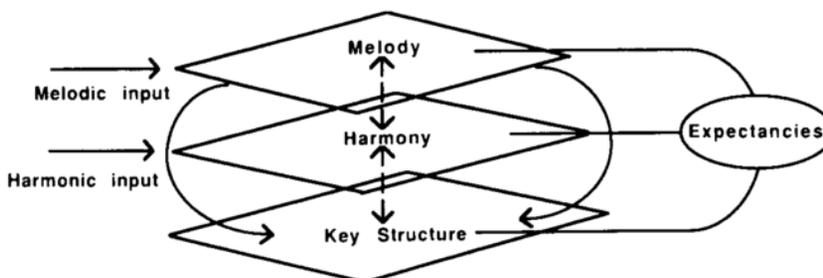


Figure 1-1. Hierarchical model on musical expectation based on key structural dimension (Thompson, 1993)

In this doctoral dissertation, I would like to propose a different way of viewing of musical expectation. This doctoral dissertation includes four experimental studies based on musical expectation, which is described in the ways of three fundamental musical elements – Harmony, Melody and Beat. In Chapter II. Harmony, two magnetoencephalography (MEG) studies are based on the same data set. STUDY I shows, among congruent, less incongruent, and incongruent harmonic cadences, a deceptive cadence of “less incongruent” is differently interpreted for music-majors with musical expertise compared to non-music-majors. STUDY II suggests that incongruent harmonic cadence process reflected in interhemispheric connection between the bilateral inferior frontal gyri (IFGs), generator of ERAN, is separate with identification of perceptual ambiguity between the cadences reflected in interhemispheric connection between the bilateral superior temporal gyri (STGs). In Chapter III. Melody, STUDY III, an MEG study, demonstrates that the brain connectivity on expectation violations of motivic regularity in melody is modulated based on a well-known French song in Mozart Variation. In Chapter IV. Beat, STUDY IV suggests that endogenous sense on beat is distinct from perception of auditory beat as input stimuli, which is processed in separate areas with distinctive intracranial EEG (iEEG) signals.

Musical expectation across these four studies is based on not key structural dimension but temporal dimension, even though harmonic and melodic violations are also included in these studies as Thompson’s model. Ultimately, through this doctoral dissertation, I aim to examine how musical expectation in the perspective

of temporal dimension is interrelated with melody, harmony, and beat and to propose new hierarchical model.

CHAPTER 2. HARMONY

STUDY I. Change in left inferior frontal connectivity with less unexpected harmonic cadence by musical expertise¹

Abstract

In terms of harmonic expectancy, compared to an expected dominant-to-tonic and an unexpected dominant-to-supertonic, a dominant-to-submediant is a less unexpected cadence, the perception of which may depend on the subject's musical expertise. The present study investigated how aforementioned 3 different cadences are processed in the networks of bilateral inferior frontal gyri (IFGs) and superior temporal gyri (STGs) with magnetoencephalography. We compared the correct rate and brain connectivity in 9 music-majors (mean age, 23.5 ± 3.4 years; musical training period, 18.7 ± 4.0 years) and 10 non-music-majors (mean age, 25.2 ± 2.6 years; musical training period, 4.2 ± 1.5 years). For the brain connectivity, we computed the summation of partial directed coherence (PDC) values for

¹Kim, C.H., Kim, J.S., Choi, Y., Kyong, J.S., Kim, Y., Yi, S.W., and Chung, C.K. (2019). Change in left inferior frontal connectivity with less unexpected harmonic cadence by musical expertise. *PloS one* 14, e0223283. (<https://doi.org/10.1371/journal.pone.0223283>); Received: May 27, 2019; Accepted: September 17, 2019; Published: November 12, 2019

inflows/outflows to/from each area (sPDC_i/sPDC_o) in bilateral IFGs and STGs. In the behavioral responses, music-majors were better than non-music-majors for all 3 cadences ($p < 0.05$). However, sPDC_i/sPDC_o was prominent only for the dominant-to-submediant in the left IFG. The sPDC_i was more strongly enhanced in music-majors than in non-music-majors ($p = 0.002$, Bonferroni corrected), while the sPDC_o was vice versa ($p = 0.005$, Bonferroni corrected). Our data show that music-majors, with higher musical expertise, are better in identifying a less unexpected cadence than non-music-majors, with connectivity changes centered on the left IFG.

Introduction

Humans exposed to Western tonal music can expect a tonic after a dominant at the end of musical pieces. Compared to a dominant-to-tonic of an “expected” condition, a dominant-to-supertonic is an “unexpected” condition, therefore eliciting an early right anterior negativity (ERAN) in previous studies (Kim et al., 2014; Kim et al., 2011; Koelsch and Jentschke, 2008). The ERAN for the unexpected condition is commonly observed both in musicians and non-musicians alike (Kim et al., 2011; Koelsch et al., 2000). In contrast, the dominant-to-submediant lies in between the “expected” and “unexpected”, thus could be called as “less unexpected”, without eliciting the ERAN of the unexpected condition (Kim et al., 2014; Kim et al., 2011). The conditional probability (Rohrmeier, 2007), of the different chords following the dominant is 0.752 for tonic, 0.106 for submediant, and 0.043 for supertonic.

The “Do Mi” in a tonic comprising of “Do Mi Sol” is also included in a submediant of “Ra Do Mi”. Since a dominant-to-submediant may sound similar to a dominant-to-tonic, it is called a deceptive cadence (Murphy and Stringham, 1951; Piston and DeVoto, 1987). In a musical piece, the deceptive cadence functions as delaying the eventual resolution to a tonic in an authentic cadence, adding suspense, and leading to longer sustained anticipation for the moment of resolution. However, the identification of dominant-to-submediant may depend on people’s musical expertise, since the difference between dominant-to-tonic and dominant-to-submediant is subtle.

The hypothesis examined in the present study is whether people with musical expertise (music-majors) are better in identification of dominant-to-submediant with specific brain connectivity change than people without it (non-music-majors). We measured behavioral response and brain connectivity with 3 different harmonic cadences of dominant-to-tonic, dominant-to-submediant, and dominant-to-supertonic in 4th and 5th chords in sequences of five chords (Figure 2-1-1).

For the brain connectivity, we used partial directed coherence (PDC) (Baccala and Sameshima, 2001), multivariate measurement of effective connectivity, estimating causal relationship between multivariate time series of 4 regions of interest (ROIs) comprised of bilateral inferior frontal gyri (IFGs) and the superior temporal gyri (STGs). We compared the summation of PDC values (sPDC) for the inflow and outflow signals in the 4 ROIs (bilateral IFGs and STGs), for 3 conditions

(*Tonic*, *Submediant*, and *Supertonic*) for 2 groups (music-majors and non-music-majors).

The figure displays three musical stimuli, each consisting of a piano score and a chord sequence. The stimuli are labeled Tonic, Submediant, and Supertonic. The Tonic stimulus ends with a Tonic (T) chord, the Submediant stimulus ends with a Submediant (SM) chord, and the Supertonic stimulus ends with a Supertonic (ST) chord. The chord sequences are T - SM - ST - D - T, T - SM - ST - D - SM, and T - SM - ST - D - ST, respectively. To the right, two brain diagrams illustrate the groups: Music-majors (top) and Non-music-majors (bottom).

Figure 2-1-1. Musical stimuli. Three conditions were presented randomly to music-majors and non-music-majors in all experiments. The three conditions had the different final chords of tonic (T), submediant (SM), and supertonic (ST) following an identical sequence of T - SM - ST - dominant (D), respectively. When the sequence of 4th and 5th chords is dominant-to-tonic (D - T, top), it is an authentic cadence which is classified as a conclusive cadence. The dominant-to-submediant (D - SM, middle) is a deceptive cadence which is classified as a progressive cadence (middle). The dominant-to-supertonic (D - ST, bottom) is not a cadential form. After D, the T is most expected, the ST is most unexpected, and the SM is less unexpected. The three conditions were named *Tonic*, *Submediant*, and *Supertonic*, respectively, according to the final chord.

Materials and Methods

Ethics statements

The present study was approved by the Institutional Review Board of the Clinical Research Institute, Seoul National University Hospital (H-1001-020-306). Prior to the experiments, the participants provided informed consent in written form. All experiments were conducted in accordance with the ethical guidelines. In the present study, we used 5 music-majors and 5 non-music-majors in the data set of our previous studies that was already published (Kim et al., 2014; Kim et al., 2011). The other participants were newly recruited. The data sets of our previous and present studies are partially overlapped, and the experimental procedure is also the same of them, however, the present study is an independent study applied novel hypotheses and analyses.

Participants

The participants were 19 females including 9 music-majors (mean age, 23.5 ± 3.4 years) and 10 non-music-majors (mean age, 25.2 ± 2.6 years). The music-majors majored in musical instruments at music colleges, and each trained for at least fifteen years (musical training period, 18.7 ± 4.0 years). Non-music-majors were not music majors (musical training period, 4.2 ± 1.5 years). All participants had normal hearing, and were right handed (mean Edinburgh Handedness coefficient, music-majors, 88.6 ± 12.8 ; non-music-majors, 91.6 ± 9.8).

Experimental procedure

The whole experiment was performed in a magnetically shielded MEG room, which minimized background noise out of musical stimuli. All music-majors and non-music-majors participated in 6 MEG recording sessions and 3 behavioral sessions. The three conditions of *Tonic*, *Submediant*, and *Supertonic* were presented randomly in all experiments. In each session, the participants listened to the five chord sequences of each condition. The individual sequence was 3,600 ms long. They were made up of five chords, 3,000 ms, and a break, 600 ms. In the MEG sessions, the participants were asked to detect a staccato chord (37.5 ms, 1/16 of other chords) randomly presented in the third to fifth chord in each sequence, and responded using a computer mouse. Each session included 100 sequences (10 staccato sequences). In the behavioral sessions, the participants were asked to categorize the 108 sequences (36 sequences per condition) in each session by type of condition, using a keypad. The whole experiment took about two hours, including preparation.

The three conditions were transposed to twelve major keys, and were randomly shuffled in each session. The musical stimuli were constructed with the piano timbre (Bösendorfer 290 Imperial grand) in Grand 3 (Steinberg Media Technologies, Hamburg, Germany) software. The wave files (sampling rate: 44.1 KHz; 16-bit; stereo; windows PCM) normalized the intensity by Cool Edit Pro 2.1 (Syntrillium Software Corporation, Phoenix, AZ, USA), and were recorded at 100 BPM using Cubase 5 (Steinberg Media Technologies, Hamburg, Germany) software. The sound pressure level in the musical stimuli was 65 dB, which was presented into MEG-

compatible tubal insert earphones (Tip-300, Nicolet, Madison, WI, USA) by the STIM² (Neuroscan, Charlotte, NC, USA).

MEG data acquisition and preprocessing

Using a 306-channel whole-head MEG System (Elekta NeuroMag VectorView™, Helsinki, Finland), MEG signals (600.615 Hz sampling rate, 0.1–200 Hz filter) were recorded in a magnetically shielded room. Electrooculograms (EOG) and electrocardiograms were also simultaneously recorded. In preprocessing, the environmental and movement noise of raw MEG signals was removed by the temporal Signal-Space Separation algorithm in MaxFilter 2.1.13 (Elekta Neuromag Oy, Helsinki, Finland) (Taulu and Hari, 2009; Taulu and Simola, 2006). Periods/Epochs containing EOG artifacts were manually rejected based upon visually inspection. The MEG data was filtered with a 1-20Hz band-pass filter.

Source estimation

The signals for multiple equivalent current dipoles in the bilateral IFGs and STGs were extracted from epochs of 400 ms after the onset of the final chord (tonic, submediant, and supertonic) in each condition using BESA 5.1.8.10 (MEGIS Software GmbH, Gräfelfing, Germany). For the dipole locations of the bilateral IFGs and STGs (4 ROIs), there was no significant difference between the music-majors and the non-music-majors (Mann–Whitney U test, $p > 0.05$ in all cases, uncorrected for multiple comparisons; see Figure 2-1-2). The Talairach coordinates (x, y, and z;

millimeters) in the left STG were -44.3, -7.1, and 3.2 for music-majors, and were -45.9, -11.6, and 0.6 for non-music-majors (Euclidian distance: 5.4 mm). The right STG was 41.3, -0.5, and 3.6 for music-majors, and were 45, -5.6, and 0.1 for non-music-majors (Euclidian distance: 7.2 mm). The left IFG was -41.9, 24.1, and 13.3 for music-majors, and were -39.8, 12.4, and 16.6 for non-music-majors (Euclidian distance: 12.3 mm). The right IFG was 39.1, 23.9, and 12.3 for music-majors, and were 36.4, 17.8, and 16.1 for non-music-majors (Euclidian distance: 7.7 mm).

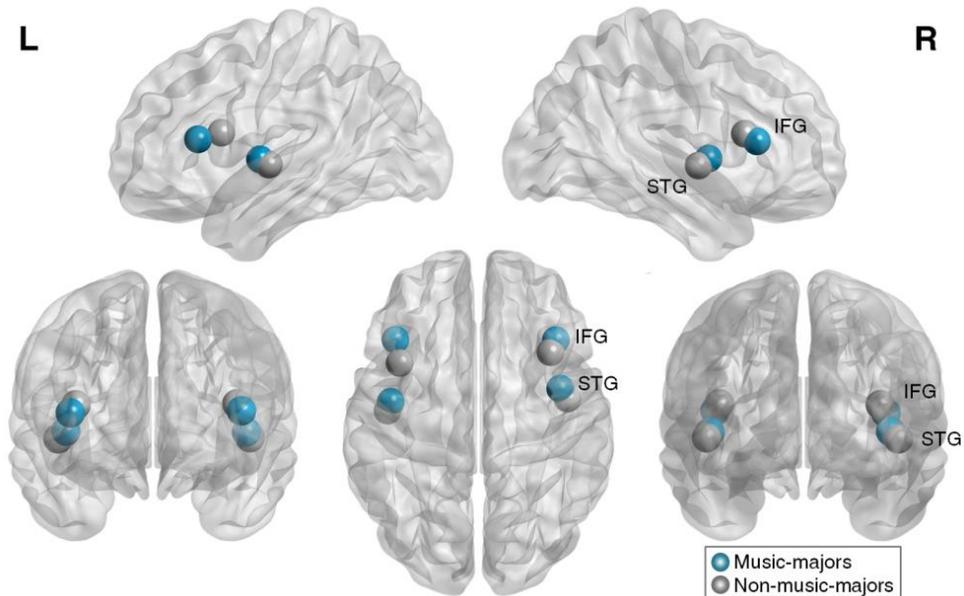


Figure 2-1-2. The grand mean dipole source for music-majors and non-music-majors. The dipole source locations for the bilateral IFGs and STGs were not significantly different between the music-majors and the non-music-majors (Mann–Whitney U test, $p > 0.05$ in all cases, uncorrected for multiple comparisons). The Talairach coordinates of mean dipole sources for the 4 ROIs in two groups were visualized using BrainNet Viewer (<http://nitrc.org/projects/bnv/>). See the Materials and Methods section for Talairach coordinates of music-majors and non-music-majors.

PDC analysis

The effective connectivity between the bilateral IFGs and STGs was computed by PDC (Baccala and Sameshima, 2001). The PDC is a measure used to identify causality between two signals in the frequency domain, and for the concept of Granger causality in a time domain, which is derived from the multivariate autoregressive (MVAR) model as

$$X(n) = \sum_{k=1}^p A_k X(n-k) + E(n) \quad (1)$$

where $X(n)$ is the data vector X of M time series, $X(n) = [X_1(n), X_2(n), X_3(n), \dots, X_M(n)]^N$ ($M = 4$; the number of ROIs in the present study), and $E(n)$ is multivariate uncorrected noise. A_k is $N \times N$ coefficient matrix. P is the model order, which was determined by Akaike's information criterion.

We examined the causal relationship between the four ROIs. To evaluate the property in the frequency band, Eq. (1) is transposed into the frequency domain as

$$A(f) = I - \sum_{k=1}^p A_k e^{-2\pi i k f} \quad (2)$$

where $A(f)$ is the Fourier transform of coefficient matrix A_k , and I is the identity matrix. The model order (p) was determined by Bayesian information criteria. Thus, the PDC value, γ_{ji} , from ROI j to ROI i at frequency f is defined as

$$\gamma_{ji}(f) = \frac{\bar{A}_{ij}(f)}{\sqrt{\bar{a}_j^H \cdot \bar{a}_j(f)}} \quad (3)$$

where $\overline{A_{ij}}(f)$ is the i th and j th elements of matrix A_k , and H is the Hermetian operator. In addition, the inflow to ROI i is emphasized because the PDC value is normalized with respect to the outflow from ROI j . The PDC value is “1” when signal to ROI i comes from the outflow signal from ROI j . If there is no signal flow from ROI j to ROI i , the value is close to “0”. The PDC values for twelve connections ($4P_2$; 12 permutations of four ROIs) and three conditions in individual participants were averaged over 1-20Hz frequency range. The mean PDC values were normalized by Fisher’s Z-transformation. The value of Z-transposed PDC was over the range of 0-1.

Based on the twelve Z-transposed PDC values for four ROIs of the bilateral IFGs and STGs, we computed the summation of the Z-transposed PDC values for the inflows and outflows in individual ROIs (left IFG, right IFG, left STG, and right STG); i.e. the inflow in the left IFG was the summation of the Z-transposed PDC values of “Left STG \rightarrow Left IFG”, “Right STG \rightarrow Left IFG”, and “Left STG \rightarrow Left IFG” among twelve connections, while the outflow in the left IFG was the summation of “Left IFG \rightarrow Left STG”, “Left IFG \rightarrow Right STG”, and “Left IFG \rightarrow Right IFG”. Hereafter, we used the “sPDC_i” as the term referring to the summation of the Z-transposed PDC values for the inflows and the “sPDC_o” as the term referring to the summation of the Z-transposed PDC values for the outflows.

Statistics

The data of the dipole location and behavioral responses did not follow a normal distribution. We conducted nonparametric analysis of the Mann–Whitney U test and Friedman test to test the difference between groups and conditions for the dipole location and behavioral responses. The $sPDC_i/sPDC_o$ was tested by four-way repeated measures ANOVA with the factors of Condition (*Tonic*, *Submediant*, and *Supertonic*) \times Group (music-majors and non-music-majors) \times Site (IFG and STG) \times Hemisphere (left hemisphere and right hemisphere) and three-way repeated measures ANOVA with the factors of Condition \times Group \times Flow (inflow and outflow). In all ANOVAs for the $sPDC_i$ and $sPDC_o$, the Greenhouse-Geisser's correction was applied when the Mauchly Sphericity test was significant ($p < 0.05$). The P -values ($p < 0.05$) for multiple comparisons in the results of all statistical analyses were adjusted based on the Bonferroni test. The statistical analyses were performed by SPSS 21.0 software (IBM, Armonk, NY, USA).

Results

Behavioral tests

In the behavioral experiment, the music-majors responded more correctly and more quickly than the non-music-majors (Figure 2-1-3). The correct rate was different between the two groups under all conditions (Mann–Whitney U test, *Tonic*, $Z = -3.700$, $p = 0.0006$; *Submediant*, $Z = -2.8$, $p = 0.012$; *Supertonic*, $Z = -3.016$, $p = 0.006$,

Bonferroni corrected). The music-majors' mean correct rates were over 90% in all conditions, whereas the non-music-majors' mean correct rates were under 80%.

Additionally, for the behavioral results on detecting the staccato sequence in the MEG experiment, no participant incorrectly responded more than 5%, which was the same for music-majors and non-music-majors ($p > 0.5$ in all cases). All participants concentrated on the musical stimuli during the MEG experiment.

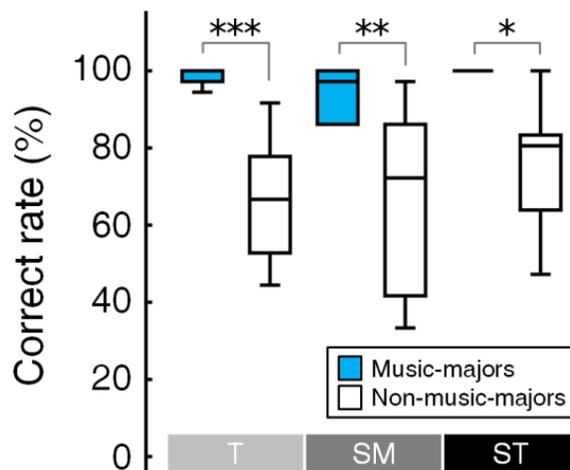


Figure 2-1-3. Group difference in the correct rate. Music-majors responded more correctly than non-music-majors for all conditions. Correct rates for the *Tonic*, *Submediant*, and *Supertonic* were higher in music-majors than in non-music-majors (Mann–Whitney U test, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, Bonferroni corrected). See also the Results section for the details of statistical results. In each box plots, the box represents 1st and 3rd quartiles, the line is the median value, and the whisker represents the most extreme non-outlier value. T = *Tonic*, SM = *Submediant*, and ST = *Supertonic*.

PDC

Four-way repeated measures ANOVAs with the factors of Condition \times Group \times Site \times Hemisphere were tested for both inflow (sPDC_i) and outflow (sPDC_o). For both inflow (sPDC_i) and outflow (sPDC_o), the interactions of Condition \times Group \times Site \times Hemisphere were significant [Inflow, $F(2, 136) = 5.963, p = 0.007$; Outflow, $F(2, 136) = 5.681, p = 0.009$]. See the Table 2-1-1 the details of statistical results of four-way repeated measures ANOVAs.

