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Neuromagnetic responses to chords are modified by preceding musical scale

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Neuromagnetic responses to chords are modified by preceding musical scale

Abstract

Previous psychological studies have shown that musical chords primed by Western musical scale in a tonal and modal schema are perceived in a hierarchy of stability. We investigated such priming effects on auditory magnetic responses to tonic-major and submediant-minor chords preceded by major scales and tonic-minor and submediant-major chords preceded by minor scales. Musically trained subjects participated in the experiment. During MEG recordings, subjects judged perceptual stability of the chords. The tonic chords were judged to be stable, whereas the submediant chords were judged to be unstable. Dipole moments of N1m response originating in the auditory cortex were larger in the left hemisphere for the submediant chords than for the tonic chords preceded by the major but not minor scales. No difference in the N1m or P2m moment was found for the chords presented without preceding scales. These results suggest priming effects of the tonal schema, interacting with contextual modality, on neural activity of the auditory cortex as well as perceptual stability of the chords. It is inferred that modulation of the auditory cortical activity is associated with attention induced by tonal instability and modality shift, which characterize the submediant chords.

Keywords: MEG, neuromagnetic response, auditory evoked field, chord, tonality, modality

Introduction

The structural framework of Western tonal music is generally determined by a tonal and modal schema, such as "C major", representing the key or a note defining the tonal center (C) and modality (major). Modality of either major or minor is decided by intervallic arrangements of notes within an octave. Major chords are formed by notes having intervals of 4 and 7 semitones, whereas the intervals in minor chords are 3 and 7 semitones. Such a difference in modality is known to induce particular emotional effects in the listeners' cognition even when the chords are presented singly (Pallesen et al., 2003). On the other hand, tonality is assigned to tones and chords when they are referenced to a particular note. The diatonic tones and chords, denoted as I, II, to VII in order of ascending pitch, are perceived in a hierarchy of stability (Krumhansl, 2004), serving for the basis for the concept of tonality. The tonal hierarchy plays an important role in the perception of structural dynamism such as progression and closure of Western tonal music.

Krumhansl, with her colleagues, performed behavioral experiments to evaluate the tonal hierarchy of chords quantitatively using listeners' ratings for perceptual stability (Krumhansl & Shepard, 1979; Krumhansl & Kessler, 1982; Krumhansl, 1990). Their experimental paradigm is called the "probe-tone method", which has been widely used in the field of music psychology (Cuddy & Badertcher, 1987; Steinke et al., 1997; Leman, 2000). In this method, subjects judge the stability of chords that have been primed tonally and modally by preceding musical context such as diatonic scales. The results showed that the perceptual stability was highest for tonic chords (I), e.g., CEG in

C major context, which was followed by dominant (V) and subdominant chords (IV), and much lower for submediant chords (VI) , e.g., ACE. Similar patterns of hierarchical ordering have been observed for chords primed in major and minor contexts (Krumhansl, 1990). Interestingly, however, the chords in major context obtained finer discriminations, resulting in an increased difference between the tonic (I) and submediant (VI) chords in major than minor context. These results suggest an interactive effect of the tonal and modal schema on perception of chords primed by musical context.

The auditory perceptual/cognitive process has been widely investigated in relation to N1m and P2m responses of the auditory evoked fields (AEF). The AEFs reflect exogenous factors of input sounds (Pantev et al., 1989; Hari et al., 1990; Mizouchi et al., 2005; Tiitinen et al., 2005; Kuriki et al., 2006, 2007). They are also modulated by selective attention (Hari et al., 1989; Woldorff et al., 1993; Petkov et al., 2004; Neelon et al., 2006a, 2006b), i.e., a top-down modulation of the auditory cortical activity caused by an instruction or self-initiated decision to attend to the signal (Frith et al., 1996). Deviation from musical context such as melody and harmonic progression enhances the activity in the auditory cortex over the N1m and P2m latencies (Kuriki et al., 2005) and that in the inferior frontolateral cortex in/after the P2m latency (Maess et al., 2001). The enhancement of these cortical activities may be associated with selective attention. Selective attention prerequisites, by detection of contextual deviance, comparison and separation of an input sound (Giard et al., 2000), i.e., a process of template matching of an input sound with a template which is formed according to the task or the rule or pattern of preceding sounds. The results of Krumhansl's probe-tone experiment

(Krumahnsl, 1990) behaviorally suggest that the tonic, i.e., the tonal center, functions as the template and that the precision of template matching depends on the modality of the priming context. However, there has been no studies on such a priming effect of tonality interacting with contextual modality on musical chords in relation to the modulation of auditory cortical activity as indexed by AEFs.