In *post hoc*, the Group difference was only observed in the left IFG, in both inflow and outflow, which was observed only in the *Submediant* among the three conditions (Figure 2-1-4). The sPDC_i for music-majors was much higher than it was for non-music-majors [$t(17) = 4.934, p = 0.002$, Bonferroni corrected], whereas the sPDC_o for music-majors were much lower than it was for non-music-majors [$t(17) = -4.391, p = 0.005$, Bonferroni corrected] (See also the Tables 2-1-2 and 1-4 for the details of statistical results).

Also *post hoc* for the Hemisphere difference was only observed in the *Submediant* in both inflow and outflow (Figure 2-1-5). Only in the bilateral IFG of the music-majors, the sPDC_i was higher in the left IFG than in the right IFG [$t(8) = 5.262, p = 0.009$, Bonferroni corrected], and the sPDC_o was lower in the left IFG than in the right IFG [$t(8) = -4.889, p = 0.015$, Bonferroni corrected] (See also Table 2-1-2 for the details of statistical results). Except for the two, there were on significant differences between hemispheres.

In the Figure 2-1-5, the difference between conditions was tested by post hoc one-way repeated measures ANOVA. The effect of Condition was only significant for the left IFG among 4 ROIs [Inflow, Music-majors, $F(2, 16) = 7.583, p = 0.039$, Bonferroni corrected; Outflow, Music-majors, $F(2, 16) = 8.969, p = 0.020$, Bonferroni corrected; Inflow, Non-music-majors, $F(2, 18) = 9.825, p = 0.010$, Bonferroni corrected; Outflow, Non-music-majors, $F(2, 18) = 7.987, p = 0.026$, Bonferroni corrected] (See also Table 2-1-4 for the details of statistical results). In music-majors, the sPDC_i for the *Submediant* was higher than for the other conditions [*Tonic*, $t(8) = -3.153, p = 0.041$, Bonferroni corrected; *Supertonic*, $t(8) = 4.509, p = 0.006$, Bonferroni corrected], and the sPDC_o was lower for the *Submediant* than for the *Supertonic* [$t(8) = -4.143, p = 0.010$, Bonferroni corrected]. In non-music-majors, the sPDC_i for the *Tonic* was higher than for *Supertonic* [$t(9) = 4.151, p = 0.007$, Bonferroni corrected], and the sPDC_o for the *Tonic* was lower than for the *Supertonic* [$t(8) = -3.887, p = 0.011$, Bonferroni corrected]. There were no significant differences in the other pairs.

Flow difference was tested by separate models of three-way repeated measures ANOVAs with the factors of Condition \times Group \times Flow. Among the 4 ROIs, the interaction of Condition \times Group \times Flow was only significant for the left IFG [$F(2, 68) = 14.661, p = 0.00002$, Bonferroni corrected] (See also Table 2-1-5 for the details of statistical results). In *post hoc* for the left IFG, the difference between sPDC_i and sPDC_o was only significant for the *Submediant* of music-majors [$t(8) = 5.929, p = 0.002$, Bonferroni corrected]. In the left IFG, the sPDC_i of the *Submediant*

was higher than the sPDC_o (Figure 2-1-6). In non-music majors, the significant Flow differences were not observed.

Among 4 ROIs, for the right IFG, the interaction of Group \times Flow was also significant [$F(1, 34) = 11.583, p = 0.008$, Bonferroni corrected] (See also Table 2-1-5 for the details of statistical results). Music-majors showed the difference between sPDC_i and sPDC_o in the *Submediant*, unlike non-music-majors. The sPDC_i for the *Submediant* was significantly lower than its sPDC_o [$t(8) = -3.784, p = 0.032$, Bonferroni corrected]. In non-music-majors and the other condition pairs of music-majors, there were no significant differences. For the left and right STG, the Flow effects were only significant [Left STG, $F(1, 34) = 12.196, p = 0.004$, Bonferroni corrected; Right STG, $F(1, 34) = 14.477, p = 0.004$, Bonferroni corrected].

Accordingly, the group difference between music-majors and non-music-majors was only observed in the sPDC_i and sPDC_o for the *Submediant* in the left IFG. Moreover, the sPDC_i and sPDC_o for the *Submediant* in the left IFG were extremely prominent for the Condition, Hemisphere, and Flow factors. Even though the sPDC_i and sPDC_o for the *Tonic* of non-music-majors in the left IFG showed the significant differences between the conditions, it was distinct from the result of music-majors for the *Submediant*.

Table 2-1-1. Four-way repeated measures ANOVA for the factors of Condition, Group, Site and Hemisphere. The significant *P*-values were marked in bold letters (* *p* < 0.05, ** *p* < 0.01, and *** *p* < 0.001).

	<i>Inflow</i>		<i>Outflow</i>	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
<i>Condition</i>	0.004	0.996	0.034	0.967
<i>Condition</i> × <i>Group</i>	0.044	0.957	0.377	0.686
<i>Condition</i> × <i>Site</i>	3.059	0.050	6.054	0.003 **
<i>Condition</i> × <i>Hemisphere</i>	5.037	0.008 **	3.364	0.037 *
<i>Condition</i> × <i>Group</i> × <i>Site</i>	3.584	0.030 *	4.295	0.016 *
<i>Condition</i> × <i>Group</i> × <i>Hemisphere</i>	6.052	0.003 **	3.474	0.034 *
<i>Condition</i> × <i>Site</i> × <i>Hemisphere</i>	5.722	0.004 **	4.832	0.009 **
<i>Condition</i> × <i>Group</i> × <i>Site</i> × <i>Hemisphere</i>	5.963	0.003 **	5.681	0.004 **
<i>Group</i>	0.000	0.993	0.001	0.981
<i>Site</i>	22.734	0.993	25.557	0.000003 ***
<i>Hemisphere</i>	5.283	0.0001 ***	2.767	0.101
<i>Group</i> × <i>Site</i>	0.062	0.025 *	0.274	0.602
<i>Group</i> × <i>Hemisphere</i>	5.422	0.805	6.783	0.011 *
<i>Site</i> × <i>Hemisphere</i>	3.664	0.023 *	3.425	0.069
<i>Group</i> × <i>Site</i> × <i>Hemisphere</i>	7.002	0.060	8.982	0.004 **

Table 2-1-2. Post hoc for Group factor in four-way repeated measures ANOVA. The significant *P*-values were marked in bold letters. In *post hoc t* test for 3 conditions × 2 sites × 2 hemispheres, the significance levels of *P*-values adjusted by the Bonferroni test are * *p* < 0.05, ** *p* < 0.01, and *** *p* < 0.001. The uncorrected *P*-values are also presented.

		<i>Inflow</i>			<i>Outflow</i>		
		<i>t</i>	<i>P (uncorrected)</i>	<i>P (corrected)</i>	<i>t</i>	<i>P (uncorrected)</i>	<i>P (corrected)</i>
<i>Left IFG</i>	<i>Tonic</i>	-1.208	0.244	1.0	0.864	0.4	1.0
	<i>Submediant</i>	4.934	0.0001 **	0.002 **	-4.391	0.0004 **	0.005 **
	<i>Supertonic</i>	1.809	0.088	1.0	-1.145	0.268	1.0
<i>Right IFG</i>	<i>Tonic</i>	0.244	0.810	1.0	0.240	0.813	1.0
	<i>Submediant</i>	-2.456	0.025	0.301	2.531	0.022	0.258
	<i>Supertonic</i>	-1.893	0.075	0.905	2.581	0.019	0.233
<i>Left STG</i>	<i>Tonic</i>	0.500	0.623	1.0	-1.565	0.136	1.0
	<i>Submediant</i>	-1.941	0.069	0.828	2.447	0.026	0.307
	<i>Supertonic</i>	0.247	0.808	1.0	-0.206	0.839	1.0
<i>Right STG</i>	<i>Tonic</i>	1.022	0.321	1.0	-1.386	0.184	1.0
	<i>Submediant</i>	-0.991	0.335	1.0	0.758	0.459	1.0
	<i>Supertonic</i>	0.339	0.739	1.0	-0.494	0.628	1.0

Table 2-1-3. *Post hoc* for Hemisphere factor in four-way repeated measures ANOVA. The significant *P*-values were marked in bold letters. In *post hoc t* test for 3 conditions × 2 sites × 2 hemispheres, the significance levels of *P*-values adjusted by the Bonferroni test are * *p* < 0.05 and ** *p* < 0.01. Also, the uncorrected *P*-values are presented.

			<i>Inflow</i>			<i>Outflow</i>		
			<i>t</i>	<i>P</i> (uncorrected)	<i>P</i> (corrected)	<i>t</i>	<i>P</i> (uncorrected)	<i>P</i> (corrected)
<i>Music-majors</i>	<i>IFG</i>	<i>Tonic</i>	0.834	0.429	1.0	-0.774	0.461	1.0
		<i>Submediant</i>	5.262	0.00076 **	0.009 **	-4.889	0.001 *	0.015 *
		<i>Supertonic</i>	0.837	0.427	1.0	-1.021	0.337	1.0
	<i>STG</i>	<i>Tonic</i>	1.425	0.192	1.0	-1.247	0.248	1.0
		<i>Submediant</i>	-1.217	0.258	1.0	1.332	0.219	1.0
		<i>Supertonic</i>	0.043	0.967	1.0	0.249	0.809	1.0
<i>Non-music-majors</i>	<i>IFG</i>	<i>Tonic</i>	2.022	0.074	0.886	-1.423	0.188	1.0
		<i>Submediant</i>	-0.674	0.517	1.0	0.691	0.507	1.0
		<i>Supertonic</i>	-2.410	0.039	0.471	2.151	0.060	0.719
	<i>STG</i>	<i>Tonic</i>	1.585	0.147	1.0	-0.868	0.408	1.0
		<i>Submediant</i>	-0.622	0.549	1.0	0.380	0.713	1.0
		<i>Supertonic</i>	0.096	0.926	1.0	-0.013	0.990	1.0

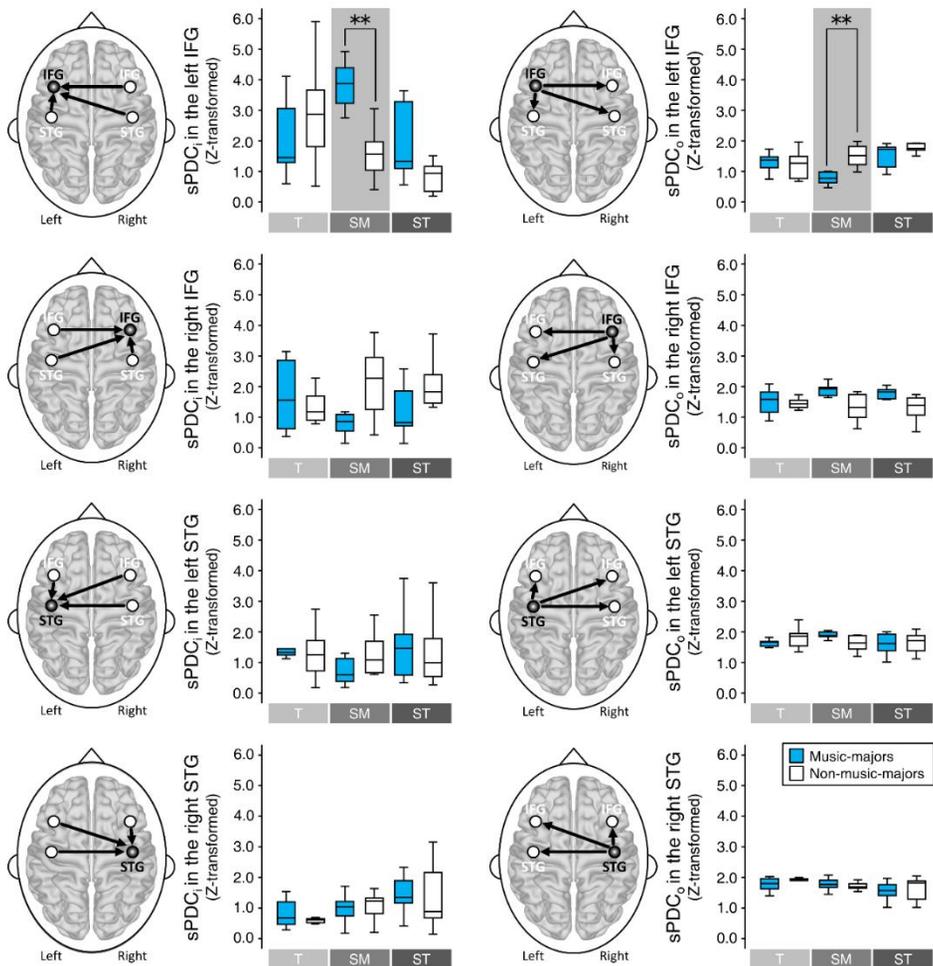


Figure 2-1-4. Group difference in the PDC. Group difference was observed only for the *Submediant* in both inflow and outflow of the left IFG (gray shaded boxes). The $sPDC_i$ for the *Submediant* was higher in music-majors than in non-music-majors, while the $sPDC_o$ for the *Submediant* was lower in music-majors than in non-music-majors (** $p < 0.01$, Bonferroni corrected). See also Tables 2-1-2 and 2-1-3 for the detail of statistical results. In each box plots, the box represents 1st and 3rd quartiles, the line is the median value, and the whisker represents the most extreme non-outlier value. T = *Tonic*, SM = *Submediant*, and ST = *Supertonic*.

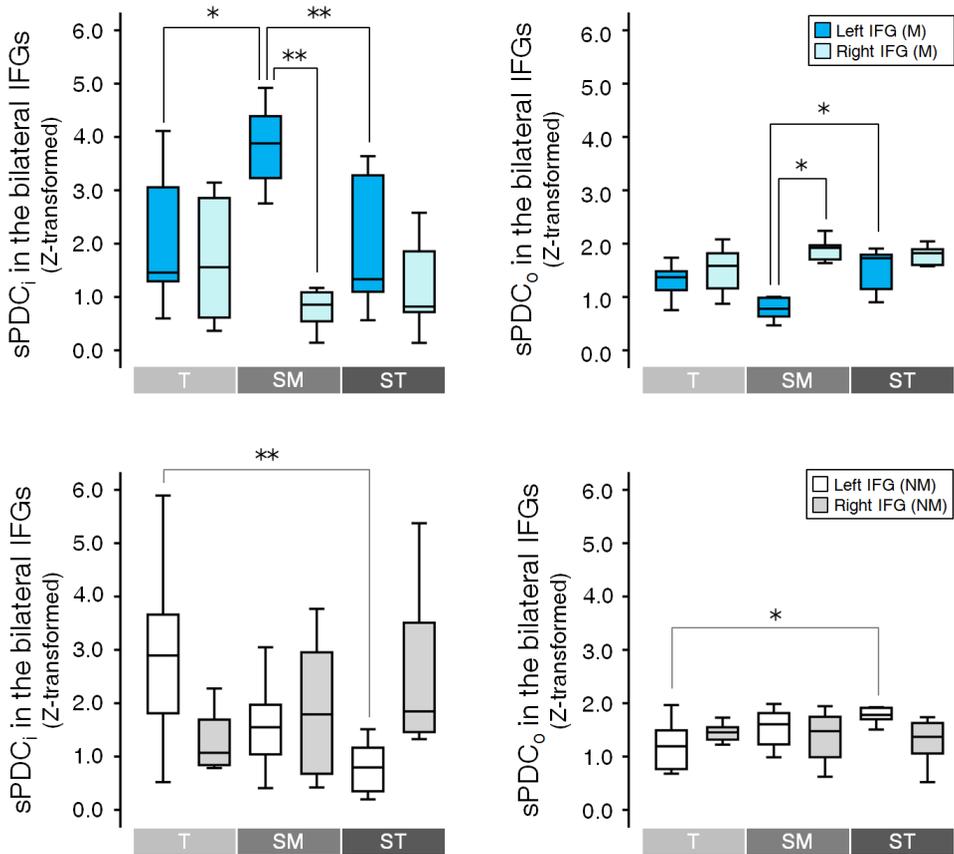


Figure 2-1-5. Hemisphere difference and Condition difference in the PDC. The hemispheric difference was observed only for the *Submediant* of music-majors in the IFG (See Table 2-1-3 for the detail of statistical results). The $sPDC_i$ was higher for the left IFG than for the right IFG, and the $sPDC_o$ was lower for the left IFG than for the right IFG ($* p < 0.05$ and $** p < 0.01$, Bonferroni corrected). Condition difference was observed in both groups (See also Table 2-1-4 for the detail of statistical results). In music-majors, the $sPDC_i$ was significantly higher for the *Submediant* than for the other conditions. In the $sPDC_o$, the *Submediant* was significantly lower than the *Supertonic*. In non-music-majors, the difference between the conditions was observed between the *Tonic* and the *Supertonic*. The $sPDC_i/sPDC_o$ was higher/lower for the *Tonic* than for the *Supertonic*. The box represents 1st and 3rd quartiles, the line is the median value, and the whisker represents the most extreme non-outlier value. T = *Tonic*, SM = *Submediant*, ST = *Supertonic*, M = music-majors, NM = Non-music-majors.

Table 2-1-4. Post hoc for Condition factor in four-way repeated measures ANOVA. The significant *P*-values were marked in bold letters. In *post hoc* one-way ANOVAs for 2 groups × 2 hemispheres × 2 sites and in paired *t* test for 3 conditions, the significance levels of *P*-values corrected by the Bonferroni test are * *p* < 0.05 and ** *p* < 0.01. The uncorrected *P*-values are also presented. T = Tonic, SM = Submediant, ST = Supertonic

			<i>Inflow</i>			<i>Outflow</i>		
			<i>F/t</i>	<i>P</i> (uncorrected)	<i>P</i> (corrected)	<i>F/t</i>	<i>P</i> (uncorrected)	<i>P</i> (corrected)
<i>Music-majors</i>	<i>Left IFG</i>	<i>Condition effect</i>	7.583	0.005 *	0.039 *	8.969	0.002 **	0.020 **
		<i>T vs. SM</i>	-3.153	0.014 *	0.041 *	2.921	0.019	0.058
		<i>SM vs. ST</i>	4.509	0.002 **	0.006 **	-4.143	0.003 *	0.010 *
		<i>T vs. ST</i>	0.350	0.736	1.0	-1.151	0.283	0.849
	<i>Right IFG</i>	<i>Condition effect</i>	1.106	0.330	1.0	1.836	0.210	0.840
	<i>Left STG</i>	<i>Condition effect</i>	3.559	0.053	0.211	4.563	0.027	0.108
	<i>Right STG</i>	<i>Condition effect</i>	1.340	0.290	1.158	0.941	0.411	1.0
<i>Non-music-majors</i>	<i>Left IFG</i>	<i>Condition effect</i>	9.825	0.001 **	0.010 **	7.987	0.003 *	0.026 *
		<i>T vs. SM</i>	2.761	0.022	0.066	-2.618	0.028	0.084
		<i>SM vs. ST</i>	1.494	0.169	0.508	-1.311	0.222	0.667
		<i>T vs. ST</i>	4.151	0.002 **	0.007 **	-3.887	0.004 **	0.011 *
	<i>Right IFG</i>	<i>Condition effect</i>	1.923	0.175	0.700	0.704	0.508	1.0
	<i>Left STG</i>	<i>Condition effect</i>	0.125	0.883	1.0	1.199	0.325	1.0
	<i>Right STG</i>	<i>Condition effect</i>	2.493	0.137	0.547	2.681	0.096	0.383

Table 2-1-5. Three-way repeated measures ANOVAs for the factors of Condition, Group, and Flow, and *post hoc* results. The significant *P*-values were marked in bold letters. In three-way ANOVAs for 2 groups × 2 flows, and in *post hoc* paired *t* test for 2 groups × 3 conditions, the significance levels of *P*-values corrected by the Bonferroni test are * *p* < 0.05, ** *p* < 0.001, and *** *p* < 0.001.