In this study, we investigated the auditory neuromagnetic responses, N1m and P2m, elicited by tonic (I) and submediant (VI) chords primed in major and minor contexts. The probe-tone method (Krumhansl, 1990) was adopted as the experimental paradigm. As a control, the same set of the chords were presented without any priming contexts. We hypothesized that auditory responses to the chords are modulated as an interactive function of the tonal and modal schema that primes the chords. Specifically, the response to the submediant chord (VI) in major context, which showed the lowest perceptual stability in Krumhansl's data, would be augmented by an attentional effect compared with that to the tonic chord (I) in major context, as primed by the preceding context.

Methods

Nine right-handed subjects (4 males and 5 females) of 20 to 26 years of age (mean age of 21.4 years) with normal hearing and no history of otological or neurological disorder participated in the experiment. They were all amateur string players of a university symphony orchestra who had been taking private musical lessons for one or more instruments since 3-16 (mean of 7.6) years of age continuously to the time of measurements. The experiment was approved by the Ethics Committee of Hokkaido University. The subjects gave informed consent in writing for participation in the study after the purpose and procedures of the experiment had been fully explained.

Figure 1 (top) shows an example of musical score of stimulus sounds composed of a diatonic scale made of 15 notes ascending in pitch in two octaves and a four-note chord. The chords of the sequences were characterized tonally and modally as tonic-major and submediant-minor chords preceded by a major scale, denoted as I_{maj} and VI_{maj}, respectively, and tonic-minor and submediant-major chords preceded by a minor scale, denoted as I_{min} and VI_{min}, respectively. In order to offset the effect of a particular key, the sequences were prepared in two different keys (Fig. 1, middle), which resulted in tuning the chords for I_{maj} in C major with notes of C5E5G5C6 (denoted as C) and in F major with notes of F5A5C6F6 (F). The chords for VI_{maj} were tuned in A minor with notes of A4C5E5A5 (A_m) and in D minor with D5F5A5D6 (D_m). These chords of C/F and A_m/D_m were preceded by C major and F major scales, respectively. The chords for I_{min} were tuned in E minor with notes of E4G4B4E5 (E_m) and in A minor (A_m), and the chords for VI_{min} were tuned in C major (C) and F major (F). These chords of E_m/A_m and C/F were preceded by E-natural minor and A-natural minor scales, respectively. It should be noted that the chords C/F of I_{maj} were identical to the chords C/F of VI_{min} except for the key and modality of the preceding scale.

The stimulus sounds were generated in standard piano timber in MIDI format (Yamaha, XGworks v.4.0) and converted to WAV format (Adobe Systems, Inc., Audition v.1.0). The duration of the chord was 312.5 ms with a 10-ms ramp of linear decrease applied at the end. The interval between the onset of the last note of the scale and the onset of the chord was 1250 ms. We measured the hearing threshold for each chord in individual subjects in the same condition of binaural stimulation as in the MEG recording. The sound intensity was adjusted for each of five different chords, i.e., C, F, A_m, D_m and E_m, to a level of 60 dB above the hearing threshold. The mean sound pressure level (SPL) of the five chords in each subject was 68.0 - 71.0 dB, which was used to adjust the SPL of the notes of the preceding scale.

MEG measurements were made using a custom-made helmet-shaped SQUID system with 76-channel magnetometer sensors (Elekta-Neuromag, Helsinki). In the main session, the sequences composed of the scales and chords, I_{maj}, VI_{maj}, I_{min} and VI_{min}, tuned in two different keys, were mixed in pseudo-random order and repeated for more than 50 times. The onset-to-onset interval of the sequences was 6250 ms. Subjects were instructed to listen to the stimulus sequence and judge whether the chord presented at the end was stable or unstable, with regard to the preceding scale. The subjects responded by moving the right or left index finger at a response time notified with a drum sound after the MEG recording period (Fig. 1, bottom). In the control session, all of the five chords, C, F, A_m, D_m and E_m, were presented singly without a preceding scale and repetitively for more than 50 times. The onset-to-onset interval of the chords was 625 ms. Subjects were not required to perform any task other than listening passively to the single chords. Magnetic signals of 100 ms before and up to 500 ms after onset of the chord were recorded in both main and control sessions. Epochs contaminated with artifacts exceeding 3.0 pT were rejected online, resulting in removal of less than five epochs in single conditions.

The recorded magnetic signals were bandpass-filtered offline using a fourth-order bidirectional Butterworth filter with a cutoff frequency of 1-20 Hz. This relatively narrow bandwidth was used to reduce the low-frequency and power line (50 Hz) noises in the environment, which existed at high amplitudes in the signals detected by the magnetometer-type sensors. A notch filter at 50 Hz (3.14 Hz width) was also applied to assure the removal of the power line noise. Magnetic signals of 50 epochs were averaged for each chord separately. Averages of 100 epochs were made by summing further the chords of C and F, A_m and D_m, and E_m and A_m, respectively, for conditions of I_{maj}, VI_{maj}, I_{min} and VI_{min} in the main session and C/F, A_m/D_m and E_m/A_m in the control session. The mean of the signal in a 100-ms period before onset of the chord served as the baseline.

The equivalent current dipoles were localized separately for the N1m and P2m components elicited by each chord. The estimation was performed using 38-channel field data from each hemisphere of each subject. The coordinates and directions of N1m and P2m dipoles were not statistically different among the chords or between the sessions in each hemisphere, as examined by one-way repeated-measures ANOVA with a factor of chord or session. We therefore averaged all of the chords in both sessions, from which template dipoles having the mean coordinates and directions were obtained for N1m and P2m components in the left and right hemispheres. The moment was further normalized with its magnitude. The time course of dipole moment was calculated by the signal space projection (SSP) method (Tesche et al., 1995; Fujioka et al., 2005; Kuriki et al., 2006) by projecting the measured neuromagnetic fields on the fields that were given by the template dipoles for N1m and P2m components. This method provides a quantitative measure of the dipole moment even from data of low signal-to-noise ratio. The magnitudes of the projected moment for the N1m and P2m components were obtained at their peak latencies.

The projected moments of N1m and P2m components were assessed statistically by two-way repeated-measures ANOVA with factors of hemisphere and session and post-hoc Scheffe's tests. The analysis was performed for each pair of corresponding conditions, i.e., C/F and I_{maj}, A_m/D_m and VI_{maj}, E_m/A_m and I_{min}, and C/F and VI_{min}, across the control and main sessions. In order to examine the difference among the dipole moments of I_{maj}, VI_{maj}, I_{min}, and VI_{min} in the main session, three-way repeated-measures ANOVA was performed with factors of hemisphere, modality of preceding scale (major or minor) and tonality of chord (I or VI). The conditions of C/F, A_m/D_m, E_m/A_m in the control session were examined separately by two-way repeated-measures ANOVA with factors of hemisphere and chords.

Results

The behavioral judgments of stability of the chords were consistent among subjects. The group mean across subjects showed that I_{maj} and I_{min} were judged as stable in 96.5% (1.6% of SE) and 85.3% (5.6%) of 100 epochs, respectively, while VI_{maj} and VI_{min} were judged as unstable in 90.1% (3.6%) and 91.7% (3.5%) of epochs, respectively. These percent values were well above the chance level of judgment, being significantly larger than 50% ($p<0.001$).

Figure 2a shows the waveform of superposed fields of 38 channels over the right hemisphere of one subject for the response to the chord of I_{maj}. Clearly elicited N1m and P2m components of neuromagnetic response were observed at latencies of about 100 and 170 ms, respectively, after onset of the chord. The dipolar pattern of the measured field distribution over the Sylvian fissure and also the mean location of the dipoles (Fig. 2a) in the structure of a template brain (Neuroscan, Curry 5.0.8) indicated a single current dipole source for each component in the auditory area of the superior temporal cortex. Figure 2b displays grand-mean (n=9) coordinates of N1m and P2m dipoles for each chord in the control and main sessions. One-way repeated-measures ANOVA with a factor of chord or session showed no significant difference in the N1m and P2m dipole coordinates and orientations in each hemisphere. These results support the validity of using the mean locations among the chords and between the sessions as SSP templates for N1m and P2m components. Figure 2c shows the dipole moments obtained by projecting the measured fields to the template fields of the grand-mean single source of the N1m component, where the results of the grand-mean and different subjects are superposed. Such a dipole moment as a function of latency represents the time course of the source activity, when a single source of the N1m component is assumed. The group means of the source activity for different chords (Fig. 3) indicated a slight difference in the amplitude of the N1m moment for VI_{maj} in the left hemisphere for the main session. The source activity for the P2m component calculated using the grand-mean template dipole of the P2m moment showed a similar result for VI_{maj}.

Quantitative evaluation of the N1m and P2m moments was made from their peak values of the source activities in different conditions (Fig. 4). The two-way repeated-measures ANOVA with factors of hemisphere and session showed the main effect of session between the pairs of A_m/D_m and VI_{maj} ($F_{(1,8)}=10.47$; $p<0.01$), E_m/A_m and I_{min} ($F_{(1,8)}=10.03$; $p<0.01$), and C/F and VI_{min} ($F_{(1,8)}=5.08$; $p<0.05$), with the N1m moments in the main session being significantly larger than those in the control session. There was also an interaction between session and hemisphere in the pair of C/F and I_{maj} ($F_{(1,8)}=5.77$; $p<0.04$), with the N1m moments to I_{maj} in the right hemisphere being marginally larger than those in the left hemisphere in the main session ($p<0.06$). No significant effects were found in any pairs of the P2m moments. The repeated-measures ANOVA with factors of hemisphere, modality of preceding scale and tonality of chord showed a three-way interaction effect ($F_{(1,8)}=6.73$; $p<0.03$) on the N1m moment for the main session. A post-hoc Scheffe's test revealed that VI_{maj} was significantly larger than I_{maj} ($p<0.05$) in the left hemisphere. No significant differences were found in the right hemisphere. No effects of any factors were observed for the P2m moments. Also, the results for the control session showed no significant effects on the N1m and P2m moments.