		<i>F/t</i>	<i>P (uncorrected)</i>	<i>P (corrected)</i>
Three-way ANOVA in the left IFG	Condition	2.859	0.064	0.257
	Condition × Group	4.634	0.013	0.052
	Condition × Flow	12.442	0.00002 ***	0.0001 ***
	Condition × Group × Flow	14.661	0.000005 ***	0.00002 ***
	Group	1.632	0.210	0.840
	Flow	18.875	0.0001 **	0.0005 **
	Group × Flow	6.443	0.016	0.636
Three-way ANOVA in the right IFG	Condition	0.758	0.445	1.0
	Condition × Group	0.730	0.456	1.0
	Condition × Flow	1.588	0.216	0.865
	Condition × Group × Flow	2.880	0.077	0.306
	Group	1.703	0.201	0.803
	Flow	0.292	0.593	1.0
	Group × Flow	11.583	0.002 **	0.007 **
Three-way ANOVA in the left STG	Condition	0.812	0.448	0.448
	Condition × Group	0.276	0.760	0.760
	Condition × Flow	3.094	0.052	0.207
	Condition × Group × Flow	2.539	0.086	0.346
	Group	0.113	0.739	1.0
	Flow	12.196	0.001 ***	0.005 ***

		<i>Group</i> × <i>Flow</i>	0.087	0.770	1.0
<i>Three-way ANOVA in the right STG</i>		<i>Condition</i>	0.986	0.360	1.0
		<i>Condition</i> × <i>Group</i>	0.322	0.666	1.0
		<i>Condition</i> × <i>Flow</i>	4.601	0.022	0.090
		<i>Condition</i> × <i>Group</i> × <i>Flow</i>	1.800	0.183	0.730
		<i>Group</i>	0.016	0.900	1.0
		<i>Flow</i>	14.477	0.0006 **	0.002 **
		<i>Group</i> × <i>Flow</i>	0.046	0.832	1.0
<i>Post hoc paired t test (Flow difference in the left IFG)</i>	<i>Music-majors</i>	<i>Tonic</i>	1.631	0.142	0.849
		<i>Submediant</i>	5.929	0.00035 **	0.002 **
		<i>Supertonic</i>	0.829	0.431	0.257
	<i>Non-Music-majors</i>	<i>Tonic</i>	2.994	0.015	0.091
		<i>Submediant</i>	0.086	0.934	1.0
		<i>Supertonic</i>	-1.561	0.153	0.917
<i>Post hoc paired t test (Flow difference in the right IFG)</i>	<i>Music-majors</i>	<i>Tonic</i>	0.175	0.865	1.0
		<i>Submediant</i>	-3.784	0.005 *	0.032 *
		<i>Supertonic</i>	-0.657	0.530	1.0
	<i>Non-Music-majors</i>	<i>Tonic</i>	0.030	0.977	0.091
		<i>Submediant</i>	0.989	0.349	1.0
		<i>Supertonic</i>	2.226	0.053	0.917

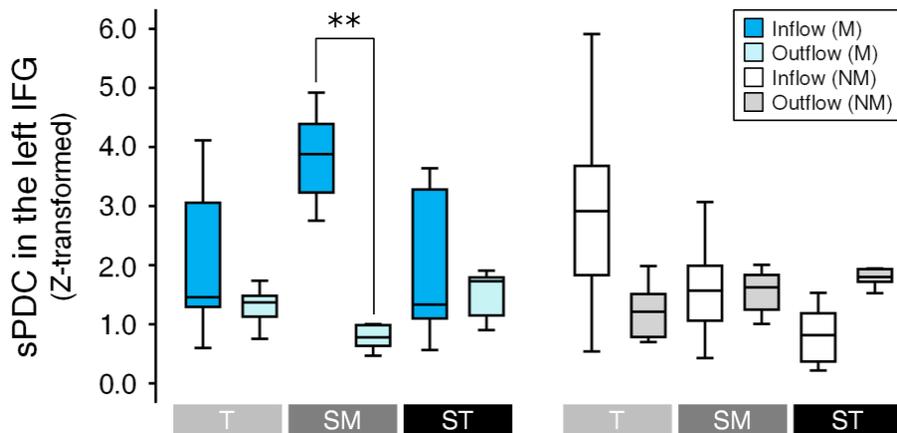


Figure 2-1-6. Flow difference in the PDC. In three-way repeated measures ANOVAs with the factors of Condition \times Group \times Flow, the interaction of Condition \times Group \times Flow was only significant for the left IFG [$F(2, 68) = 14.661, p = 0.00002$, Bonferroni corrected]. In the left IFG, the difference between $sPDC_i$ and $sPDC_o$ was only observed in the *Submediant* for music-majors (** $p < 0.01$, Bonferroni corrected). The $sPDC_i$ was higher than the $sPDC_o$. See Table 2-1-5 for the detail of statistical results. The box represents 1st and 3rd quartiles, the line is the median value, and the whisker represents the most extreme non-outlier value. T = *Tonic*, SM = *Submediant*, ST = *Supertonic*, M = music-majors, and NM = Non-music-majors.

Discussion

Music-majors were better than non-music-majors for all conditions in the behavioral experiment. However, consistent with our hypothesis, the difference between groups was only observed in the $sPDC_i/sPDC_o$ for the *Submediant* and the left IFG. Moreover, for music-majors, the inflows to the left IFG were strongly enhanced compared to the outflows from the left IFG. This indicates that the information for the *Submediant* collected from other areas (right IFG and bilateral STGs) is centered on the left IFG, where the information would be analyzed and integrated. These

results imply that the sPDC_i/sPDC_o in the left IFG was specialized in the processing of a deceptive cadence in the *Submediant*, and it depended on musical expertise.

The IFG and STG are well known to be associated with the processing of, and syntax of harmony and melody (Dohn et al., 2015; Janata et al., 2002; Kim et al., 2014; Kim et al., 2011; Koelsch and Jentschke, 2010; Maess et al., 2001; Patel and Balaban, 2001; Patterson et al., 2002; Sammler et al., 2009; Schneider et al., 2005). Although syntax in music is dominantly processed in the right IFG (Maess et al., 2001), the left IFG is prerequisite in the processing of musical syntax (Sammler et al., 2011). The left IFG is also highly activated by complexities in syntax (Obleser et al., 2011). However, it has not been studied how the deceptive cadence is processed in the network of bilateral IFGs and STGs. The present study demonstrated that the IFG plays a pivotal role in connections of bilateral IFGs and STGs, which was only related with the processing of the *Submediant* among three conditions.

Only in music-majors, the inflow (sPDC_i) for the *Submediant* was higher in the left IFG than in right IFG, which was inversed in the outflow (sPDC_o). Also, the inflow in the left IFG for music-majors was much higher than its outflow, whereas, the inflow was lower than the outflow in the right IFG. These results imply that when processing the *Submediant* music-majors have used the left hemisphere of the IFG much more than non-music-majors. The quantity of information sending to the left IFG is also relatively more than the right IFG.

Previous studies have reported that the left hemisphere of music-majors is something different by musical knowledge and training. The left IFG is associated with the different strategies of musicians such as pitch labeling (Dohn et al., 2015). In the melody processing, the activation of the left IFG related with the working memory is increased in musicians (Nan et al., 2008). In terms of the whole brain, the musician's brain reveals left hemisphere asymmetry during perceiving harmony (Evers et al., 1999). Furthermore, musical training affects connectivity between the regions as well as activation in each region. The connectivity in peri-sylvian areas related with pitch processing is more increased in musicians with absolute pitch (Jancke et al., 2012; Loui et al., 2011). The listening strategies of musicians are different from those of non-musicians, which are revealed as a left hemispheric dominance in functional connectivity between the brain regions (Bhattacharya and Petsche, 2005). Further extending previous studies, the present study revealed that the music-majors with musical knowledge of the deceptive cadence of dominant-to-submediant had left hemispheric asymmetry in connectivity when processing the *Submediant*.

The *Submediant* of dominant-to-submediant is an unexpected cadence compared with the *Tonic* of dominant-to-tonic in the levels of harmonic expectancy (Huron, 2006; James et al., 2008). Also it is a deceptive cadence (Biancorosso, 2008). The conditional probability (Rohrmeier, 2007), based on the harmonic expectancy, of the *Submediant* was less expected than the most expected *Tonic* (only about 1/7); when the sum of the conditional probability for six cases according to the different chords

following a dominant is 1, tonic is 0.752, submediant is 0.106, subdominant is 0.053, mediant is 0.045, supertonic is 0.043, and subtonic is 0.001. However, the *Submediant* was not the unexpected condition in our present study, unlike the unexpected *Supertonic* with the conditional probability of 1/17 for the *Tonic* (Kim et al., 2014; Kim et al., 2011). Moreover, the group difference in the sPDC for the *Submediant* did not reflect the sensitivity of musical training for the processing of harmonic expectancy (Jentschke and Koelsch, 2009; Koelsch et al., 2002a). If the sPDC for the *Submediant* was elicited by unexpected cadence, the sPDC and group difference would be more strongly prominent for the *Supertonic*. Thus, for *Submediant*, the relative increase in sPDC_i and the decrease in sPDC_o in the left IFG would not reflect harmonic expectancy in the dominant-to-submediant.

A previous study reported that when listening to a deceptive cadence, musicians anticipate that the music will continue, while non-musicians regard it as the ending of the music. However, there was no group difference for an authentic cadence of dominant-to-tonic (Sears et al., 2014). Based on this, in the present study, only music-majors might be able to perceive the deceptive cadence or progressive cadence in the *Submediant*, and they might think that “the deceptive cadence thwarts the expectation for the more probable dominant-to-tonic (Huron, 2006)”. Therefore, we interpret that the prominent sPDC_i and sPDC_o in music-majors reflects the detection and comprehension of the more technical meaning of deceptive cadence in the *Submediant*. Thus, musical expertise in our present study does not necessarily

indicate increased sensitivity or development, but a different schema based on professional training.

There is one caveat which should be mentioned. Although the ROIs in our present study include the key areas of the bilateral IFGs and STGs in music processing, it is far from depicting the whole brain network by musical expertise, experience, and harmonic cadence processing. Therefore, it warrants further study, examining the difference in effective connectivity measurements and the whole brain connectivity for musical expertise, experience, and harmonic cadence processing. Nevertheless, our data show that music-majors, with higher musical expertise, are better in identifying a less unexpected cadence than non-music-majors, with connectivity changes centered on the left IFG.

Acknowledgements

We would like to thank Ji Hyang Nam for the technical support in MEG acquisition.

STUDY II. Dissociation of connectivity for syntactic irregularity and perceptual ambiguity in musical chord stimuli

Abstract

Previously syntactic irregularity has been most studied with chord sequences. However, the same chord may be interpreted as having different harmonic functions, implying perceptual ambiguity. Hence, syntactic irregularity and perceptual ambiguity may be processed simultaneously. We devised 3 different 5-chord sequences in which the ending chord differed with the tonic (T), submediant (SM), and supertonic (ST). In terms of syntactic regularity, T is most regular, ST is most irregular. However, in terms of perceptual ambiguity, the most irregular ST had the salient highest voice. Therefore, the SM was the most ambiguous condition. We investigated how the human brain separates syntactic irregularity and perceptual ambiguity in terms of effective connectivity in bilateral inferior frontal gyri (IFGs) and superior temporal gyri (STGs) with magnetoencephalography in 19 subjects. Correct rate was lower for the most ambiguous chord (SM) ($P = 0.020$) as expected. Connectivity from the right to the left IFG was enhanced for the most irregular chord (ST) ($P = 0.024$, false discovery rate (FDR) corrected), whereas connectivity from the right to the left STG was enhanced for the most ambiguous chord (SM) ($P < 0.001$, FDR corrected). The correct rate was negatively correlated with connectivity

in the STG, further reflecting perceptual ambiguity ($P = 0.026$). We found that syntactic irregularity and perceptual ambiguity in music are dissociated in connectivity between bilateral IFGs and STGs, respectively.

Significance Statement

We provide the first neurophysiological evidence of the processing of perceptual ambiguity, other than syntactic irregularity, implied in musical chords. We found that the notion of “perceptually ambiguity” is applicable to musical chord stimuli different in syntactic irregularity, and that perceptual ambiguity is separate from syntactic irregularity. Our data demonstrate that the brain interprets the three conditions of musical chords as both “from regular to irregular” and “from ambiguous to unambiguous” conditions simultaneously. This study is the first to unveil dissociation of connectivity by syntactic irregularity and perceptual ambiguity involved in musical chord stimuli.

Introduction

Previous studies on musical syntax using chord sequences have only focused on classifying syntactic regularity and irregularity of harmony using chord sequences (Kim et al., 2011; Koelsch et al., 2002a; Maess et al., 2001; Patel, 2003). However, the same notes, intervals, or chords can be interpreted as having different harmonic

functions, implying perceptual ambiguity. Even composers often exploit such potential ambiguities. Hence, the two processes of syntactic irregularity and perceptual ambiguity are overlapping.

The term “ambiguity” generally refers to uncertainty caused by two or more interpretations of an object, which is distinct from “vagueness” referring to interpretive uncertainty implied in a unity of different meanings (Kennedy, 2019; Tuggy, 1993). Ambiguity can occur in music, too, as in language. It occurs on various levels. For instance, metric ambiguity can happen when two or more possible metric interpretations are possible such as hemiola between duple and triple meter (Agawu, 1994). In tonal music, the same triad of C-E-G can be interpreted as the tonic (I) of C major or the dominant (V) of F major. Tritone substitution between the V7 chord and the flat II7 chord often occurs in jazz as the tritone (B-F), for instance, can be either a part of the chord of G7 or that of Db7 (Karpinski, 2012).

Since most previous music studies used 2 different chord sequences, syntactic irregularity and perceptual ambiguity could not be separated. However, if we use 3 different chord sequences, syntactic irregularity and perceptual ambiguity could not be in the same direction. We found the notion of ambiguity applicable to the level of cadences in music. Figure 2-2-1A shows three 5-chord sequences with different endings on the three chords of tonic (T), submediant (SM), and supertonic (ST), which are different in syntactic irregularity (T = most regular, SM = less regular, ST = most irregular).

The SM was the most ambiguous condition among the three conditions. The SM is difficult to distinguish from the T, because it is a substitute chord of the T, sharing the same notes of “C” and “E”. It is a deceptive cadence implying both of closure and progression, and it has the non-salient melodic line of “E” which is the same with the T. The SM is also difficult to distinguish from the ST, because the sonic quality is the same minor triad as the ST and both SM and ST are syntactically irregular chords, compared to the T. Given these relations, the SM is most ambiguous, and the ST is most unambiguous.

We investigated how perceptually ambiguous chord is processed in the brain, and how the human brain separates syntactic irregularity and perceptual ambiguity in terms of effective connectivity. Using linearized time delayed mutual information (LTDMI; see Materials and Methods section) (Jin et al., 2010), we estimated connectivities modulated by the most irregular and ambiguous conditions among twelve directional connectivities between the bilateral inferior frontal gyri (IFGs) and superior temporal gyri (STGs).

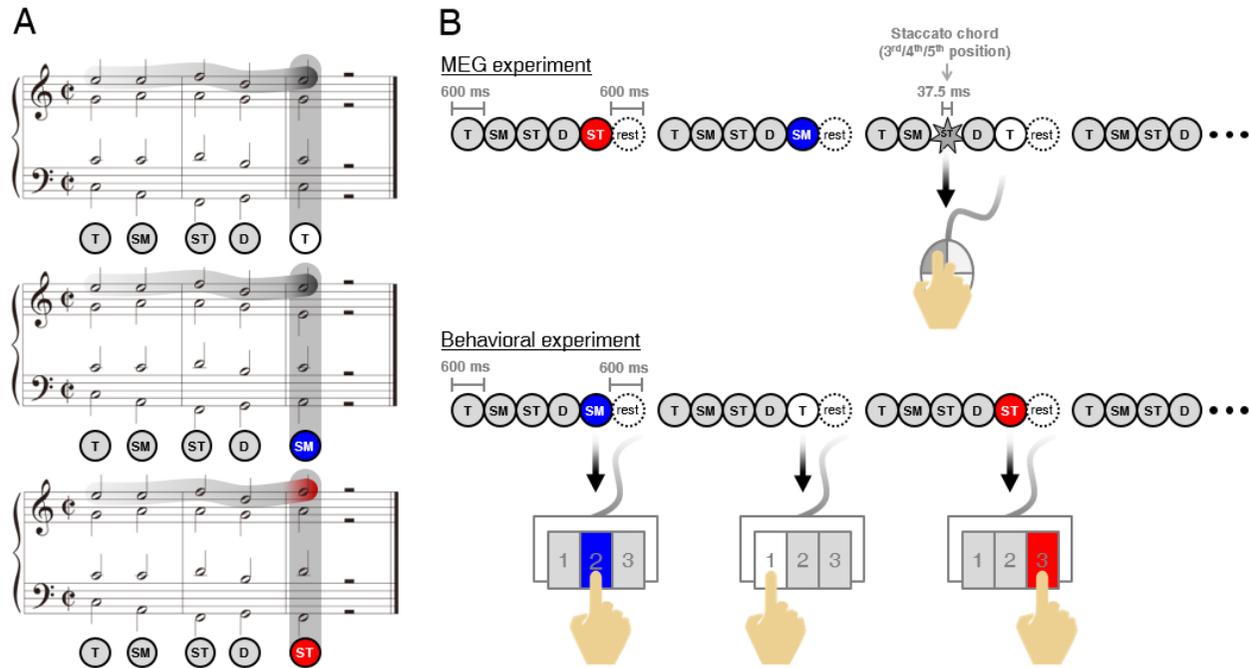


Figure 2-2-1. Musical stimuli and experimental paradigm. (A) Five chords in each condition differ in harmony and melodic line of the ending chords following dominant (D). Harmonies are tonic (T), submediant (SM), and supertonic (ST). The highest voices of melodic line are “E” (dark gray shadow) in the T and SM, an “F” (red shadow) in the ST. (B) In the MEG experiment (top), the participants listened to the three conditions carefully and were asked to detect the staccato chord among chord sequences in the three conditions and to click a mouse (to check the level of attending the conditions). The staccato sequences (10% of all sequences) were excluded in the MEG data analysis. In the behavioral experiment (bottom), the participants discriminated the three conditions and responded by using the 1, 2, and 3 buttons on the keypad.

Materials and Methods

Ethics statement

In the present study, we used the same data sets of our previous study (Kim et al., 2019) that was approved by the Institutional Review Board of the Clinical Research Institute, Seoul National University Hospital (H-1001-020-306), and applied novel hypotheses and analyses. All participants provided informed consent of written form prior to the experiments.

Participants

All participants were 19 females (mean age, 24.3 ± 3.0 years) of 9 music-majors and 10 non-music-majors. They were all had normal hearing and were right-handed.

Musical stimuli

We used 3 different conditions: T, SM, and ST (Figure 2-2-1A). The T was comprised of “tonic-submediant-supertonic-dominant-tonic”. The ending chord of “tonic” was replaced with “submediant” and “supertonic” in the SM and ST, respectively. The chords from first to fourth were the same in all conditions. The “F” of the highest voice in the final chord in the ST was different from “E” in the other two conditions. In each condition, the duration of a chord was 600 ms. A chord sequence totaled 3600 ms, including five chords and a 600 ms resting period (Figure 2-2-1B). All conditions transposed into 12 major keys, were randomly shuffled in

each session and were recorded at 100 BPM using Cubase 5 (Steinberg Media Technologies, Hamburg, Germany) software. The intensity was normalized in each wave file (sampling rate: 44.1 KHz; 16-bit; stereo; windows PCM) using Cool Edit Pro 2.1 (Syntrillium Software Corporation, Phoenix, AZ, USA). The piano timbre (Bösendorfer 290 Imperial grand) in each chord was created by Grand 3 (Steinberg Media Technologies, Hamburg, Germany) software.

MEG recording

The whole experimental paradigm was comprised of 3 behavioral test sessions after 6 MEG recording sessions (Figure 2-2-1B). Each MEG session included 100 sequences consisting of 30 sequences per condition and 10 staccato sequences. In individual staccato sequences, a staccato chord of 37.5 ms duration was presented in the third, fourth, or fifth chords. The participants were asked to detect staccato chord and to respond using a mouse. The response for staccato sequences was excluded in the MEG data analysis. In each behavioral session after MEG recording, 12 sequences per condition were randomly presented. All participants were asked to identify each condition of T, SM, and ST using the 1, 2, and 3 buttons on keypad. The musical stimuli were presented at the sound pressure level of 65 dB into MEG-compatible tubal insert earphones (Tip-300, Nicolet, Madison, WI, USA) using the STIM² (Neuroscan, Charlotte, NC, USA) system. The whole experiment took about two hours. MEG signals were recorded in a magnetically shielded room using a 306-channel whole-head MEG System (Elekta NeuroMag VectorView™, Helsinki,

Finland), with a sampling rate of 600.615 Hz using 0.1–200 Hz band pass filter. Electrooculograms (EOG) and electrocardiograms (ECG) were simultaneously recorded to later remove ocular and cardiac noise.

MEG analysis

The environmental magnetic noise of raw MEG signals was eliminated by the temporal Signal-Space Separation (tSSS) algorithm in MaxFilter 2.1.13 (Elekta Neuromag Oy, Helsinki, Finland) (Taulu and Hari, 2009; Taulu and Simola, 2006). The 204 orthogonal planar gradiometer in 102 locations was used in the further analysis procedure.

Source analysis of four ROIs (bilateral IFGs and STGs) was performed using BESA 5.1.8.10 (MEGIS Software GmbH, Gräfelfing, Germany). The multiple equivalent current dipoles (ECDs) were estimated with the same procedures as on our previous studies (Kim et al., 2014; Kim et al., 2011). After the ECDs of P2's magnetic counterpart (P2m) were estimated in the peak latency of 180–190 ms for the first “tonic” chord of the chord sequence in the bilateral STGs, the ECDs of ERANm were estimated in 140–220 ms for all ending chords (mean of the tonic, submediant, and supertonic chords) in the bilateral IFGs. The multiple dipoles were more than 80% of the goodness of fit (GOF). The estimated dipoles in the IFG were superior and anterior to these in the STG (Kim et al., 2014; Kim et al., 2011; Maess et al., 2001). The *x*, *y*, and *z* in Talairach coordinates (millimeters) were -45.1, -8.9, and 1.9 in the left STG, 43.1, -2.6, and 2 in the right STG, -40.8, 18.5, and 15.6 in

the left IFG, and 37.6, 21.2, and 15.1 in the right IFG, respectively (Figure 2-2-2A). The signal for ECDs was extracted in 400 ms epochs after the onset of the ending chord using 1–20 Hz band-pass filter for each participant. The 400 ms was the time window involving the peak latencies of P2m and ERANm in our previous studies (Kim et al., 2014; Kim et al., 2011) (Fig. 2-2-2B).

Using the ECDs signals of the time window of 400 ms in the bilateral IFGs and STGs for each condition, we estimated the information flows in 12 directional connections between the bilateral IFGs and STGs for the three conditions. Effective connectivity for 12 connections was calculated by LTDMI (Jin et al., 2010). The LTDMI is an information theoretic measure of functional coupling based on mutual information (MI) (Jin et al., 2012; Jin et al., 2011) which predicts information transmission between two time series.