Discussion

In the behavioral performance, tonic chords I_{maj} and I_{min} were judged to be stable and submediant chords VI_{maj} and VI_{min} were judged to be unstable. The results agree with the behavioral data reported by Krumhansl (1990). Specifically, the different judgment obtained for the acoustically identical chords, I_{maj} and VI_{min}, suggests that the priming of the preceding musical scale functioned to induce hierarchy in the perceptual stability of the chords, i.e., tonality.

There was a significant interaction effect of tonality by contextual modality in the main session, with VI_{maj} eliciting significantly larger N1m moments than I_{maj} in the left hemisphere. This tonal-modal interaction effect confirmed our hypothesis that the factors of tonality of the chords and contextual modality defined by the preceding scale are reflected interactively in the auditory cortical activities. The significant difference between VI_{maj} and I_{maj} agrees with the maximum difference in the ratings of perceptual stability between I and VI in major modality (Krumhansl, 1990), suggesting the involvement of cortical activity at the N1m latency in the subsequent cognitive judgment. The chords presented without the preceding scales in the control session, C/F and A_m/D_m, which acoustically corresponded to I_{maj} and VI_{maj} of the main session, showed no difference in amplitude, in agreement with the results of a previous fMRI study (Pallesen et al., 2005). This supports the notion that the difference between the N1m responses to I_{maj} and VI_{maj} was a result of priming by the preceding context and was not caused by the acoustic features of the chords.

Kuriki et al. (2004) recorded neuromagnetic responses elicited by final notes tuned in I or IV#, e.g., C or F# in C major context, of musical melodies and observed that the auditory cortical activities were significantly larger to IV# than to I over the latencies of N1m and P2m responses. In Western diatonic music composed in the tonal-modal schema, strong expectancy for the tonal center, I, is induced at the end of the musical progression (Tillman et al., 2003). In contrast, IV# deviates from the anticipated tonality (I) and also violates the tonal-modal rule established by the preceding part of the melodies. Similarly, in the present study, VI_{maj} was a deviation in terms of modality, i.e., a minor chord in major context, and also tonality, i.e., a submediant chord that is distant from the tonal center defined by the preceding scale. Assuming that the chords primed in the tonal-modal schema were processed in reference to the tonic chord, I_{maj}, that functioned as a template, it would be efficient for the subjects to perform the task by initiating their attention to the deviant chord, VI_{maj}, that did not fit with the template. Then the selective attention may induce augmentation of the N1m activity for VI_{maj}. We speculate that such cortical modulation could occur at an earlier stage in parallel with acoustic analysis of input sound in the auditory cortex, through the efferent influence of attention on the expeditious filtering of irrelevant/unattended (i.e., template) sounds at peripherals (Giard et al., 1994; 2000). It should be noted that VI_{maj} was not a physical oddball in a regular pattern. Furthermore, VI_{maj} was presented at an equal frequency with the other conditions for I_{maj}, I_{min} and VI_{min}. Therefore, the mechanism underlying the augmentation of N1m activity for VI_{maj} may be distinct from sensory adaptation and gating effect of the feature-specific auditory neurons (Hari et al., 1982), which is partly associated with the classical mismatch negativity (MMN) generation mechanism (Jaaskelainen et al., 2004).

In contrast, VI_{min} did not augment the responses in spite of the common characteristics of tonality (VI), perceptual stability and modality shift from the preceding scale. Krumhansl (1990) reported a difference in perceptual stability as a function of contextual modality, with the chords in major context obtaining finer discriminations than those in minor context. A previous psychological study also showed that major context predisposes musically trained subjects to apprehend auditory regularity (Oram and Cuddy, 1995). It is therefore suggested that augmentation of the response to VI_{maj}, but not to VI_{min}, is associated with the subjects' sensitivity to the tonal schema established more firmly by the preceding scales of the major modality.

The notes contained in I_{maj} were presented near the end of the preceding scale, whereas the notes in I_{min} occurred in the first half of the scale. The notes in VI_{maj} and VI_{min} occurred in the middle part of the scale. Thus, the effect of adaptation due to frequency overlap is expected to be maximal for I_{maj}, which may have contributed to the difference between I_{maj} and VI_{maj}.