MI is defined as the quantity of information shared in two time series of $X(n)$ and $Y(n)$ ($n = 1, 2, \dots, N$), at N discrete points. The probability density function (PDF) of $X(n)$ and $Y(n)$ are $p(X(n), \kappa) \equiv p(X(n))$ and $p(Y(n), \kappa) \equiv p(Y(n))$ with $n = 1, 2, \dots, \text{bin}$, respectively. The MI is computed by $p(X(n), Y(n))$, the joint PDF between $X(n)$ and $Y(n)$, as follows:

$$MI = MI_{XY} = MI_{YX} = MI(X(n), Y(n)) = - \sum_k p(X(n), Y(n)) \log \frac{p(X(n), Y(n))}{p(X(n))p(Y(n))} \quad (1)$$

If $X(n)$ and $Y(n)$ are completely identical, the MI is maximum. However, if two time series are independent of each other, the MI is zero. The directional information

transmission between the two time series can be calculated by time delayed mutual information (TDMI) (Jin et al., 2010):

$$\begin{aligned}
TDMI_{XY} &= TDMI(X(n), Y(n + \tau)) = - \sum_k p(X(n), Y(n + \\
&\tau)) \log \frac{p(X(n), Y(n + \tau))}{p(X(n))p(Y(n + \tau))}. \\
TDMI_{YX} &= TDMI(Y(n), X(n + \tau)) = - \sum_k p(Y(n), X(n + \\
&\tau)) \log \frac{p(Y(n), X(n + \tau))}{p(Y(n))p(X(n + \tau))} \quad (2)
\end{aligned}$$

TDMI can detect linear and non-linear correlation between two time series. Since the data length used in the present study (400 ms epoch) was insufficient to reconstruct a reliable PDF for general TDMI presented in equation (2), we used LTDMI as an effective connectivity measure in this study. LTDMI is adopted as follows:

$$\begin{aligned}
LTDMI_{XY} &= LTDMI(X(n), Y(n + \tau)) = -\frac{1}{2} \log(1 - \rho_{X(n)Y(n+\tau)}^2) \\
LTDMI_{YX} &= LTDMI(Y(n), X(n + \tau)) = -\frac{1}{2} \log(1 - \rho_{Y(n)X(n+\tau)}^2) \quad (3)
\end{aligned}$$

where $\rho_{X(n)Y(n+\tau)}$ and $\rho_{Y(n)X(n+\tau)}$ are a cross-correlation coefficient, and τ is delay time, which was 120 ms in our present study. To estimate the linearized information flow between the time series, each time series is assumed with the Gaussian distributed function with zero-mean, and variance σ_X^2 , σ_Y^2 , i.e. $p(X) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp(-X^2/2\sigma^2)$. The LTDMI values were averaged over delay time.

Differences in the LTDMI values among the three conditions of T, SM, and ST in 12 connections were tested by the two-way repeated measures ANOVA. In all *post hoc* analysis steps, the alpha levels for multiple comparisons were adjusted by the FDR correction ($P < 0.05$). Additionally, the group difference for the LTDMI values was tested by the independent t test ($P < 0.05$).

In the MEG experiment, the mean CR for staccato chord detection was calculated for each participant. In the behavioral experiment, the difference between the three conditions for the CR was determined by the one-way repeated measure for all conditions.

Correlation analysis was performed to test the relationships between the LTDMI value and CR for all conditions of all participants (i.e., for the merged data set of 3 conditions of 18 participants). In the correlation analysis for the LTDMI value and the CR, the correlation was tested using the Spearman rank correlation because the data was not normally distributed. The correlation was calculated using the one-tailed test, because the ambiguous stimuli lead to slower and less accurate responses than the easy stimuli (Fleming et al., 2010; Jastorff et al., 2009; Sabri et al., 2006). The alpha level was adjusted by the Benjamin-Hochberg false discovery rate (FDR) correction for the multiple comparisons testing of the three conditions ($P < 0.05$). The Greenhouse-Geisser's correction was applied because the sphericity of the data was violated via the Mauchly sphericity test. All statistical analyses were performed using SPSS 21.0 software (IBM, Armonk, NY, USA).

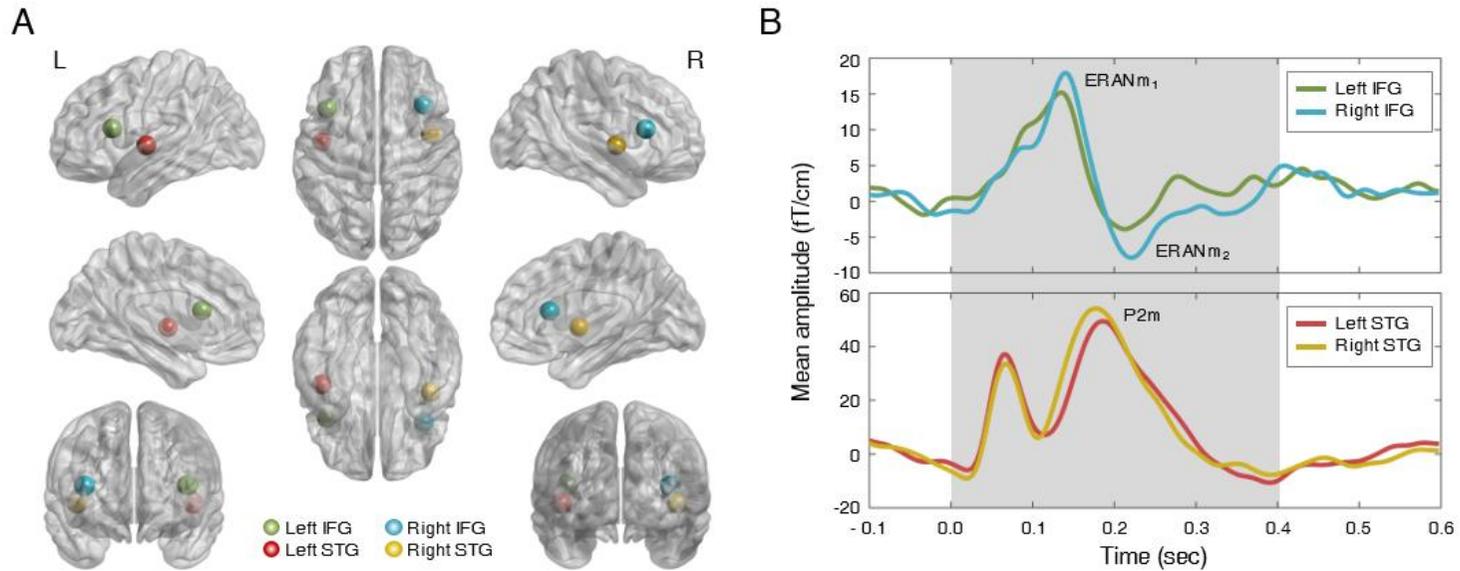


Figure 2-2-2. Mean dipole source locations of all participants in the bilateral IFGs and STGs, and the time window. (A) The ECDs of P2m (magnetic counterpart of P2) and ERANm (magnetic counterpart of ERAN) in the ending chord in each condition were localized in the bilateral IFGs and STGs. The green dot (left IFG), sky blue dot (right IFG), red dot (left STG), and yellow dot (right STG) indicate the grand average ($n = 19$) of individual ECDs estimated by BESA 5.1.8.10. (x , y , and z in Talairach coordinates, millimeters, left IFG, -40.8, 18.5, and 15.6; right IFG, 37.6, 21.2, and 15.1; left STG, -45.1, -8.9, and 1.9; right STG, 43.1, -2.6, and 2). The brain map and dipole source location were generated by BrainNet Viewer (<http://nitrc.org/projects/bnv/>). (B) The LTDMI values were calculated in the time window of 0 ms to 400 ms after the ending chord onset in the MEG signal of ECDs for four ROIs. The green, sky blue, red, and yellow lines denotes the mean amplitudes of three conditions ($n = 19$) in each ROI across all participants. The gray shadow indicates the time window of 400 ms encompassing the peak latencies of ERANm₁ and ERANm₂ in the bilateral IFGs and P2m in the bilateral STGs, respectively.

Results

LTDMI values for three conditions

Using the LTDMI (Jin et al., 2010), we calculated effective connectivity for 12 connections among 4 regions of interest (ROIs) of the bilateral IFGs and STGs for three conditions of the T, SM, and ST in 19 participants. For the LTDMI values, we performed a two-way repeated measures analysis of variance (ANOVA) with two factors of Condition and Connection. The ANOVA ($n = 19$) showed a significant main effect of Condition [$F(1.872, 404.247) = 3.108, P = 0.049$] and a significant interaction of Condition \times Connection [$F(20.587, 404.247) = 2.555, P = 0.0002$], and a significant effect of Connection [$F(1, 216) = 1.920, P = 0.038$]. *Post hoc* one-way repeated measures ANOVAs with the Condition factor in 12 connections confirmed a connection reflecting the difference among the three conditions. The difference between the three conditions was revealed only in two connections from the right to the left IFG [$F(2, 36) = 6.526, P = 0.024$, false discovery rate (FDR) corrected] and from the right to the left STG [$F(2, 36) = 12.373, P < 0.001$, FDR corrected] among 12 connections (Figure 2-2-3B,C; see also Table 2-2-1).

Hereafter, we use the term “IFG-LTDMI” to refer to the LTDMI values from the right to the left IFG, and the term “STG-LTDMI” to refer to those from the right to the left STG. In the two interhemispheric connections, the SM and ST of the most ambiguous and irregular conditions showed the highest STG-LTDMI and IFG-LTDMI, respectively. In a *post hoc* paired *t* test, the IFG-LTDMI was higher for the ST than for the T [$t(17) = 3.289, P = 0.009$, FDR corrected] and for the SM [$t(17) =$

2.711, $P = 0.009$, FDR corrected], while the IFG-LTDMI for the T and SM was not significantly different [$t(17) = -0.061$, $P = 0.952$, FDR corrected]. The STG-LTDMI was higher for the SM than for the T [$t(17) = -2.691$, $P = 0.023$, FDR corrected], and the ST [$t(17) = 5.357$, $P = 0.0001$, FDR corrected], while was significantly higher for the T than for the ST [$t(17) = 2.259$, $P = 0.037$, FDR corrected].

Table 2-2-1. Post hoc one-way repeated measures ANOVAs results of the LTDMI for the Condition factor in 12 connections. The P -values were corrected by FDR for multiple comparisons of 12 connections. * $P < 0.05$, and *** $P < 0.01$.

	<i>df</i>	<i>F</i>	<i>P</i>
<i>Left STG → Right STG</i>	2/36	1.275	0.501
<i>Left STG → Left IFG</i>	2/36	3.235	0.153
<i>Left STG → Right IFG</i>	2/36	0.023	0.977
<i>Right STG → Left STG</i>	2/36	12.373	*** < 0.001
<i>Right STG → Left IFG</i>	2/36	4.828	0.056
<i>Right STG → Right IFG</i>	2/36	0.478	0.749
<i>Left IFG → Left STG</i>	2/36	0.234	0.864
<i>Left IFG → Right STG</i>	1.399/25.187	1.024	0.522
<i>Left IFG → Right IFG</i>	1.220/21.951	3.030	0.178
<i>Right IFG → Left STG</i>	2/36	0.905	0.552
<i>Right IFG → Right STG</i>	2/36	2.855	0.170
<i>Right IFG → Left IFG</i>	2/36	6.526	* 0.024

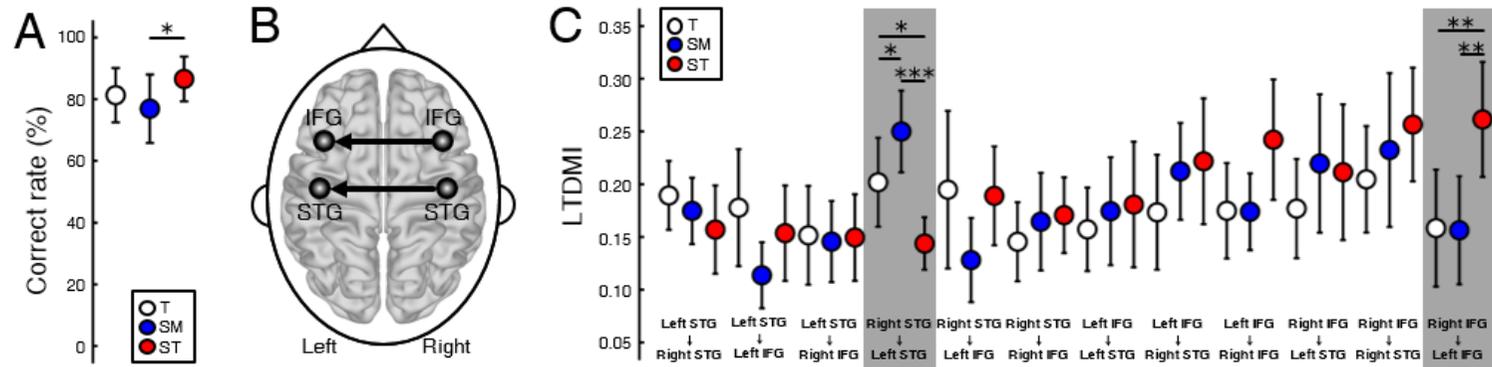


Figure 2-2-3. Difference in the LTDMI values for the three conditions. (A) CF of SM is significantly lower than the CR of ST. The other pairs are not statistically significant. $* P < 0.05$. (B) Difference between the conditions for LTDMI was revealed in only two interhemispheric connections, which were termed “IFG-LTDMI” and “STG-LTDMI”. (C) The STG-LTDMIs were different between all pairs. In the IFG-LTDMI, the SM was higher in the other conditions. $* P < 0.05$, $** P < 0.01$, and $*** P < 0.001$ (FDR corrected). Error bars denote 95% confidence intervals. See also Table 2-2-1.

Behavioral response

During magnetoencephalography (MEG) experiment, participants were asked to listen to each condition carefully and to detect the sequences including a staccato chord in order to check the level of attending to the condition (Figure 2-2-1B). All participants detected the staccato chord with more than 95% including the number of missed buttons. This indicates that the participants paid attention to musical stimuli. After the MEG experiment, participants performed a behavioral test discriminating among the three conditions (Figure 2-2-1B). The mean CR ($n = 18$) was lower in the SM (77.0%) than in the T (82.4%) and the ST (88.7%). The one-way repeated measure ANOVA ($n = 18$, excluded 1 outlier) showed a significant main effect of Condition [$F(2,34) = 4.799, P = 0.015$]. In a *post hoc* analysis, the difference between the CRs was significant only between the SM and the ST (Figure 2-2-3A). The SM was significantly lower than the ST [$t(17) = -2.574, P = 0.020$]. There were no significant differences in the pairs of T vs. SM [$t(17) = 1.772, P = 0.094$] and T vs. ST [$t(17) = -1.753, P = 0.098$].

Correlation between the LTDMI values and correct rate

To confirm whether the STG-LTDMI reflected perceptual ambiguity, and, if it was so, whether it was specific for the STG-LTDMI among the IFG-LTDMI and the STG-LTDMI, we tested the correlation between the LTDMI values of STG-LTDMI/IFG-LTDMI and the behavioral response of CR. The correlation was tested using the values for all conditions and participants ($n = 57, 3 \text{ conditions} \times 19$

participants). A significant correlation with the CR was observed not in the IFG-LTDMI but in the STG-LTDMI (one-tailed Spearman's rank correlation; STG-LTDMI, Spearman's $\rho = -0.260$, $P = 0.026$; IFG-LTDMI, Spearman's $\rho = 0.064$, $P = 0.319$) (Figure 2-2-4).

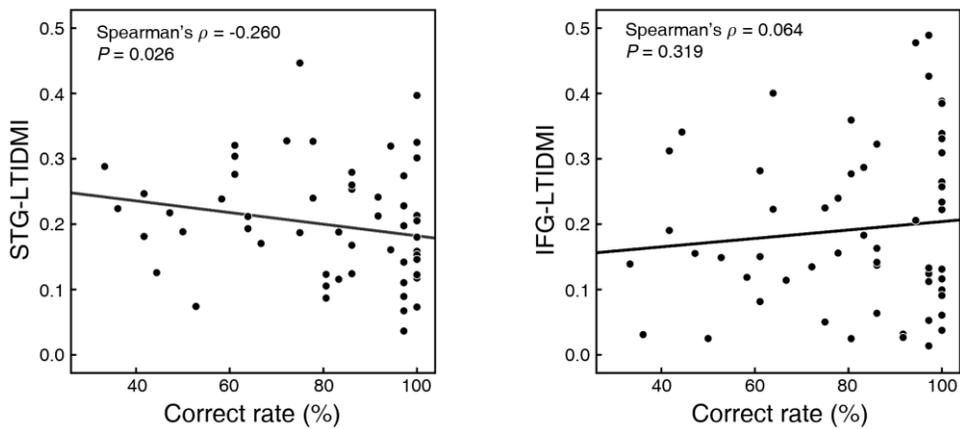


Figure 2-2-4. Correlation between CR and STG-LTDMI/IFG-LTDMI. The CR was only negatively correlated with the STG-LTDMI ($n = 57$, one-tailed Spearman's rank correlation). However, the CR did not show a correlation with the IFG-LTDMI ($n = 57$, one-tailed Spearman's rank correlation).

Discussion

The IFG-LTDMI was enhanced for the ST of the most irregular condition. The STG-LTDMI was enhanced for the SM of the most ambiguous condition. The processing of syntactic irregularity and perceptual ambiguity in the three conditions was dissociated in the IFG-LTDMI and the STG-LTDMI, respectively. This implies that

the brain interprets the three conditions as both “from regular to irregular” and “from ambiguous to unambiguous” conditions simultaneously.

The highest IFG-LTDMI for the ST is a further extension of the highest ERAN response elicited only for the irregular condition (ST) in our previous study, which found that a prominent early right anterior negativity’s magnetic counterpart (ERANm) was not observed in the SM of the less irregular condition in terms of syntactic irregularity (Kim et al., 2014). The IFG-LTDMI in terms of effective connectivity may underlie the ERAN. Moreover, the IFG-LTDMI from the right to the left IFGs is one step forward from the previous reports that the bilateral IFGs are the neural generator of ERAN (Kim et al., 2014; Kim et al., 2011; Maess et al., 2001; Sammler et al., 2009). Our data suggests that the left IFG and the right IFG interrelate in the processing of musical syntax, in terms of effective connectivity.

The STG-LTDMI was highest for the most ambiguous SM. The ST was lowest. Unambiguous stimuli of speech and ambiguous stimuli of speech like song differently activate the STG (Tierney et al., 2013). The patterns of STG-LTDMI between all conditions were consistent with our hypotheses that the SM would be most ambiguous. Moreover, these results show that the T was more ambiguous than the ST with the salient highest voice. The smallest unit comprising of harmony and melodic line in chord sequence is a single tone. In language, a phoneme is the smallest unit. Acoustic–phonetic processing is related with the STG (Callan et al., 2004). Auditory areas involving Heschl’s gyrus are activated by ambiguous phonemes (Kilian-Hutten et al., 2011). Based on the aforementioned studies, we interpret our

findings in the bilateral STGs as indicating neural substrates for the perception of ambiguity implied in harmony and melodic line in chord sequence.

In previous studies, the connection between the IFG and STG is involved in the processing of syntax in music and language (Friederici, 2011; Musso et al., 2015; Sakai et al., 2002; Sammler et al., 2009). Moreover, a fMRI study using a real musical piece reported that the different level of syntactic irregularity was reflected in functional connectivity between the IFG and STG (Seger et al., 2013). In another fMRI study on acoustic–phonetic processing, IFG-STG coupling is increased by ambiguous acoustic signal (Leitman et al., 2010). However, our data did not show the connection between the IFG and the STG in either syntactic irregularity or perceptual ambiguity. Instead, the connectivity was dissociated in each of IFG and STG. Furthermore, the direction of effective connectivity was from the right to the left hemisphere in both the IFG-LTDMI and STG-LTDMI. We interpret dissociation of the IFG and STG in connectivity as indicating the functional segregation related with syntax and ambiguity processing. Also, we interpret that the same direction of information transmission in the bilateral IFGs and STGs as indicating the different roles of bilateral hemispheres in music processing and indicating the IFG-LTDMI and STG-LTDMI commonly based on the rightward asymmetry.

Considering the STG-LTDMI, the SM is most ambiguous among the three conditions, and the ST is less ambiguous than the T. The more ambiguous condition may be more difficult to response than the less ambiguous condition. However, the CR was only significantly different between the SM and the ST. Our results

demonstrate that the ST with a note of “D” in the highest voice, not included in the other conditions, was most unambiguous. These are consistent with previous studies addressing the perceptual prominence of melodic line (Marie and Trainor, 2013). Music-majors were more sensitive to harmony, while non-music-majors were more sensitive to melodic line (Fujioka et al., 2005). Our results show that the relationship between harmony and voice leading importantly affects chord perception.

Furthermore, for all participants, a significant correlation was only observed in the STG-LTDMI, not in the IFG-LTDMI. Also the following point should be taken into account. In the MEG experiment, the participants were asked to detect the “staccato” chords. Thus, both IFG-LTDMI and STG-LTDMI, based on the MEG data, would not reflect the attentive processing of the three conditions. Syntactic irregularity for harmony and melody of the highest voice can be perceived pre-attentively, which elicits an ERAN response (Koelsch et al., 2002b). Moreover, a deviant tone in tone sequence, eliciting mismatch negativity (MMN), can also be processed unconsciously (Brattico et al., 2006; Dürschmid et al., 2016). This indicates that both syntactic irregularity and perceptual ambiguity based on harmony and melodic line can be perceived pre-attentively. Nevertheless, there was a positive correlation between STG-LTDMI and CR, although the STG-LTDMI was pre-attentive and the behavioral CR was attentive.