A significant effect of chord was observed in the left, but not right, hemisphere. It has been reported that auditory responses are enhanced in musically trained listeners bilaterally with right hemisphere dominance (Shahin, et al., 2003; Kuriki, et al., 2004; Bosnyak, et al., 2004). However, piano tones elicit larger N1m response than envelope-matched pure tones do in the left hemisphere of both musicians and non-musicians (Lütkenhöner, et al., 2006). Furthermore, the left hemisphere is known to show dominance in the analysis of pitch interval (Liégeois-Chauvel et al., 1998; Ehrlé et al., 2001; Samson et al., 2001). It is therefore suggested that the significant difference between the chords in the left hemisphere was a result of identification and differentiation of the frequency characteristics of the chords of piano timber, relative to the tonal center, I, determined by the preceding scale.

N1m/P2m responses are attenuated by repetitive presentation of sounds due to the adaptation of auditory cortical neurons (Kuriki et al., 2007), which depends on the interval between the stimulus (Hari et al., 1982; Ioannides et al., 2003) and the frequency characteristics of preceding sounds (Watanabe, 2003). The observed effect of session on the N1m moments is thought to be mainly caused by the adaptation that existed strongly in the control session, due to the frequency overlapping by repetition of an identical chord and the short inter-stimulus-interval of 625 ms. In the main session, intermission between the chord and the preceding tone was 1250 ms, and only some of the frequency components were overlapped between the chord and the last note of the preceding scale.

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Figure captions

Figure 1. Stimulus sequences and MEG recording. Musical score of stimulus sounds forming a sequence by combining a preceding scale and a target chord (top). The five chords, C, A_m, F, D_m and E_m, primed by the scales in keys of either C, F, E_m or A_m. The chords were assigned tonality of either I or VI to form four conditions of I_{maj}, VI_{maj}, I_{min} and VI_{min} (middle). The time schematics of the stimulus sequence presentation, MEG recording and behavioural response are shown at the bottom.

Figure 2. Measured magnetic fields and calculated dipole moments of auditory evoked responses elicited by the chord of I_{maj}. (a) Superposed magnetic fields of 38 channels over the right hemisphere of one subject, with the field distributions and source locations and directions of equivalent current dipoles estimated at N1m and P2m peaks. (b) Grand-mean (n=9) coordinates of N1m and P2m dipoles projected on coronal and axial planes for each chord in the control and main sessions. (c) Dipole moments as a function of latency obtained by projecting the measured fields to the template fields of the grand-mean single source of N1m response. The results for each of nine subjects and their mean are indicated by thin and thick lines, respectively.

Figure 3. Grand-mean projected moments of N1m sources in the left (LH) and right (RH) hemispheres obtained in control and main sessions. The results of different conditions are compared by superposition.

Figure 4. Summarized results of the projected moments at (a) N1m and (b) P2m peaks in the left (LH) and right (RH) hemispheres obtained in control and main sessions. Significant difference and tendency between the conditions are indicated. Significant

differences for the factors of session and hemisphere are omitted for clarity.