Though our data suggest perceptual segregation of syntactic irregularity and perceptual ambiguity in chord sequences, we could not conclude that the present findings are relevant to whole chords in Western music theory. This would be

completed by using musical stimuli specifying the level of syntactic irregularity and perceptual ambiguity. Moreover, our data only focused on the 4 ROIs of the bilateral IFGs and STGs based on our hypothesis. The syntactic irregularity and perceptual ambiguity processes responding to the whole chord of Western tonal music would be also examined in terms of the relevant brain regions including the 4 ROIs of the bilateral IFGs and STGs on our hypothesis.

Nevertheless, we demonstrate for the first time that interhemispheric connectivity in the bilateral IFGs and STGs respectively dissociates syntactic irregularity and perceptual ambiguity in chord sequences. Our results suggest that syntactic irregularity and perceptual ambiguity in music, are processed simultaneously and separately.

Acknowledgements

We would like to thank Ji Hyang Nam for the technical support in MEG acquisition.

CHAPTER 3. MELODY

STUDY III. Fronto-temporal connectivity changes by a real melody in music

Abstract

In real music, the original melody may appear intact, with little elaboration only, or significantly modified. Since a melody is most easily perceived in music, hearing significantly modified melody may change a brain connectivity. Mozart KV 265 is comprised of an original melody of “Twinkle Twinkle Little Star” with its significant variations. We studied whether effective connectivity changes with significantly modified melody, between bilateral inferior frontal gyri (IFGs) and Heschl’s gyri (HGs) using magnetoencephalography (MEG). Among the 12 connectivities, the connectivity from the left IFG to the right HG was consistently increased with significantly modified melody compared to the original melody in 2 separate sets of the same rhythmic pattern with different melody ($p = 0.005$ and 0.034 , Bonferroni corrected). Our findings show that the modification of an original melody in a real music changes the brain connectivity.

Significant statements

Our data show how a regional connectivity changes when the original melody is intact or significantly modified, consistent in two different sets of variations with the same rhythmic patterns but with the different melody pattern. The present study employed real music of Mozart's Variation KV 265 as musical stimuli, dissected musical elements in each variation, and devised the two comparable sets of variation, which have the same rhythmic pattern but different melody. We exploited naturalistic conditions in real music instead of devising artificial conditions, and successfully demonstrated how variations of melody in real music change a regional connectivity in the brain.

Introduction

Melody is a feature effortlessly extracted from music, which sometimes represents the music itself. Beethoven symphony No. 9 is known as "Ode to joy", since the melody of "Ode to joy" appears repeatedly across the 4th movement of the symphony, which is easily and prominently detected. The human brain has several interconnected key regions processing melody, including bilateral inferior frontal gyri (IFGs) and Heschl's gyri (HGs) (Grahn and Rowe, 2009; Janata et al., 2002; Maess et al., 2001; Patel and Balaban, 2001; Patterson et al., 2002; Schneider et al., 2005; Seol et al., 2011). Extracting and interpreting a melody in music would be accompanied with changes in a regional connectivity.

Mozart 12 Variations KV 265 on “Ah! vous dirai-je Maman” of a French chanson is well-known as “Twinkle Twinkle Little Star” Variations, of an English lullaby. In some of the variations, the original melody appears intact or with little elaboration only. In others, it is significantly modified. We call the former variations with original melody (VOM) and the latter variations with modified melody (VMM). The original melody of “Twinkle Twinkle Little Star” in the *Theme* is modified or repeated in 12 variations. Five conditions of the *Theme*, *Variation I*, *Variation II*, *Variation III*, and *Variation IV* are composed in the same key, harmony, meter, timbre, and ternary form. Among the five conditions, the original melody is present in the *Variation II* and *IV*. However, the original melody is significantly modified in the *Variation I* and *III*. In terms of rhythmic pattern, the *Variation I* and *II* are of 16th notes, while the *Variation III* and *IV* are of 8th notes. Hence, two sets of “*Variation I* vs. *II*” and “*Variation III* vs. *IV*” are of the same rhythmic patterns, but of different melodies (Figure 3-1). We hypothesized that the presence or absence of the original melody in the two sets of “*Variation I* vs. *II*” and “*Variation III* vs. *IV*” would change effective connectivity between the bilateral IFGs and HGs. For effective connectivity, we calculated the linearized time delayed mutual information (LTDMI) (Jin et al., 2010).

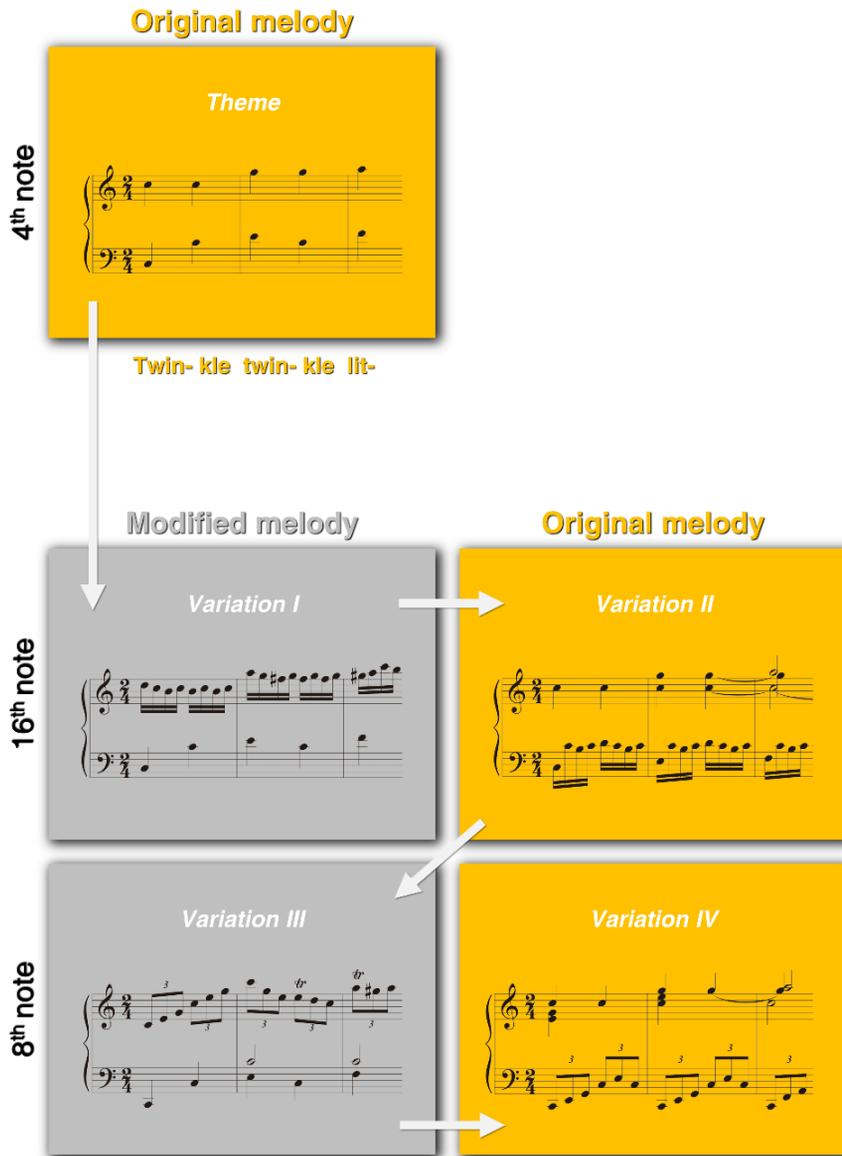


Figure 3-1. Musical stimuli. Five conditions of the *Theme*, *Variation I*, *II*, *III*, and *IV* selected in Mozart 12 Variations on “Ah! vous dirai-je Maman”KV 265. The original melody of “C5 - C5 - G5 - G5 - A5 (Twin- kle twin- kle lit-)” is included in the *Theme*, *Variation II*, and *Variation IV* (orange boxes). The *Variation I* and *Variation III* include the modified melodies (gray boxes). Rhythmic patterns are consistent in each set of “*Variation I* and *Variation II*” (16th notes) and “*Variation III* and *Variation IV*” (8th notes).

Materials and Methods

Ethics Statement

The study was approved by the Institutional Review Board of the Clinical Research Institute, Seoul National University Hospital (IRB No. C-1003-015-311). All experiments were conducted in accordance with the ethical guidelines and regulations.

Participants

Twenty-five participants (15 females, mean age, 26.8 ± 3.4 years) were all right-handed (mean Edinburgh Handedness coefficient, 95.7 ± 7.1). All participants had normal hearing, and had not received any formal musical training. Prior to the experiments, all the participants provided the informed consent in a written form.

Musical stimuli

Out of the theme and the 12 Variations in Mozart's Variation on "Ah! vous dirai-je Maman" KV 265, we selected the five conditions of *Theme*, *Variation I*, *II*, *III*, and *IV* in Figure 3-1, composed in the same key (C major), harmony (tonic-tonic-subdominant-tonic...), meter (2/4), and structure (ternary form). In magnetoencephalography (MEG) experiment, all participants were asked to passively listen to the musical stimuli without paying any attention to any specific musical feature, such as melody.

Time window

The time window was selected based on the concept of the motif (Drabkin, 2014). Previous studies reported that differences in melody were detected by listening to a segment of three to six notes in a motif of an original melody (Bella et al., 2003). The ascending five quarter notes of “C5 - C5 - G5 - G5 - A5” (2,100 ms) of the time window were in the motif of “C5 - C5 - G5 - G5 - A5 - A5 - G5 - G5”. For the five quarter notes of in the *Theme*, the number of 16th notes or 8th notes (in triplets) subdivided in accompaniments was the same between the *Variation I, II, III, and IV*.

The present musical stimuli were recorded music that was presented continuously, without intervening breaks between movements of a theme and variations. To select the proper time window, we had to consider all the subdivided notes included in a quarter note in each time window in all conditions. The time window of 2,100 ms was the most suitable duration because (1) 2,100 ms covered the onset of the first quarter note to the offset of the last quarter note in the time window; (2) the number of additional notes did not exceed a quarter note in all the conditions; and (3) fade-out times of the final note in the preceding condition did not overlap with the onset of the time window in the following condition. The same phrases of the time window were repeated four times in each condition. However, to rule out the effect of repetition (Guo and Koelsch, 2015), we analyzed only the “C5 - C5 - G5 - G5 - A5” in the opening in each condition.

Data recording

The MEG signal was recorded with a sampling frequency of 1,000 Hz using a 0.1–200 Hz band pass filter in a magnetically shielded room with a 306-channel whole-head MEG System (Elekta Neuromag Vector View™, Helsinki, Finland). Electrooculograms (EOG) and electrocardiograms (ECG) were also simultaneously recorded to remove ocular and cardiac noise at a later time. We eliminated the environmental magnetic noise of raw MEG signals with the temporal signal space separation (tSSS) algorithm in MaxFilter 2.1.13 (Elekta Neuromag Oy, Helsinki, Finland) (Taulu and Hari, 2009).

During the MEG recording, for about five minutes, all participants sat in a magnetically shielded room and passively listened to music (Mozart 12 Variations on “Ah! vous dirai-je Maman” KV 265, 2011, Brilliant classics, Dutch). Musical stimuli were presented binaurally through plastic tubal silicone earpieces, 50 cm in length using STIM2™ (Neuroscan, Charlotte, NC, USA) at 100 dB. Visual stimuli of a silent movie clip (Love Actually, 2003, Universal Pictures, USA) were presented on a screen to keep the participants awake (Koelsch and Jentschke, 2008; Ruiz et al., 2009) while the musical stimuli were being presented. For MEG signals, EOG, ECG, muscle artifact was removed using the independent component analysis. Epochs were determined from -100 ms to 2,100 ms after the onset of each condition, and the baseline of each epoch was from -100 ms to 0 ms.

Data analysis

The source coordinates for the ROIs of the bilateral HGs and IFGs were based on the standard Talairach coordinates; Heschl's gyrus (transverse, BA 41, BA 42) and the inferior frontal gyrus (triangular part, BA 45); the x, y, and z *in* Talairach coordinates (millimeters) were -53.5, -30.5, and 12.6 in the left HG, 55.4, -30.5, and 12.6 in the right HG, -55.5, 11.7, and 20.6 in the left IFG, and 53.5, 12.7 and 20.6 in the right IFG, respectively (Figure 3-2). The signal for each regional source of 4 ROIs (bilateral HGs and IFGs) was extracted using a 14–30 Hz band-pass filter for each participant using BESA 5.1.8.10 (MEGIS Software GmbH, Gräfelfing, Germany), which was averaged at MATLAB 7.7.0.471 (Math Works Inc., Natick, MA, USA). In Figure 3-2, The Talairach coordinates were visualized using BrainNet Viewer (<http://nitrc.org/projects/bnv/>).

For the twelve connections among the bilateral HGs and IFGs, effective connectivity for twelve connections was estimated using LTDMI (Jin et al., 2010). The mutual information (MI) is a measure testing the relationship between the conditions by measuring the amount of information between two random variables. The LTDMI is an information theoretic measure estimating the directional information transmission of functional coupling based on MI:

$$MI = MI_{AB} = MI_{BA} = MI(A(n), B(n)) = - \sum_k p(A(n), B(n)) \log \frac{p(A(n), B(n))}{p(A(n))p(B(n))} \quad (1)$$

Based on MI, the linear correlation for the information transmission between time series A and B is estimated by LTDMI:

$$LTDMI_{AB} = LTDMI(A(n), B(n + \tau)) = -\frac{1}{2} \log(1 - \rho_{A(n)B(n+\tau)}^2)$$

$$LTDMI_{BA} = LTDMI(B(n), A(n + \tau)) = -\frac{1}{2} \log(1 - \rho_{B(n)A(n+\tau)}^2) \quad (2)$$

where τ is delay time, and $\rho_{A(n)B(n+\tau)}$ or $\rho_{B(n)A(n+\tau)}$ is a cross-correlation coefficient. The LTDMI value was averaged over delay time, which was calculated for every individual participant for each of the four conditions and twelve connections. See our previous study (Jin et al., 2010) for the details of the LTDMI.

The mean LTDMI value for the time window of 2,100 ms in each condition was calculated for the twelve connections between the four ROIs. Because the data set was not normally distributed, the differences in LTDMI values of the conditions including “Twinkle Twinkle Little Star” melody or not were tested by the Wilcoxon signed rank test using SPSS 21.0 software (IBM, Armonk, NY, USA). Multiple comparisons for the twelve connections in each set were adjusted by the Bonferroni test ($p < 0.05$).

Results

The Wilcoxon signed-rank test revealed that the LTDMI from the left IFG to the right HG was significantly different between “*Variation I* vs. *Variation IP*” ($Z = -3.512$, $p = 0.005$, Bonferroni corrected) as well as between “*Variation III* vs. *Variation IV*” ($Z = -2.987$, $p = 0.034$, Bonferroni corrected) (Table 3-1). In this fronto-temporal connection, the LTDMI values increased in the VMM (*Variation I* and *III*) compared to the VOM (*Variation II* and *IV*) (Figure 3-2).

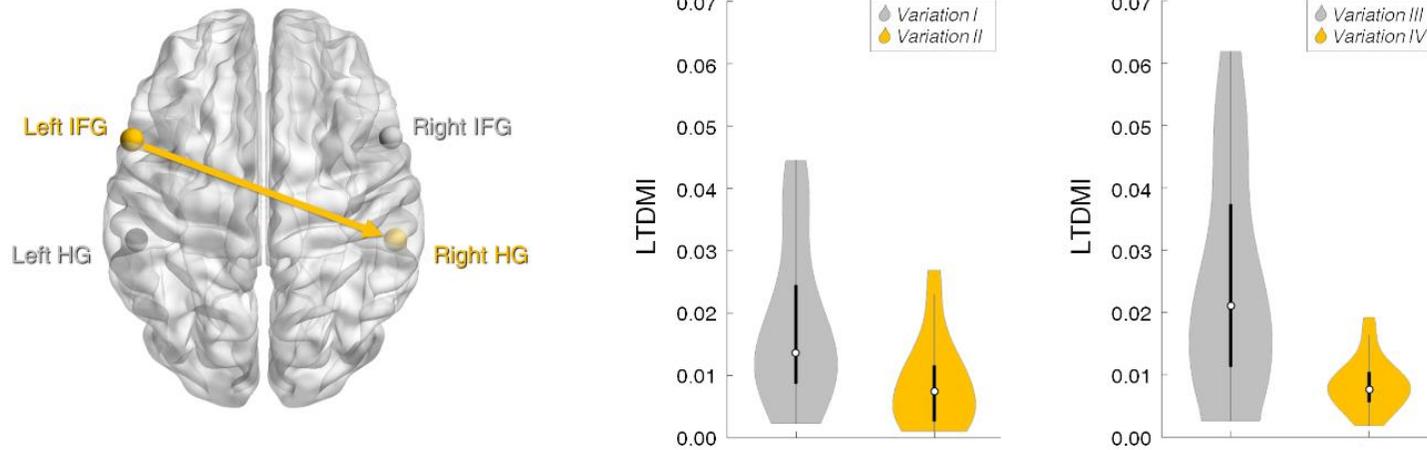


Figure 3-2. Difference in effective connectivity from the left IFG to the right HG for the modified and original melodies. Effective connectivity in both sets of “*Variation I vs. Variation II*” and “*Variation III vs. Variation IV*” showed an identical pattern in the Wilcoxon signed-rank test. Violin plots show that the LTDMI values are significantly higher for the *Variation I* and *III* with the modified melodies than for the *Variation II* and *IV* with the original melody; “*Variation I vs. Variation II*”, $Z = -3.512$, $p = 0.005$, Bonferroni corrected; “*Variation III vs. Variation IV*”, $Z = -2.987$, $p = 0.034$, Bonferroni corrected (See also Table 3-1).

Table 3-1. LTDMI difference between the conditions with the modified or original melodies. For the both sets of “*Variation I vs. Variation IP*” and “*Variation III vs. Variation IV*”, the LTDMI values differed in a connection from the left IFG to the right HG among twelve connections (Wilcoxon signed-rank test, N = 25, Bonferroni corrected * $p < 0.05$ and ** $p < 0.01$).

	<i>Variation I vs. Variation II</i>			<i>Variation III vs. Variation IV</i>		
	<i>Z</i>	<i>P</i> _(uncorrected)	<i>P</i> _(corrected)	<i>Z</i>	<i>P</i> _(uncorrected)	<i>P</i> _(corrected)
<i>Left HG → Right HG</i>	-0.565	0.572	1.0	-1.090	0.276	1.0
<i>Left HG → Left IFG</i>	-0.727	0.468	1.0	-1.843	0.065	0.784
<i>Left HG → Right IFG</i>	-0.148	0.882	1.0	-0.229	0.819	1.0
<i>Right HG → Left HG</i>	-1.493	0.135	1.0	-0.175	0.861	1.0
<i>Right HG → Left IFG</i>	-1.286	0.199	1.0	-1.029	0.304	1.0
<i>Right HG → Right HG</i>	-1.305	0.192	1.0	-0.148	0.882	1.0
<i>Left IFG → Left HG</i>	-1.117	0.264	1.0	-1.655	0.098	1.0
<i>Left IFG → Right HG</i>	-3.512	0.0004	0.005 **	-2.987	0.0028	0.034 *
<i>Left IFG → Right IFG</i>	-0.875	0.382	1.0	-1.238	0.216	1.0
<i>Right IFG → Left HG</i>	-1.129	0.259	1.0	-0.498	0.619	1.0
<i>Right IFG → Right HG</i>	-1.762	0.078	0.936	-0.982	0.326	1.0
<i>Right IFG → Left IFG</i>	-2.193	0.028	0.340	-0.848	0.397	1.0

Discussion

Effective connectivity from the left IFG to the right HG increased when the original melody of “Twinkle Twinkle Little Star” was significantly modified (VMM), compared with that when the original melody was intact (VOM). It appeared consistent in two different sets with the same rhythmic patterns but with the different melody pattern.

The present study employed real music with its variations as musical stimuli, dissected musical elements in each condition, and devised the two comparable sets of conditions, which have the same rhythmic pattern but different melody. Here, we exploited naturalistic conditions in real music instead of devising artificial conditions, and successfully demonstrated how significant variations of melody in real music change a regional connectivity in the human brain. These are distinct from the attempts in previous studies used to original musical pieces (Burunat et al., 2014; Plailly et al., 2007; Platel et al., 2003; Sridharan et al., 2007; Wilkins et al., 2014).

An fMRI study, using a real music of “Adios Nonino”, studied the effects of motif repetitions on effective connectivity changes. Specifically they found that the hippocampal connectivity is modulated by motif repetitions, showing strong connections with working memory-relevant areas (Burunat et al., 2014). In another fMRI study using real musics of classical, country, rap/hip hop, rock, and unfamiliar cultural musical genres, connectivity strength enhanced for preferred music (Wilkins et al., 2014). These studies show real musics and characteristics within those can change the brain connectivities.

When hearing real music the brain regions would interact to support complex cognitive processes (Patel, 2008; Salimpoor et al., 2011). In the perspective of the brain networks, the change in effective connectivity from the left IFG to the right HG could be interpreted in the syntactic process. The effective connectivity from the left IFG to the right HG would underlie the processing of the original melody of “Twinkle Twinkle Little Star”. It is familiar and is repeated in the musical piece. Musical syntax arouses an expectation in musical context. Therefore, “Twinkle Twinkle Little Star” melody may arouse an expectation when each condition is sequentially presented following the *Theme*. Then, the significantly modified melody, relatively novel melody, would enhance effective connectivity involving relevant brain regions. The enhanced connectivity in our results is a further extension of previous studies that the conditions in violating syntax enhance not only the ERP responses such as the ERAN but also connectivity strength (Kim et al., 2014; Maess et al., 2001; Seger et al., 2013). Even though the bilateral IFGs are associated with musical syntactic processing, the left IFG is especially crucial (Sammler et al., 2011). In our previous study (Kim et al., 2019), the brain networks centered in the left IFG was related with the processing of particular information which only the musically trained people could identify. In this regards, the fronto-temporal connectivity was increased in the VMM compared to the VOM with the “Twinkle Twinkle Little Star”.