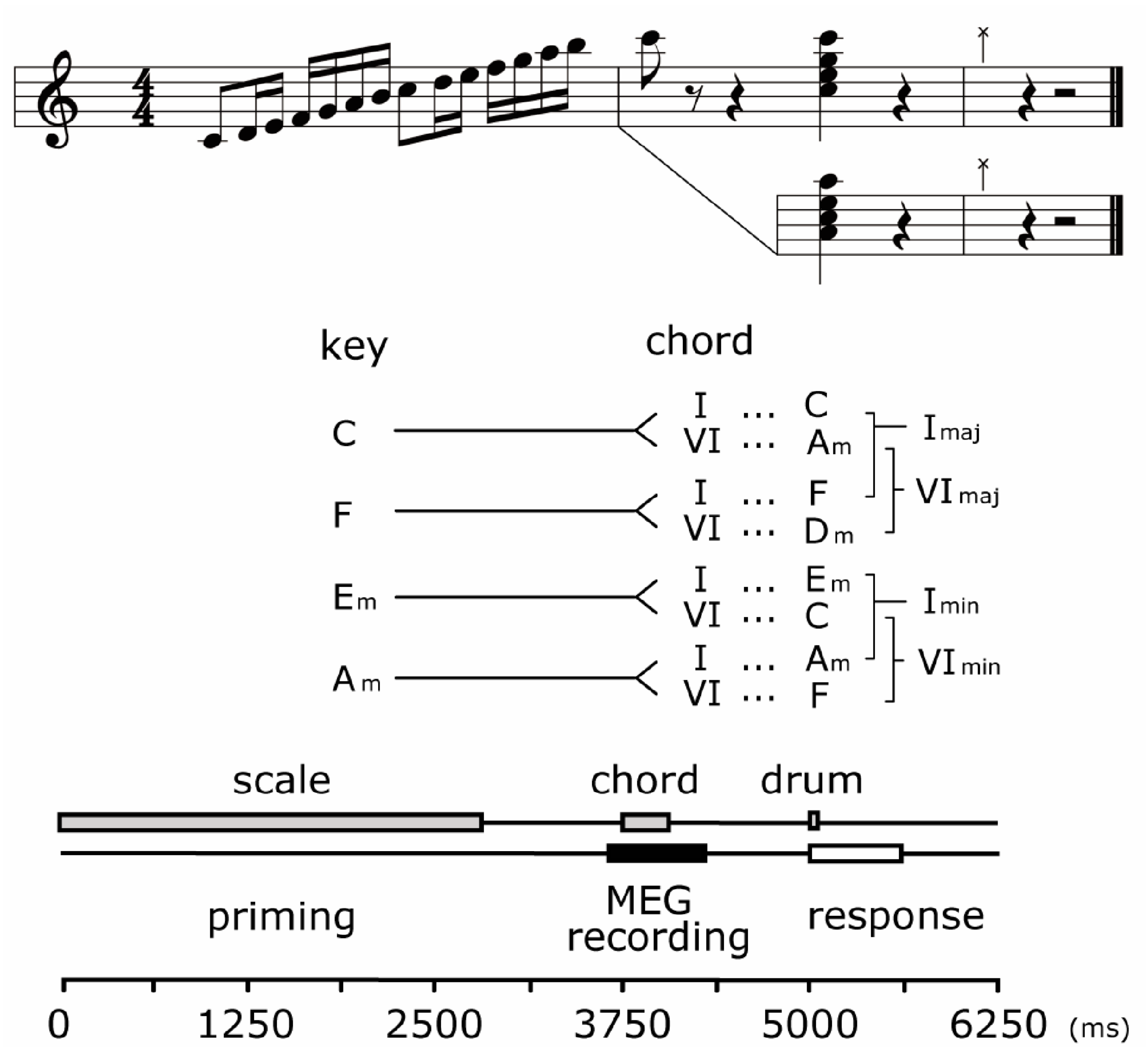
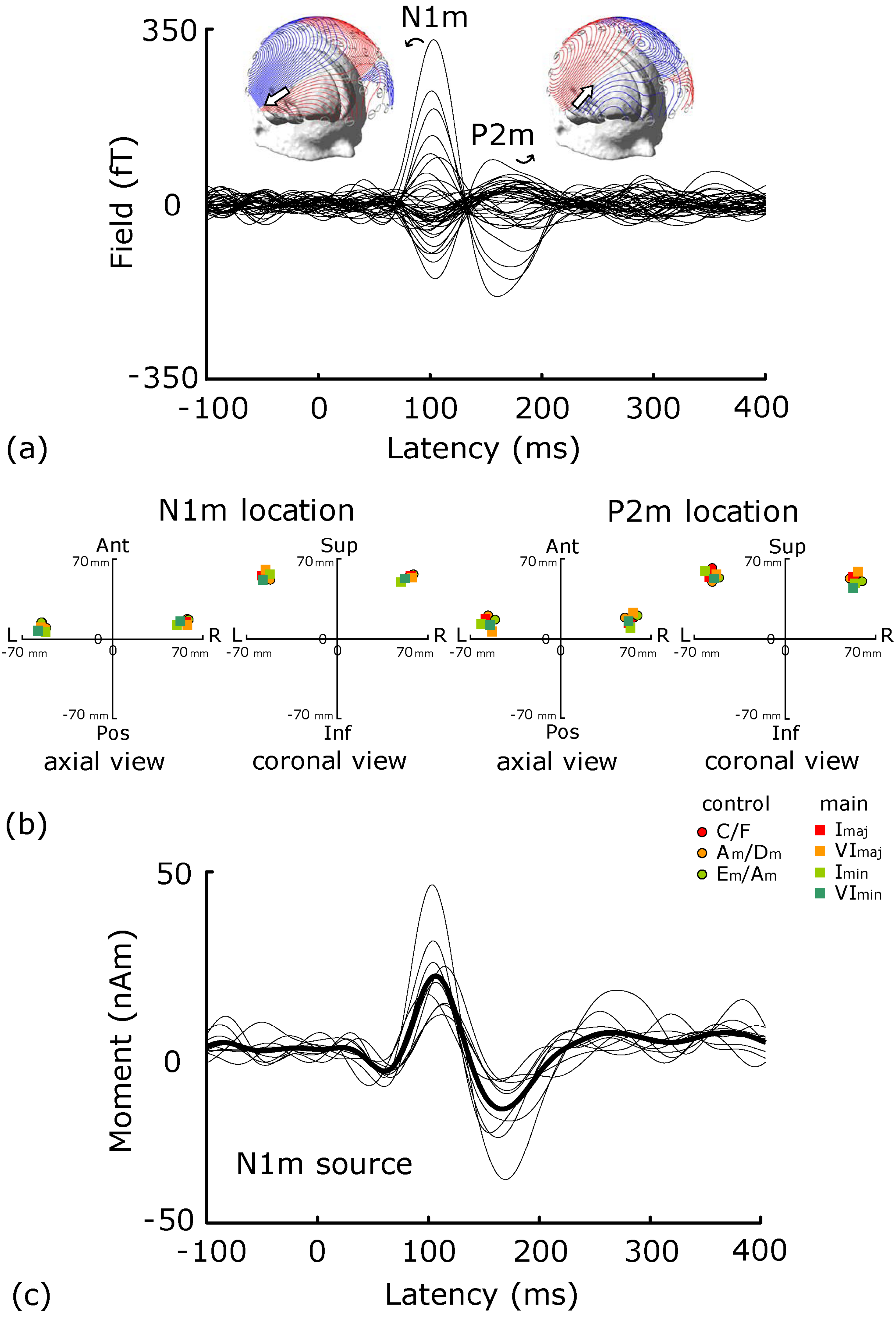