Also it is interesting that the change in fronto-temporal connectivity was observed in the beta frequency band (see also the Materials and Methods section). The connectivity changes were consistent in the two sets of “*Variation I vs. II*” and

“*Variation III vs. IV*”, which are different in the rhythmic patterns of 16th and 8th notes sequences, respectively. Generally the beta frequency band is associated with the processing of deviant stimuli (Kim and Chung, 2008) and memory/categorical perception (Weiss and Mueller, 2012). The connectivity in the beta frequency band would reflect the categorization of the deviant WMM and the WOM based on the information of the original melody acquired in real-life.

Also, beta frequency is related with beat perception. While regular auditory stimuli were presented, beta oscillation was synchronized with the beat, while it was increased when the beat was omitted (Fujioka et al., 2009, 2012). Therefore, the changes in fronto-temporal connectivity at the beta frequency band might reflect omission of the beats on the original melody of quarter notes sequence in each condition, regardless of changes in rhythmic patterns. It may be an alternative explanation why the fronto-temporal connectivity increased with modified melody conditions compared to the original melody.

In our study, the time window of five notes, “C5 - C5 - G5 - G5 - A5” (2.1 sec) was set based on the “C5 - C5 - G5 - G5 - A5 - A5 - G5 - G5” motif of “Twinkle Twinkle Little Star” song in the *Theme*. In a previous study, the isolation point, the point at which a melody is correctly identified, is about 2.5 sec of 5 notes for highly familiar melodies (Bella et al., 2003). Therefore, the five notes in the motif, which we analyzed were long enough to detect the original melody.

There are several limitations in our study. The present study looked at the particular music, Mozart KV 265 with its theme and 4 variations. Hence, we could

not assert that our findings could extend to the other real musics. Also the present study was limited to 4 regions of interest, including bilateral inferior frontal and superior temporal area. There should be further studies covering the whole brain. Finally, in order to focus on melody difference, we tried our best to eliminate the effects of other elements implied in naturalistic conditions. However, it should be discovered through further studies.

In conclusion, the fronto-temporal connectivity from the left IFG to the right HG was enhanced when the modified melody was presented, compared with the original melody of “Twinkle Twinkle Little Star” in Mozart “Ah! vous dirai-je Maman” KV 265. Our findings show that the modification of an original melody in a real music changes the brain connectivity.

Acknowledgements

We would like to thank Ji Hyang Nam for the technical support in MEG acquisition.

CHAPTER 4. BEAT

STUDY IV. Auditory beats evoke coherent widespread brain oscillations

Abstract

We can incorporate beat when hearing regularly presented auditory stimuli. However, incorporation of beat would be distinct from perception of auditory stimuli presented regularly. After beat are incorporated, it might continue even when several auditory stimuli were omitted. This hypothesis was examined in electrocorticography data of 30 epilepsy patients, using an oddball paradigm including one stimulus randomly omitted in sequentially presented stimuli. Auditory evoked potentials were observed by the auditory stimuli in auditory area. Mismatch negativity was also observed in superior temporal area, when auditory stimulus was omitted. Interestingly, sinusoidal signals of 2 Hz synchronized on the onset point of auditory stimuli persisted even when omitting one stimulus, which was observed widespread in anterior/posterior superior/middle temporal area except auditory area. Our findings suggest incorporation of beat, entrained by temporality of auditory stimuli, is represented by widespread synchronous oscillations.

Introduction

In music and music theory, the beat is the basic unit of time, the pulse (regularly repeating event), of the mensural level (Berry, 1987; Winold, 1975). Humans innately create and perceive beat in a sound sequence of complex rhythmic patterns, such as a real music, and can tap and move in response to the beat. Perception of input stimuli may be distinct from beat incorporation. Jones and Boltz suggested that “events define time intervals and that their inherent rhythmic patternings will affect the way people attend to them and judge their duration” (Jones and Boltz, 1989). Even though auditory stimulus is randomly omitted in a temporally presented sequence, beats are predictable. Therefore, the beat incorporation provides prediction of the interval in a temporally presented sequence.

We examined the hypothesis of whether neural activities reflecting beat incorporation is distinct from activities from perception of auditory stimulus with the intracranial electroencephalography (iEEG), which has high temporal and spatial resolution. In the present study, the term “beat” means accents with volume change (Grahn and Rowe, 2009), but not perceptual accent implied in metrical structure (Winkler et al., 2009). Auditory stimuli were beat sequences including randomly omitted beat based on oddball paradigm, which were basically made up of duple meter that alternates intensities of strong and weak. The duration of stimulus was 100 msec, and the amplitudes were 65 dB SPL in strong and 47 dB SPL in weak. Hence, auditory stimuli included 4 elements of “Strong”, “Weak”, “Strong-omission”, and “Weak-omission”. The inter-onset-interval (IOI) for a beat was 500

msec from the Strong to the Weak, and it was 1,000 msec from the Strong to the next Strong in terms of volume beat; see Figure 4-1 and the Materials and Method section for the details of auditory stimuli).

The oddball paradigm is an experimental design testing the effect of deviation from standard stimuli in a sequence with temporal regularity (Squires et al., 1975). The deviation in an oddball paradigm elicits event related potentials such as P300 and mismatch negativity (MMN) (Gray et al., 2004; Näätänen et al., 1993). Perception of auditory stimulus was evaluated with auditory evoked potential (AEP) and MMN. AEP refers to electronic signals for time-locked auditory stimuli, which include N1 (90 msec) and P2 (170 msec) components (Mantzaris and Kenny, 1997). MMN also consists of a portion of AEP, which refers to a peak with negative polarity, at around 150 ms after the onset of the deviation from the standard stimuli, here as “omission” (Khouri and Nelken, 2015), in the difference wave of “deviant - standard”. Most importantly, as an evidence of beat incorporation, we searched continuous activities of 1 or 2 Hz synchronized with expected IOI.

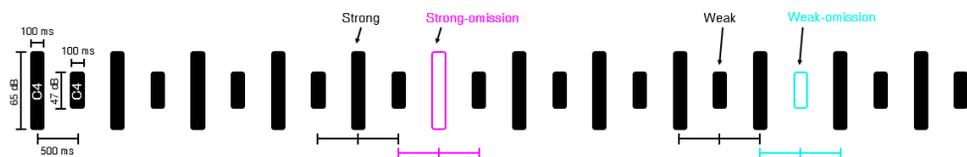


Figure 4-1. Auditory stimuli. Beat sequence was made up of C4 pure tones with interval of 500 ms, which alternating strong and weak intensities. Strong-omission and Weak-omission indicates randomly omitted stimulus in sequence of Strong and Weak. Black and pink/blue scale bars indicated below, denotes the time window of 1,000 msec oscillations presented in Figure 4-2.

Results and Discussion

In 9 patients among 30 patients, whose subdural strip electrodes were in the temporal lobe, the AEPs appeared clearly in auditory area (see also the left panels in Figure 4-2a). Also Strong/Weak-omission generated MMN (see also the right panels in Figure 4-2a), maximal in superior temporal area, peaks of which appeared at 100–250 msec (Choi et al., 2015; Shin et al., 2012) (Figure 4-2a, Table 4-1; difference wave of “deviant - standard” in Figure 4-3), generators of MMN of the superior temporal and frontal cortices (Shin et al., 2009). Previous studies indicated that the MMNs in strong omissions are more prominent than those in weak omissions, reflecting physical difference in strong and weak beats (Honing et al., 2014; Winkler et al., 2009). Hence, they claimed that MMNs are intimately related with beat incorporation, since those represent expectation and violation processes. In the present study, the MMNs were also more prominent in the Strong-omission than in the Weak-omission (See also Figure 4-4). However, 2 Hz oscillations corresponding to beat incorporation were not related with MMNs.

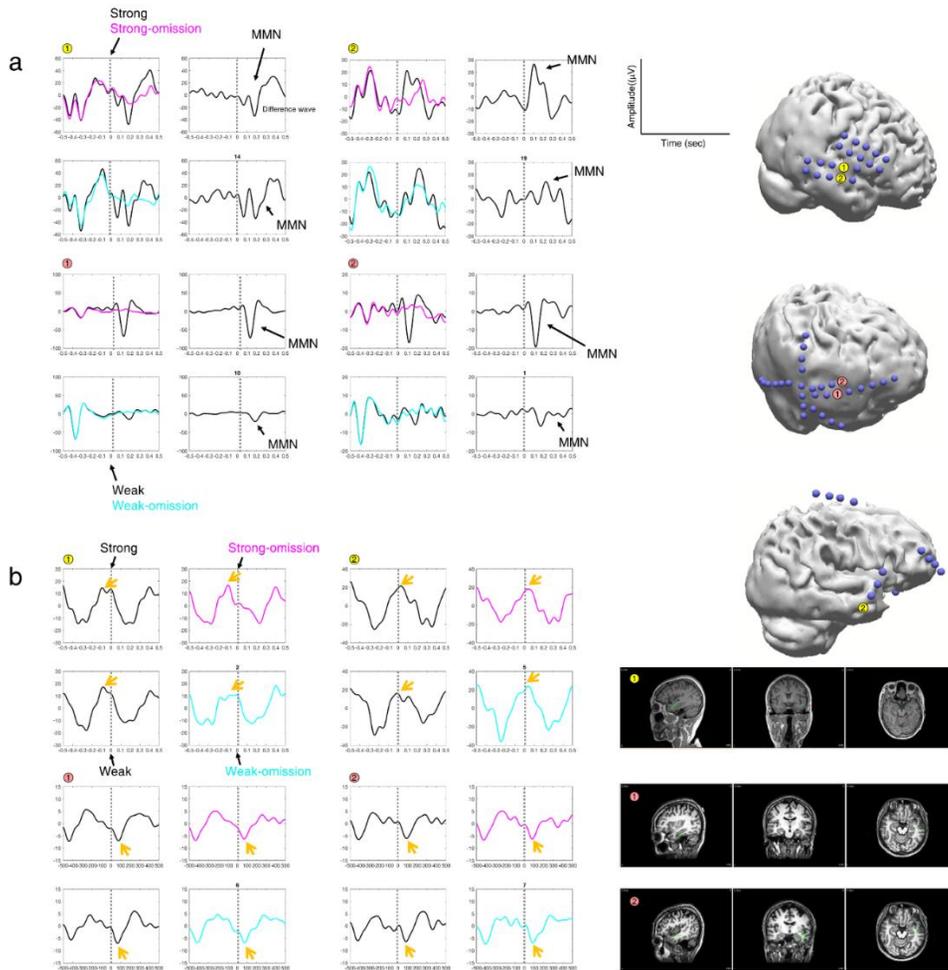
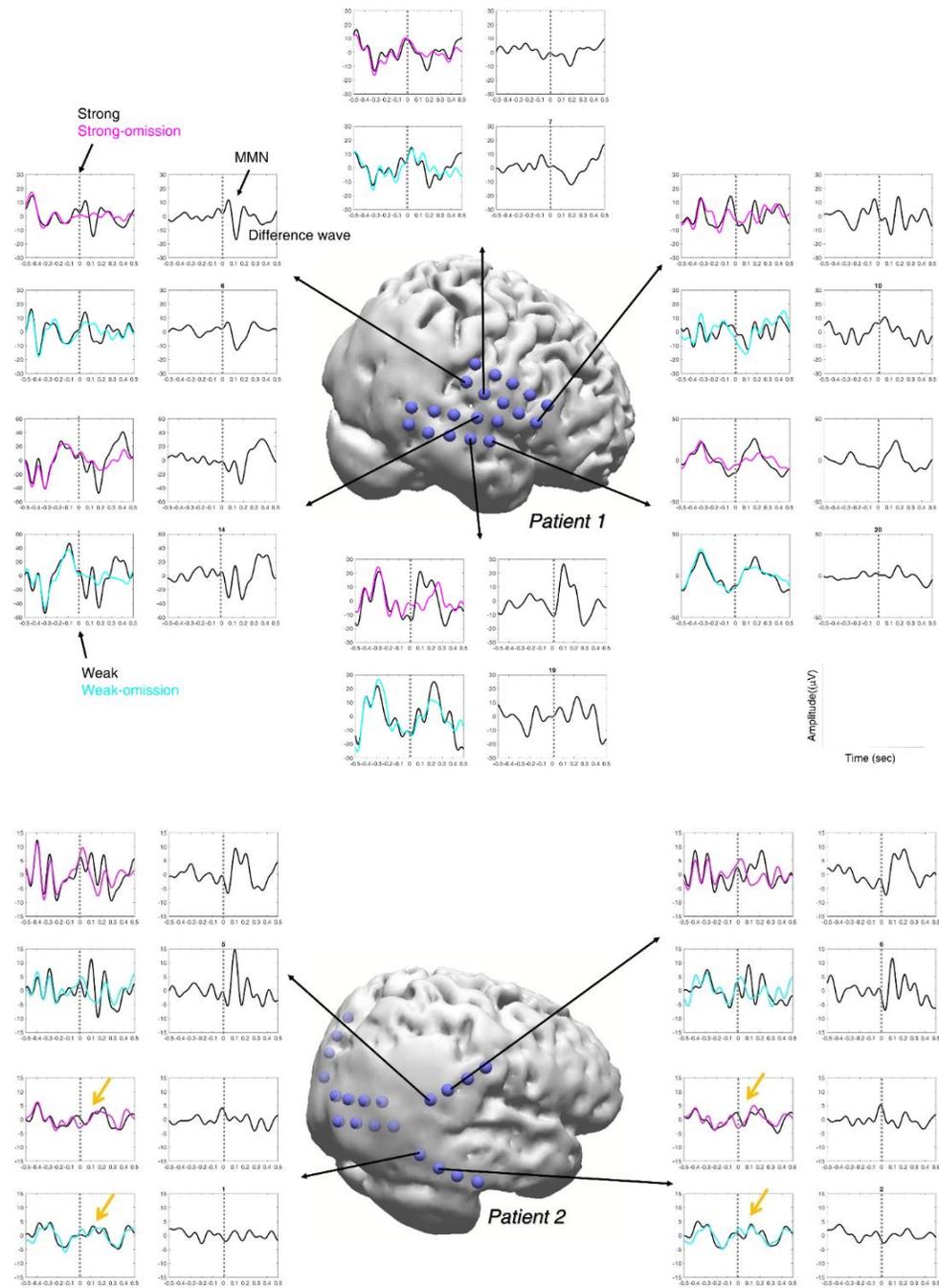
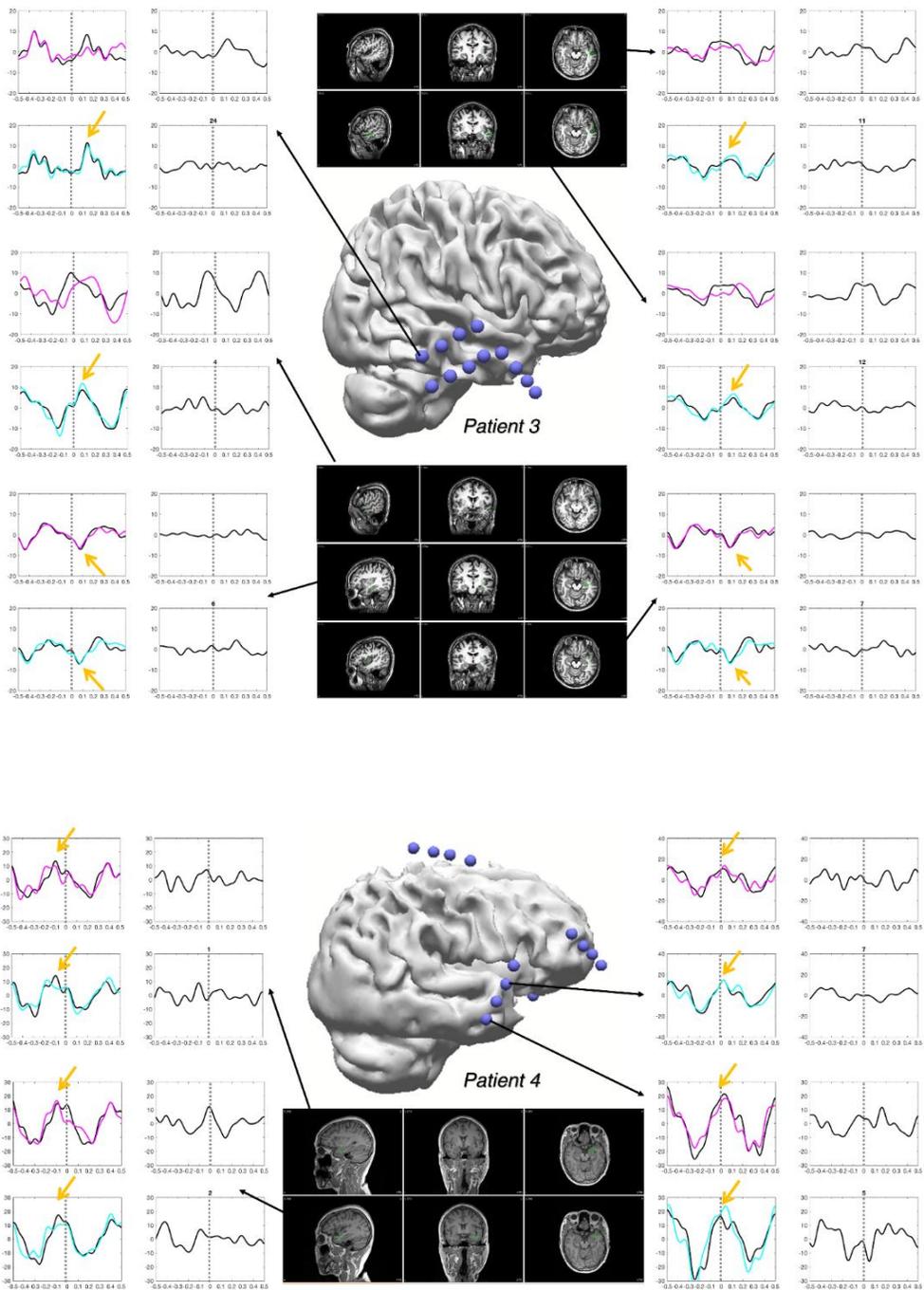
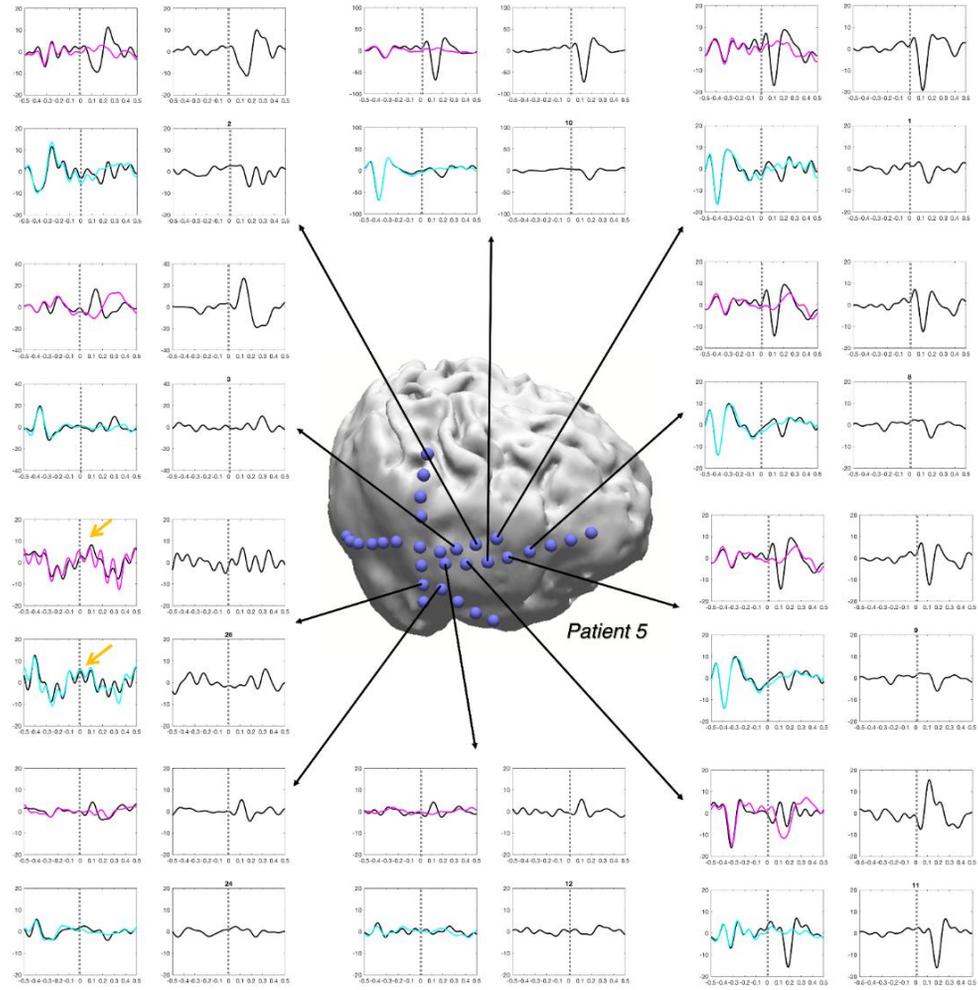