Figure 1. Otsuka et al.
Neuromagnetic responses to chords are modified
by preceding musical scale


N1m
P2m
350
0
-350
Field (fT)
-100
0
100
200
300
400
Latency (ms)
(a)
N1m location
P2m location
Ant
Pos
Sup
Inf
L
R
70 mm
-70 mm
0
axial view
coronal view
(b)
control
main
● C/F
● Am/Dm
● Em/Am
■ Imaj
■ VImaj
■ Imin
■ VImin
50
0
-50
Moment (nAm)
N1m source
-100
0
100
200
300
400
Latency (ms)
(c)

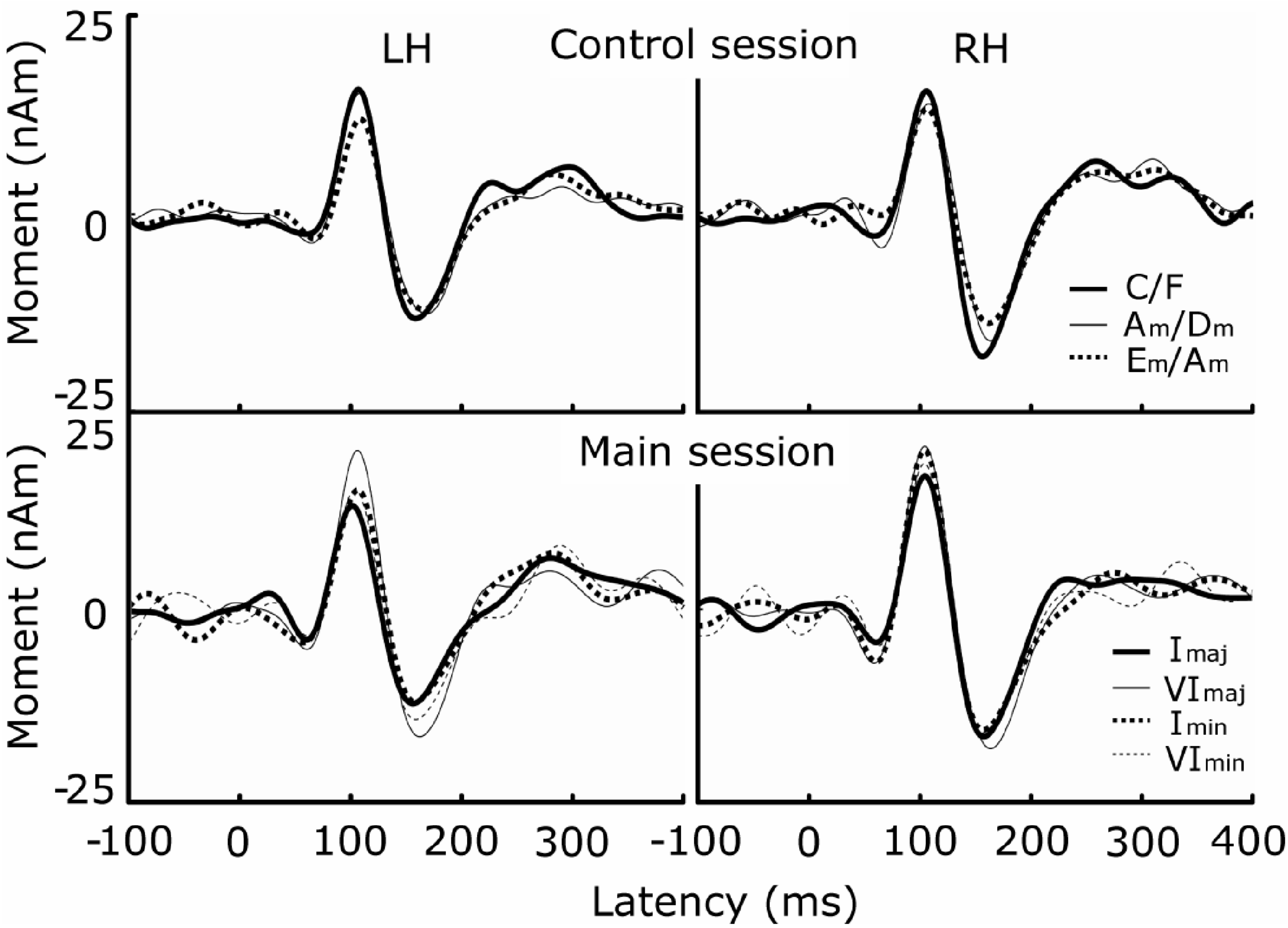


Figure 3. Otsuka et al.
Neuromagnetic responses to chords are modified by preceding musical scale

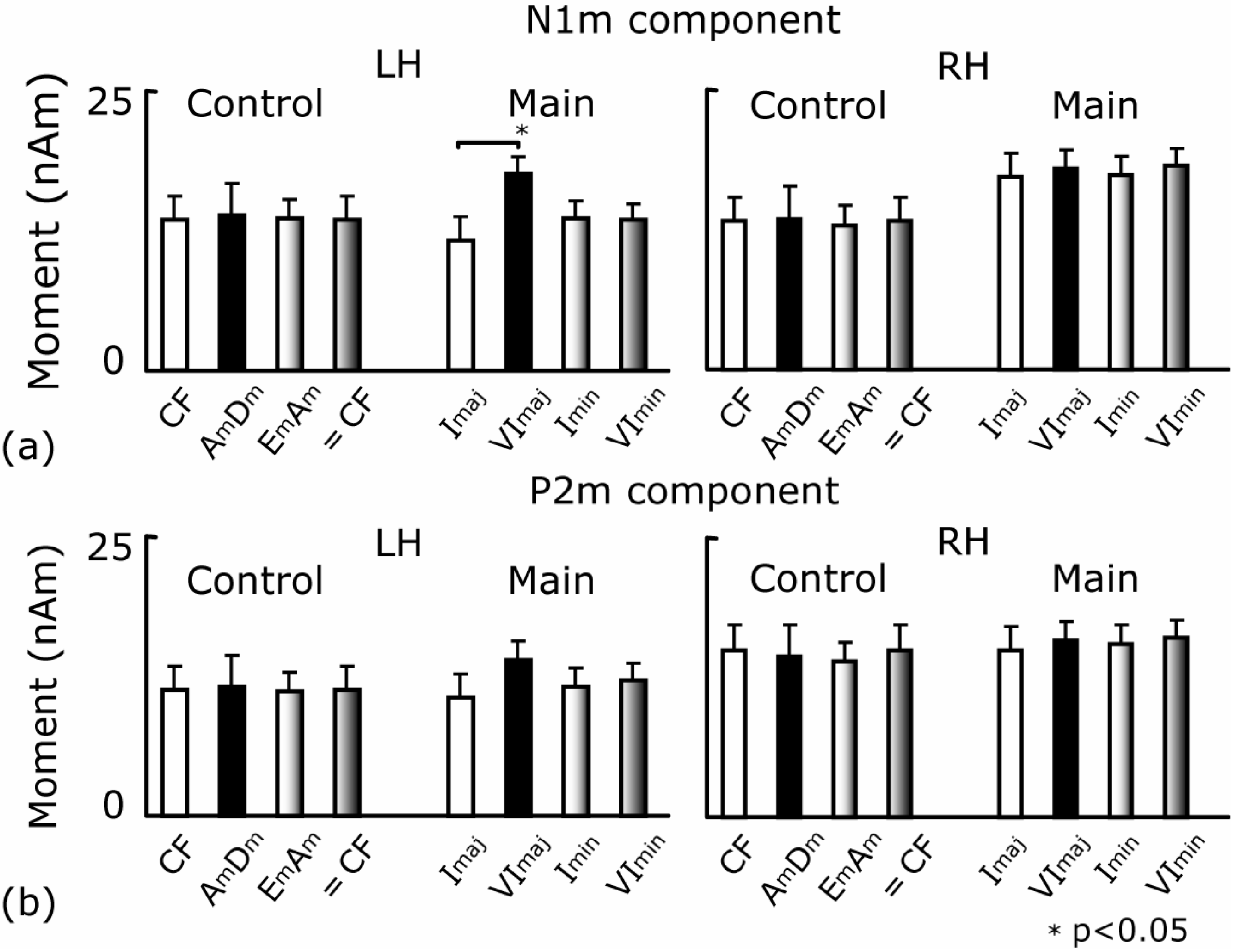


Figure 4. Otsuka et al.
Neuromagnetic responses to chords are modified
by preceding musical scale