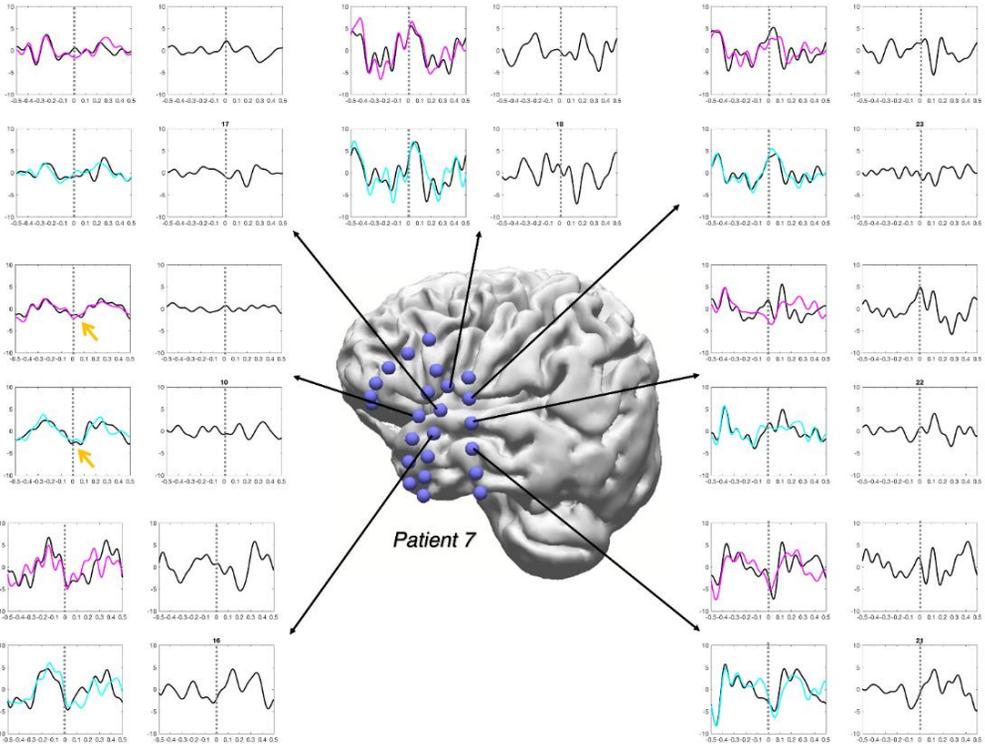
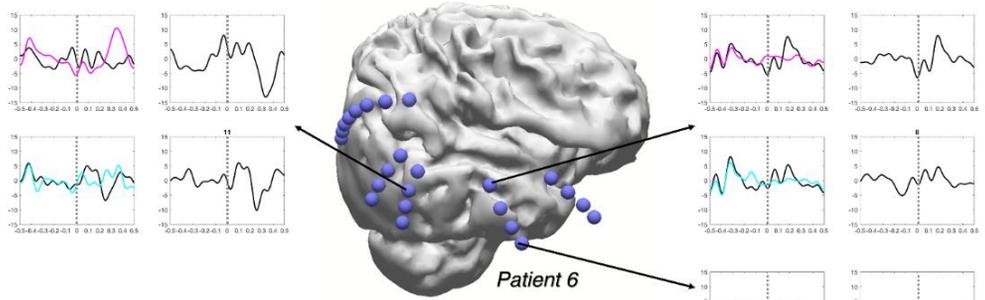
Figure 4-2. Oscillations by auditory beats. (a) Auditory MMNs in auditory area of 2 epilepsy patients. The left panel express each of Strong/Weak and Strong/Weak-omission, while the right panel express difference wave of “Strong/Weak minus Strong/Weak-omission”. In each panel, the time window of -500 to 0 msec shows auditory evoked response (AEP) to when auditory stimulus was always presented, whereas, the time window of 0 to 500 msec shows the different AEP by Strong/Weak and Strong/Weak-omission. In the right panel, MMN waveforms show clear peaks. (b) Responses to beat incorporation of 3 epilepsy patients. In sinusoidal signals having a pulse synchronized -100 to 100 ms around onset point of stimulus, Strong/Weak and Strong/Weak-omission, crests and troughs (orange arrows) were not perfectly synchronized with the stimulus onset. For purpose of graphic clarity, iEEG signals were band-pass filtered at 0.5-10 Hz. See also Supporting information.

Figure 4-3. Difference waveforms for 9 patients.









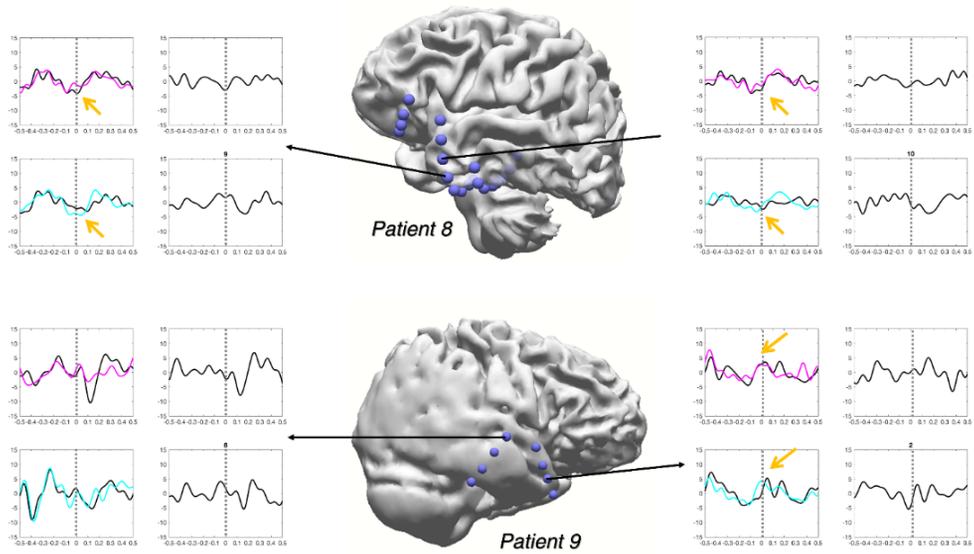


Figure 4-4. MMNs in Strong-omission and Weak-omission for 5 patients

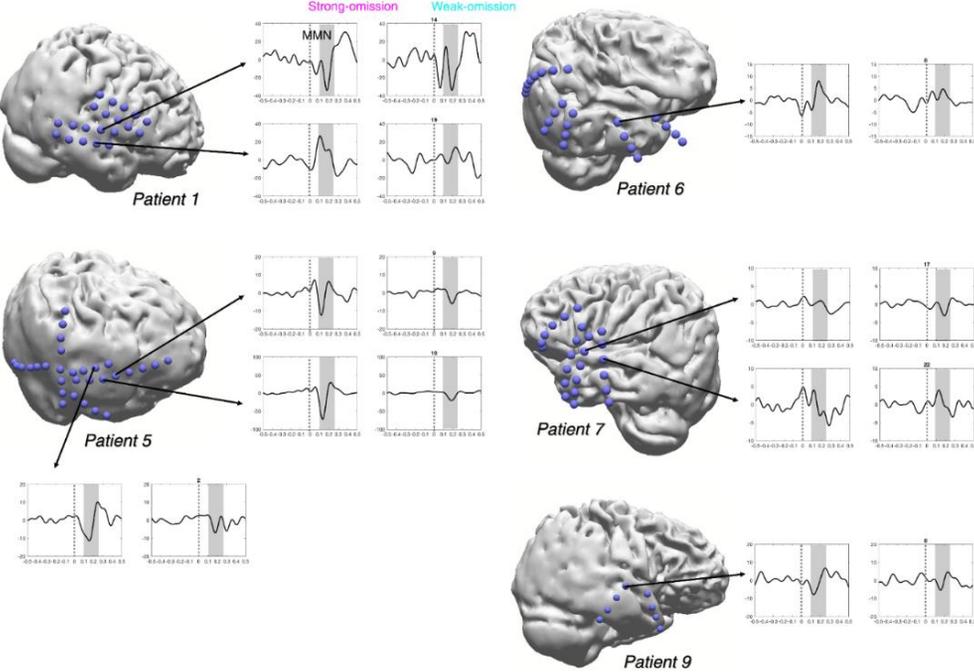
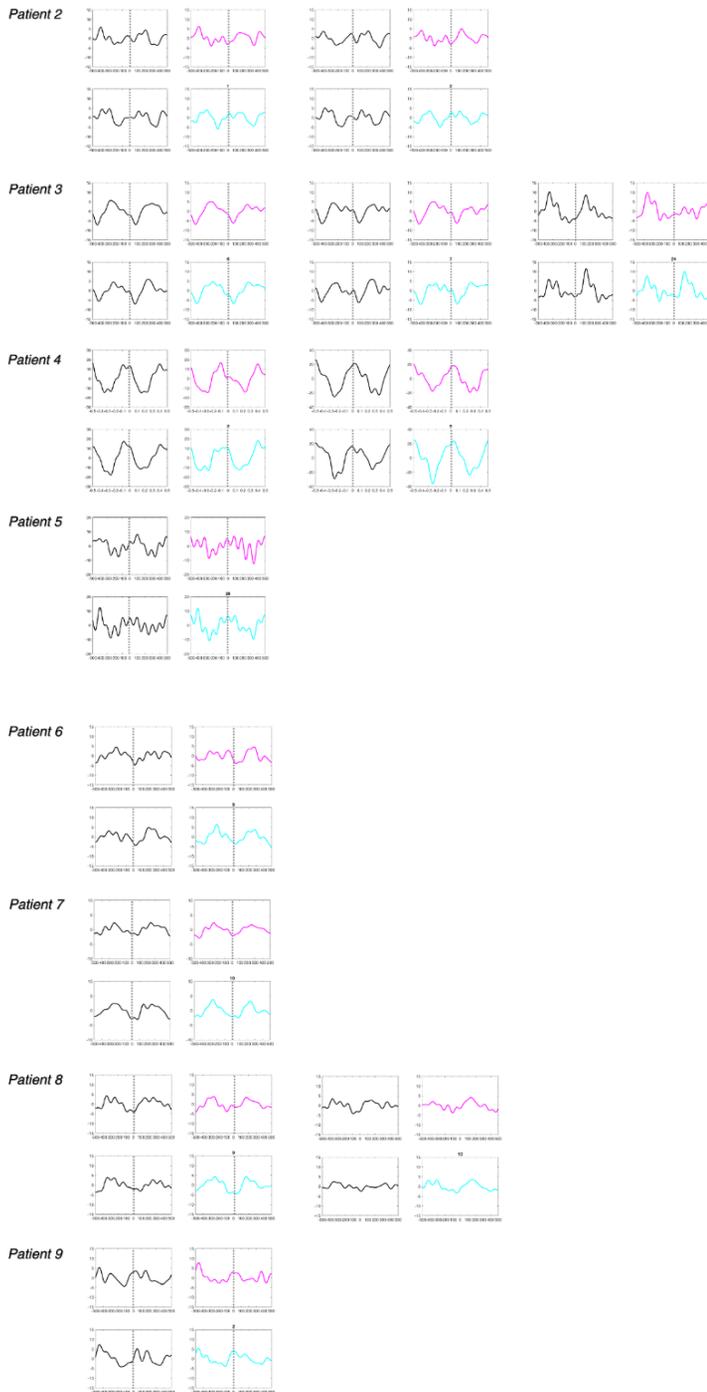


Figure 4-5. Sinusoidal signals for 8 patients.



Most interestingly, 2 Hz oscillations appeared in anterior and posterior parts of superior and middle temporal area other than auditory area (Figure 4-3, 4-5 and Table 4-1). These results indicate that beat incorporation and perception of auditory stimuli or their omission is dissociated. Furthermore, 2 Hz oscillations corresponding to beat incorporation were entrained by temporality of auditory stimuli even with random omission.

2 Hz oscillation was continuously observed regardless of beat omission, synchronized at -100 to 100 ms around onset points of beats (Figure 4-2b). The crests and troughs in waveforms of “M” and “W”, were not exactly matched with the onset of stimulus (Figure 4-2b). Considering that temporality of absolute beat is around 500-700 ms IOI (London, 2002; McAuley and Semple, 1999), the 2 Hz oscillations synchronized with expected IOIs would reflect the absolute beat incorporated in the patients. The variance in synchronization of crests/troughs might also be influenced by ability to sense a beat different between individual patients (Grahn and McAuley, 2009). Moreover, the crests/troughs which were preceded the onsets of stimulus or lagged behind those might reflect the processing of both the implicit/explicit anticipation of IOI of temporally presented stimulus (Miyake et al., 2004).

Table 4-1. Areas responded to MMN and 2 Hz oscillation based on Figure 4-3.

	AEP	MMN	2 Hz oscillation
<i>Patient 1</i>	auditory area	auditory area, superior temporal area somatosensory association area Broca's area	
<i>Patient 2</i>		temporoparietal junction	posterior middle temporal area
<i>Patient 3</i>		posterior Inferior temporal area	anterior superior temporal area posterior superior temporal area
<i>Patient 4</i>			anterior superior temporal area anterior middle temporal area
<i>Patient 5</i>	auditory area	auditory area, superior temporal area somatosensory association area Broca's area	posterior middle temporal area
<i>Patient 6</i>	auditory area	anterior superior temporal area posterior superior temporal area	anterior inferior temporal area
<i>Patient 7</i>	auditory area	auditory area, superior temporal area	anterior superior temporal area
<i>Patient 8</i>			anterior middle temporal area
<i>Patient 9</i>	auditory area	auditory area, superior temporal area	anterior middle temporal area

This study is the first to unveil oscillation synchronized on temporality of auditory sequence. Previous studies reported that beat may be related or with variance in beta and gamma oscillations according to beat omission or with envelope of the auditory beats. In several EEG studies using auditory beat sequence including randomly omitted tones, beta oscillations responded to the omitted tones, while gamma oscillations similarly responded to both presented and omitted tone (Fujioka et al., 2009, 2012). Previously steady state evoked potential studies demonstrated that EEG responses were synchronized with temporal envelope of auditory beats and meters (Nozaradan, 2014; Nozaradan et al., 2011; Nozaradan et al., 2012). Importantly, our results provided the information of phase (0.1-250Hz) responding to incorporation of beat having temporality of 2 Hz through the iEEG signals of high signal-to-noise ratio, but not the selected phases of given auditory beat, and of beta and gamma. We clearly showed that incorporation of beat through the 2 Hz oscillations is distinct from perception of auditory stimuli reflected by the AEP and MMN. Our study suggest, for the first time, sinusoidal signals of 2 Hz synchronized on the onset point of auditory stimuli persisted even when omitting one stimulus, using iEEG with high temporal and spatial resolution. Our study further shows that incorporation of beat is processed in the areas other than auditory area associated with perception of auditory stimuli.

However, there are some limitations in the present findings focusing on the 2 Hz oscillations entrained by the IOI between successive tones in auditory stimuli. The present findings did not involve beat incorporation entrained by 1 Hz oscillations

synchronized with volume beat of “Strong to the next Strong”. Beat incorporation for stimuli involving subdivided beats may be tentative according to preference of patients or absolute beat inherent in them. In this regards, it would be also another important issue whether variance of tempo with the shorter and longer IOIs is influential on beat incorporation, or not (McAuley and Semple, 1999). Moreover, triple meter of “Strong-Weak-Weak” versus duple meter of “Strong-Weak” would be an important issue.

In conclusion, the AEPs and MMNs peaks maximized in auditory area were mediated by the auditory stimuli and deviations of “omission”, respectively, involved in auditory oddball paradigm. The 2 Hz oscillations synchronized with sequentially presented stimuli, regardless of auditory stimuli or the deviations of “omission” in auditory oddball paradigm, showed that endogenous oscillator of beats exists in the temporal lobe.

Materials and Methods

Epilepsy patients

iEEG data set was acquired from 30 epilepsy patients (18 females, age range of 20-58), in whom subdural and depth electrodes (Ad-tech Medical Instrument Co.) were implanted for epilepsy monitoring in Seoul National University Hospital. All patients provided written informed consent prior to experiment. Entire experimental

procedure was approved by the Institutional Review Board of Seoul National University Hospital (H-1605-078-761).

Experiment and analysis

iEEG experiment consisted of 8 sessions. In each session, pure tone (C4) sequence including random 20 Strong-omissions and 20 Weak-omissions was presented about 4 min. Total experiment took about 1.5 hour including rest periods of patients and preparation time of the experiment. The patients were asked to pay attention to auditory stimuli.

We used 128-channel amplifier system (Neuroscan). iEEG signals digitized at 1000 Hz and filtered 0.1-250 Hz, were re-referenced to common average reference and were notch-filtered at 60 Hz. Epochs of -500 to +500 ms after the onset of Strong, Weak, Strong-omission, and Weak-omission were extracted. To localize the iEEG electrodes, pre-implantation MR was co-registered to post-implantation CT images (CURRY 7 software, Compumedics Neuroscan, Germany).

Acknowledgements

We would like to appreciate epilepsy patients participated in the iEEG experiment and their families for endurance and devotion, and Human Brain Function (HBF) Laboratory members and Seoul National University Hospital staffs for help and consideration in every iEEG experiments.

CHAPTER 5. GENERAL DISCUSSION

“Ursatz” refers to fundamental structure, named by Hienlich Shenker, i.e. “Ursatz” in Western tonal music can be explained as I-V-I progression based on Shenkerian analysis. Compared to this, “Ursatz” across musical stimuli in four experimental studies in this dissertation would be “beat”. All musical stimuli were in temporal dimension. Responding to music, the human brain also showed distinctive connectivity and network, ERP, and neural oscillation changes in temporal dimension. In other words, the brain responses of expectation violations on the musical stimuli are synchronized on referent beat implied in all musical stimuli.

In Chapter II. Harmony, 400 ms duration after the onset of the final chords of each sequence with six beats, based on both P2 in the STG and ERAN in the IFG, is a basis testing effective connectivity changes on deceptive cadence, syntactic irregularity, and perceptual ambiguity processes. The brain networks by deceptive cadence process involves the bilateral STGs and the left IFG. Syntactic irregularity process in connectivity from the left to the right IFG was simultaneously accompanied with perceptual ambiguity process in connectivity from the left to the right STG.

In Chapter III. Melody, 2100 ms duration included in motive of the theme, beats of five quarter notes synchronized with lyric of “Twin- kle- Twin- kle- Lit-”, is a cue discriminating between the conditions including modified and original melodies. The fronto-temporal connectivity from the left IFG to the right STG for the modified melody condition which five beats of “Twin- kle- Twin- kle- Lit-” were omitted, was

higher than for the original melody condition, reflecting the violation of expectation on the original melody.

In Chapter IV. Beat, expectation on regularly presented beats based on 2 Hz beat affected ERP waveforms in auditory area. Compared to conventional auditory ERP on On-beat, the ERP on Off-beat did not show clear peak amplitude. On the contrary to this, the sinusoidal signals reflecting beat sense were also synchronized on 2 Hz beat of pure tone sequence, which were observed in the brain areas excluding auditory area.

Given four experimental studies together, I interpret that the processing of expectation violations enhanced both peak amplitude of ERP and connectivity, involved with auditory area. Finally, I propose that expectation in music, in the perspective of temporal dimension, would be based on hierarchical model for melody and harmony interrelated with beat, “Ursatz” in the musical stimuli, and that can be explained based on “hierarchical model for processing melody, harmony, and beat” (Figure 5-1).

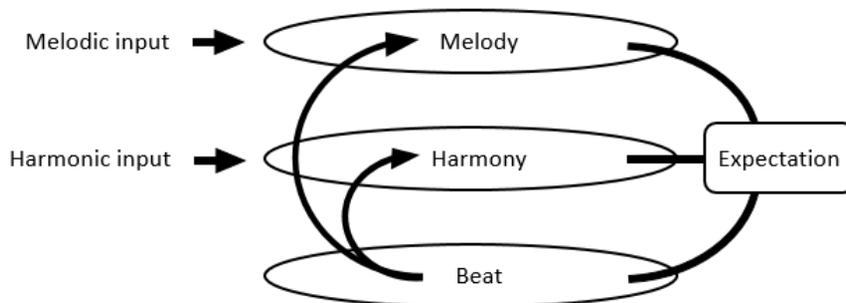


Figure 5-1. Hierarchical model on musical expectation based on temporal dimension.

REFERENCES

- Agawu, K. (1994). Ambiguity in tonal music: a preliminary study. *Theory, Analysis, and Meaning in Music*, 86-107.
- Baccala, L.A., and Sameshima, K. (2001). Partial directed coherence: a new concept in neural structure determination. *Biological cybernetics* 84, 463-474.
- Bella, S.D., Peretz, I., and Aronoff, N. (2003). Time course of melody recognition: a gating paradigm study. *Perception & psychophysics* 65, 1019-1028.
- Berry, W. (1987). *Structural functions in music* (Courier Corporation).
- Besson, M., and Macar, F. (1987). An Event-Related Potential Analysis of Incongruity in Music and Other Non-Linguistic Contexts. *Psychophysiology* 24, 14-25.
- Bhattacharya, J., and Petsche, H. (2005). Phase synchrony analysis of EEG during music perception reveals changes in functional connectivity due to musical expertise. *Signal Processing* 85, 2161-2177.
- Biancorosso, G. (2008). Whose Phenomenology of Music? David Huron's Theory of Expectation. *Music and Letters* 89, 396-404.
- Brattico, E., Tervaniemi, M., Naatanen, R., and Peretz, I. (2006). Musical scale properties are automatically processed in the human auditory cortex. *Brain research* 1117, 162-174.
- Burunat, I., Alluri, V., Toiviainen, P., Numminen, J., and Brattico, E. (2014). Dynamics of brain activity underlying working memory for music in a naturalistic condition. *Cortex; a journal devoted to the study of the nervous system and behavior* 57, 254-269.
- Callan, D.E., Jones, J.A., Callan, A.M., and Akahane-Yamada, R. (2004). Phonetic perceptual identification by native- and second-language speakers

- differentially activates brain regions involved with acoustic phonetic processing and those involved with articulatory-auditory/orosensory internal models. *NeuroImage* 22, 1182-1194.
- Choi, W., Lim, M., Kim, J.S., Kim, D.J., and Chung, C.K. (2015). Impaired pre-attentive auditory processing in fibromyalgia: A mismatch negativity (MMN) study. *Clinical Neurophysiology* 126, 1310-1318.
- Dohn, A., Garza-Villarreal, E.A., Chakravarty, M.M., Hansen, M., Lerch, J.P., and Vuust, P. (2015). Gray- and white-matter anatomy of absolute pitch possessors. *Cereb Cortex* 25, 1379-1388.
- Drabkin, W. (2014). *Grove Music Online*. Oxford Music Online. In Oxford University Press
- Durschmid, S., Edwards, E., Reichert, C., Dewar, C., Hinrichs, H., Heinze, H.J., Kirsch, H.E., Dalal, S.S., Deouell, L.Y., and Knight, R.T. (2016). Hierarchy of prediction errors for auditory events in human temporal and frontal cortex. *Proceedings of the National Academy of Sciences of the United States of America* 113, 6755-6760.
- Evers, S., Dannert, J., Rodding, D., Rotter, G., and Ringelstein, E.B. (1999). The cerebral haemodynamics of music perception. A transcranial Doppler sonography study. *Brain: a journal of neurology* 122 (Pt 1), 75-85.
- Fleming, S.M., Thomas, C.L., and Dolan, R.J. (2010). Overcoming status quo bias in the human brain. *Proceedings of the National Academy of Sciences of the United States of America* 107, 6005-6009.
- Friederici, A.D. (2011). The brain basis of language processing: from structure to function. *Physiological reviews* 91, 1357-1392.
- Fujioka, T., Trainor, L.J., Large, E.W., and Ross, B. (2009). Beta and gamma rhythms in human auditory cortex during musical beat processing. *Annals of the New York Academy of Sciences* 1169, 89-92.

- Fujioka, T., Trainor, L.J., Large, E.W., and Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic beta oscillations. *The Journal of neuroscience : the official journal of the Society for Neuroscience* 32, 1791-1802.
- Fujioka, T., Trainor, L.J., Ross, B., Kakigi, R., and Pantev, C. (2005). Automatic encoding of polyphonic melodies in musicians and nonmusicians. *Journal of cognitive neuroscience* 17, 1578-1592.
- Grahn, J.A., and McAuley, J.D. (2009). Neural bases of individual differences in beat perception. *Neuroimage* 47, 1894-1903.
- Grahn, J.A., and Rowe, J.B. (2009). Feeling the beat: premotor and striatal interactions in musicians and nonmusicians during beat perception. *The Journal of neuroscience : the official journal of the Society for Neuroscience* 29, 7540-7548.
- Gray, H.M., Ambady, N., Lowenthal, W.T., and Deldin, P. (2004). P300 as an index of attention to self-relevant stimuli. *Journal of experimental social psychology* 40, 216-224.
- Guo, S., and Koelsch, S. (2015). The effects of supervised learning on event-related potential correlates of music-syntactic processing. *Brain research* 1626, 232-246.
- Honing, H., Bouwer, F.L., and Haden, G.P. (2014). Perceiving temporal regularity in music: the role of auditory event-related potentials (ERPs) in probing beat perception. *Adv Exp Med Biol* 829, 305-323.
- Huron, D.B. (2006). *Sweet anticipation : music and the psychology of expectation* (Cambridge, Mass.: MIT Press).
- James, C.E., Britz, J., Vuilleumier, P., Hauert, C.A., and Michel, C.M. (2008). Early neuronal responses in right limbic structures mediate harmony incongruity processing in musical experts. *NeuroImage* 42, 1597-1608.

- Janata, P., Birk, J.L., Van Horn, J.D., Leman, M., Tillmann, B., and Bharucha, J.J. (2002). The cortical topography of tonal structures underlying Western music. *Science* 298, 2167-2170.
- Jancke, L., Langer, N., and Hanggi, J. (2012). Diminished whole-brain but enhanced peri-sylvian connectivity in absolute pitch musicians. *Journal of cognitive neuroscience* 24, 1447-1461.
- Jastorff, J., Kourtzi, Z., and Giese, M.A. (2009). Visual learning shapes the processing of complex movement stimuli in the human brain. *The Journal of neuroscience: the official journal of the Society for Neuroscience* 29, 14026-14038.
- Jentschke, S., and Koelsch, S. (2009). Musical training modulates the development of syntax processing in children. *NeuroImage* 47, 735-744.
- Jin, S.H., Lin, P., and Hallett, M. (2010). Linear and nonlinear information flow based on time-delayed mutual information method and its application to corticomuscular interaction. *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology* 121, 392-401.
- Jin, S.H., Lin, P., and Hallett, M. (2012). Reorganization of brain functional small-world networks during finger movements. *Human brain mapping* 33, 861-872.
- Jin, S.H., Seol, J., Kim, J.S., and Chung, C.K. (2011). How reliable are the functional connectivity networks of MEG in resting states? *Journal of neurophysiology* 106, 2888-2895.
- Jones, M.R., and Boltz, M. (1989). Dynamic attending and responses to time. *Psychological review* 96, 459.
- Karpinski, G.S. (2012). Ambiguity: Another Listen. *Music Theory Online* 18.
- Kennedy, C. (2019). 8 Ambiguity and vagueness: An overview. *Semantics-Lexical Structures and Adjectives*, 236.

- Khouri, L., and Nelken, I. (2015). Detecting the unexpected. *Current opinion in neurobiology* *35*, 142-147.
- Kilian-Hutten, N., Valente, G., Vroomen, J., and Formisano, E. (2011). Auditory cortex encodes the perceptual interpretation of ambiguous sound. *The Journal of neuroscience : the official journal of the Society for Neuroscience* *31*, 1715-1720.
- Kim, C.H., Kim, J.S., Choi, Y., Kyong, J.S., Kim, Y., Yi, S.W., and Chung, C.K. (2019). Change in left inferior frontal connectivity with less unexpected harmonic cadence by musical expertise. *PloS one* *14*, e0223283.
- Kim, C.H., Lee, S., Kim, J.S., Seol, J., Yi, S.W., and Chung, C.K. (2014). Melody effects on ERANm elicited by harmonic irregularity in musical syntax. *Brain research* *1560*, 36-45.
- Kim, J.S., and Chung, C.K. (2008). Language lateralization using MEG beta frequency desynchronization during auditory oddball stimulation with one-syllable words. *NeuroImage* *42*, 1499-1507.
- Kim, S.G., Kim, J.S., and Chung, C.K. (2011). The effect of conditional probability of chord progression on brain response: an MEG study. *PloS one* *6*, e17337.
- Koelsch, S., Gunter, T., Friederici, A.D., and Schroger, E. (2000). Brain indices of music processing: "nonmusicians" are musical. *Journal of cognitive neuroscience* *12*, 520-541.
- Koelsch, S., and Jentschke, S. (2008). Short-term effects of processing musical syntax: an ERP study. *Brain research* *1212*, 55-62.
- Koelsch, S., and Jentschke, S. (2010). Differences in electric brain responses to melodies and chords. *Journal of cognitive neuroscience* *22*, 2251-2262.

- Koelsch, S., Schmidt, B.H., and Kansok, J. (2002a). Effects of musical expertise on the early right anterior negativity: an event-related brain potential study. *Psychophysiology* 39, 657-663.
- Koelsch, S., Schroger, E., and Gunter, T.C. (2002b). Music matters: preattentive musicality of the human brain. *Psychophysiology* 39, 38-48.
- Leitman, D.I., Wolf, D.H., Ragland, J.D., Laukka, P., Loughhead, J., Valdez, J.N., Javitt, D.C., Turetsky, B.I., and Gur, R.C. (2010). "It's Not What You Say, But How You Say it": A Reciprocal Temporo-frontal Network for Affective Prosody. *Frontiers in human neuroscience* 4, 19.
- London, J. (2002). Cognitive constraints on metric systems: Some observations and hypotheses. *Music Perception: An Interdisciplinary Journal* 19, 529-550.
- Loui, P., Li, H.C., Hohmann, A., and Schlaug, G. (2011). Enhanced cortical connectivity in absolute pitch musicians: a model for local hyperconnectivity. *Journal of cognitive neuroscience* 23, 1015-1026.
- Maess, B., Koelsch, S., Gunter, T.C., and Friederici, A.D. (2001). Musical syntax is processed in Broca's area: an MEG study. *Nature neuroscience* 4, 540-545.
- Mantzaridis, H., and Kenny, G. (1997). Auditory evoked potential index: a quantitative measure of changes in auditory evoked potentials during general anaesthesia. *Anaesthesia* 52, 1030-1036.
- Marie, C., and Trainor, L.J. (2013). Development of simultaneous pitch encoding: infants show a high voice superiority effect. *Cereb Cortex* 23, 660-669.
- McAuley, J.D., and Semple, P. (1999). The effect of tempo and musical experience on perceived beat. *Australian journal of psychology* 51, 176-187.
- Meyer, L.B. (1956). *Emotion and meaning in music* (Chicago: University of Chicago Press).

- Miyake, Y., Onishi, Y., and Poppel, E. (2004). Two types of anticipation in synchronization tapping. *Acta neurobiologiae experimentalis* 64, 415-426.
- Murphy, H.A., and Stringham, E.J. (1951). *Creative harmony and musicianship; an introduction to the structure of music* (New York,: Prentice-Hall).
- Musso, M., Weiller, C., Horn, A., Glauche, V., Umarova, R., Hennig, J., Schneider, A., and Rijntjes, M. (2015). A single dual-stream framework for syntactic computations in music and language. *NeuroImage* 117, 267-283.
- Näätänen, R., Paavilainen, P., Titinen, H., Jiang, D., and Alho, K. (1993). Attention and mismatch negativity. *Psychophysiology* 30, 436-450.
- Nan, Y., Knosche, T.R., Zysset, S., and Friederici, A.D. (2008). Cross-cultural music phrase processing: an fMRI study. *Human brain mapping* 29, 312-328.
- Nozaradan, S. (2014). Exploring how musical rhythm entrains brain activity with electroencephalogram frequency-tagging. *Philosophical transactions of the Royal Society of London Series B, Biological sciences* 369, 20130393.
- Nozaradan, S., Peretz, I., Missal, M., and Mouraux, A. (2011). Tagging the neuronal entrainment to beat and meter. *The Journal of neuroscience : the official journal of the Society for Neuroscience* 31, 10234-10240.
- Nozaradan, S., Peretz, I., and Mouraux, A. (2012). Selective neuronal entrainment to the beat and meter embedded in a musical rhythm. *The Journal of neuroscience : the official journal of the Society for Neuroscience* 32, 17572-17581.
- Obleser, J., Meyer, L., and Friederici, A.D. (2011). Dynamic assignment of neural resources in auditory comprehension of complex sentences. *NeuroImage* 56, 2310-2320.

- Patel, A.D. (1998). Syntactic processing in language and music: different cognitive operations, similar neural resources? *Music Perception: An Interdisciplinary Journal* 16, 27-42.
- Patel, A.D. (2003). Language, music, syntax and the brain. *Nature neuroscience* 6, 674-681.
- Patel, A.D. (2008). Science & music: talk of the tone. *Nature* 453, 726-727.
- Patel, A.D., and Balaban, E. (2001). Human pitch perception is reflected in the timing of stimulus-related cortical activity. *Nature neuroscience* 4, 839-844.
- Patterson, R.D., Uppenkamp, S., Johnsrude, I.S., and Griffiths, T.D. (2002). The processing of temporal pitch and melody information in auditory cortex. *Neuron* 36, 767-776.
- Piston, W., and DeVoto, M. (1987). *Harmony*, 5th edn (New York: Norton).
- Plailly, J., Tillmann, B., and Royet, J.P. (2007). The feeling of familiarity of music and odors: the same neural signature? *Cereb Cortex* 17, 2650-2658.
- Platel, H., Baron, J.C., Desgranges, B., Bernard, F., and Eustache, F. (2003). Semantic and episodic memory of music are subserved by distinct neural networks. *NeuroImage* 20, 244-256.
- Rohrmeier, M.A. (2007). A generative grammar approach to diatonic harmonic structure. *Proceedings SMC'07, 4th Sound and Music Computing Conference*.
- Ruiz, M.H., Koelsch, S., and Bhattacharya, J. (2009). Decrease in early right alpha band phase synchronization and late gamma band oscillations in processing syntax in music. *Human brain mapping* 30, 1207-1225.
- Sabri, M., Liebenthal, E., Waldron, E.J., Medler, D.A., and Binder, J.R. (2006). Attentional modulation in the detection of irrelevant deviance: a simultaneous ERP/fMRI study. *Journal of cognitive neuroscience* 18, 689-700.

- Sakai, K.L., Noguchi, Y., Takeuchi, T., and Watanabe, E. (2002). Selective priming of syntactic processing by event-related transcranial magnetic stimulation of Broca's area. *Neuron* 35, 1177-1182.
- Salimpoor, V.N., Benovoy, M., Larcher, K., Dagher, A., and Zatorre, R.J. (2011). Anatomically distinct dopamine release during anticipation and experience of peak emotion to music. *Nature neuroscience* 14, 257-262.
- Sammler, D., Koelsch, S., Ball, T., Brandt, A., Elger, C.E., Friederici, A.D., Grigutsch, M., Huppertz, H.J., Knosche, T.R., Wellmer, J., *et al.* (2009). Overlap of musical and linguistic syntax processing: intracranial ERP evidence. *Annals of the New York Academy of Sciences* 1169, 494-498.
- Sammler, D., Koelsch, S., and Friederici, A.D. (2011). Are left fronto-temporal brain areas a prerequisite for normal music-syntactic processing? *Cortex; a journal devoted to the study of the nervous system and behavior* 47, 659-673.
- Schneider, P., Sluming, V., Roberts, N., Scherg, M., Goebel, R., Specht, H.J., Dosch, H.G., Bleeck, S., Stippich, C., and Rupp, A. (2005). Structural and functional asymmetry of lateral Heschl's gyrus reflects pitch perception preference. *Nature neuroscience* 8, 1241-1247.
- Sears, D., Caplin, W.E., and McAdams, S. (2014). Perceiving the Classical Cadence. *Music Perception: An Interdisciplinary Journal* 31, 397-417.
- Seger, C.A., Spiering, B.J., Sares, A.G., Quraini, S.I., Alpeter, C., David, J., and Thaut, M.H. (2013). Corticostriatal contributions to musical expectancy perception. *Journal of cognitive neuroscience* 25, 1062-1077.
- Seol, J., Oh, M., Kim, J.S., Jin, S.H., Kim, S.I., and Chung, C.K. (2011). Discrimination of timbre in early auditory responses of the human brain. *PloS one* 6, e24959.
- Shin, K.S., Kim, J.S., Kang, D.H., Koh, Y., Choi, J.S., O'Donnell, B.F., Chung, C.K., and Kwon, J.S. (2009). Pre-attentive auditory processing in ultra-high-risk for

- schizophrenia with magnetoencephalography. *Biological psychiatry* 65, 1071-1078.
- Shin, K.S., Kim, J.S., Kim, S.N., Koh, Y., Jang, J.H., An, S.K., O'Donnell, B.F., Chung, C.K., and Kwon, J.S. (2012). Aberrant auditory processing in schizophrenia and in subjects at ultra-high-risk for psychosis. *Schizophr Bull* 38, 1258-1267.
- Squires, N.K., Squires, K.C., and Hillyard, S.A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and clinical neurophysiology* 38, 387-401.
- Sridharan, D., Levitin, D.J., Chafe, C.H., Berger, J., and Menon, V. (2007). Neural dynamics of event segmentation in music: converging evidence for dissociable ventral and dorsal networks. *Neuron* 55, 521-532.
- Taulu, S., and Hari, R. (2009). Removal of magnetoencephalographic artifacts with temporal signal-space separation: demonstration with single-trial auditory-evoked responses. *Human brain mapping* 30, 1524-1534.
- Taulu, S., and Simola, J. (2006). Spatiotemporal signal space separation method for rejecting nearby interference in MEG measurements. *Physics in medicine and biology* 51, 1759-1768.
- Thompson, W.F. (1993). Modeling perceived relationships between melody, harmony, and key. *Perception & psychophysics* 53, 13-24.
- Tierney, A., Dick, F., Deutsch, D., and Sereno, M. (2013). Speech versus song: multiple pitch-sensitive areas revealed by a naturally occurring musical illusion. *Cereb Cortex* 23, 249-254.
- Tuggy, D. (1993). Ambiguity, polysemy, and vagueness. *Cognitive Linguistics (includes Cognitive Linguistic Bibliography)* 4, 273-290.

- Weiss, S., and Mueller, H.M. (2012). "Too Many betas do not Spoil the Broth": The Role of Beta Brain Oscillations in Language Processing. *Frontiers in psychology* 3, 201.
- Wilkins, R.W., Hodges, D.A., Laurienti, P.J., Steen, M., and Burdette, J.H. (2014). Network science and the effects of music preference on functional brain connectivity: from Beethoven to Eminem. *Scientific reports* 4, 6130.
- Winkler, I., Haden, G.P., Ladinig, O., Sziller, I., and Honing, H. (2009). Newborn infants detect the beat in music. *Proceedings of the National Academy of Sciences of the United States of America* 106, 2468-2471.
- Winold, A. (1975). Rhythm in twentieth-century music. *Aspects of twentieth-century music*, 208-269.

ABSTRACT IN KOREA

음악에서의 기대감

: 화성, 선율, 박에 대한 전자기학적 연구

김 찬 희

서울대학교 대학원

협동과정 뇌과학 전공

음악을 들을 때 우리는 음악이 보내오는 어떤 신호에 이끌려 동요된다. 음악이 보내는 신호는 음악의 구조 안에 포함되어 있는 화성, 선율, 조성, 리듬 등의 요소들 중 그 어떤 것도 될 수 있다. 음악의 신호에 이끌리다 보면 제시될 다음 신호에 대한 어떤 기대감을 가지게 되는데, 이런 기대감은 음악이 가지고 있는 유희성을 부각해주는 장치가 되기도 한다.

음악의 기대감에 대한 연구는 음악을 구성하는 모든 요소들의 관점에서 진행되어 왔고, 이 요소들 중 화성과 선율은 조성 구조에 포함되므로 기대감은 이들 간의 위계 구조의 관점에서 설명될 수 있었다. 그러나 본 논문에서는 조성 구조의 관점이 아닌 음악의 시간 축의 관점에서 음악의 기대감을 해석해보고자 한다. 즉, 음악의 기대감은 음악 신호가 제시되는 어떤 “시점”들을 따라 이동하는 것이므로, 음악을 구성하는 요소들 중 “박”이 음악의 구조 안에서 기대감을 유발하는 또 다른 근원이 될 수 있다고 가정하였다.

본 논문에서는 전통적 패러다임을 적용한 화성과 선율의 기대감을 연구한 세 개의 뇌자도(MEG, magnetoencephalography) 연구들과 박에 대한 두개내뇌전도(iEEG, intracranial electroencephalogram) 연구를 종합 분석해 박이 어떻게 음악의 기대감의 근원적 구조가 될 수 있는지 해석하였다. 화성과 선율 연구들에서 기대감에 대한 뇌반응은 기대감이 발현될 수 있는 “시점”에 근거해 분석되었고, 이 “시점”은 박의 단위에 근거해 뇌 영역들 간의 특징적 뇌연결(brain connectivity)과 그 강도에 영향을 주었다. 기대했던 신호에 비해, 기대감에 어긋나는 신호들에 대해 뇌연결의 강도는 상대적으로 더 컸고, 이 뇌연결은 화성과 선율의 기대감에 반응한다고 알려진 하전두이랑(Inferior frontal gyrus)과 청각 신호를 처리하는 청각영역(Auditory area), 상측두이랑(Superior temporal gyurs)을 모두 포함하고 있었다.

피질뇌파를 이용한 박 연구는 외부 자극으로서의 박을 처리하는 것과 내재되어 있는 박에 대한 감각, 즉 외부 자극과 유관하게 혹은 무관하게도 박을 생성할 수 있는 능력이 뇌에 각기 다르게 반영될 수 있다는 것을 규명하는 것을 연구목적으로 고안되었다. 연속적으로 제시되는 박 신호를 사용할 때 그 신호가 누락되는 경우가 기대감에 어긋나는 “시점”이 되는데, 이는 화성과 선율의 조성 구조를 배제하는 기대감에 어긋날 때의 뇌반응을 추출할 수 있는 방법이 되었다. 외부 자극으로서의 박에 대한 기대감을 반영하는 뇌 반응은 청각영역을 중심으로 관측되었고, 내생적인 박에 대한 감각의 뇌반응은 청각영역을 제외한 다른 영역들에서 광범위하게 관측되었다.

음악을 구성하는 화성, 선율, 박의 세 요소의 관점에서 기대감은 청각영역을 포함하는 다른 영역들 간의 뇌연결을 변화시켰고, 화성과 선율의 조성 구조를 배제한 박 신호의 기대감은 청각영역을 중심으로 반응을 보였다. 이 연구들을 종합해 본 논문은 음악의

시간 축의 관점에서 해석될 수 있는 기대감은 박을 그 근원에 두고 화성과 선율이 위계 구조를 이루는 모델로서 설명될 수 있다고 제안하고자 한다.

주요어: 기대감, 화성, 선율, 박, 청각영역, 상측두이랑, 하전두이랑, 뇌자도, 피질뇌파

학번: 2013-30122