Title	Relationship Between Early Neural Responses to Syntactic and Acoustic Irregularities in Music
Author(s)	Ishida, Kai; Nittono, Hiroshi
Citation	European Journal of Neuroscience. 2022, 56(12), p. 6201-6214
Version Type	AM
URL	https://hdl.handle.net/11094/89426
rights	© 2022 Federation of European Neuroscience Societies and John Wiley & Sons Ltd.
Note	

Relationship Between Early Neural Responses to Syntactic and Acoustic Irregularities in Music

Short title: RELATIONSHIP BETWEEN EARLY NEURAL RESPONSES

Kai Ishida[1], Hiroshi Nittono[1]

[1] Graduate School of Human Sciences, Osaka University, Osaka, Japan

Corresponding author: Kai Ishida, Graduate School of Human Sciences, Osaka University, 1-2 Yamadaoka, Suita, Osaka 565-0871, JAPAN; ishida@hus.osaka-u.ac.jp; ORCID: 0000-0001-6485-0950

Hiroshi Nittono, Graduate School of Human Sciences, Osaka University, 1-2 Yamadaoka, Suita, Osaka 565-0871, JAPAN; nittono@hus.osaka-u.ac.jp; ORCID: 0000-0001-5671-609X

Acknowledgement:

Authorship contribution statement: Kai Ishida: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing - original draft. **Hiroshi Nittono:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Project administration, Funding acquisition.

Relationship Between Early Neural Responses to Syntactic and Acoustic Irregularities in Music

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding information: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Keywords: early right anterior negativity, mismatch negativity, music syntax, harmony, N5, auditory processing

Word count: 6259

Abbreviations: ERP, event-related potential; ERAN, early right anterior negativity; MMN, mismatch negativity; ANOVA, analysis of variance; BF, Bayes factor

Data accessibility:

The sound materials and datasets used and analyzed for the present paper can be made available at https://osf.io/r9cg6/.

Abstract

Humans can detect various anomalies in a sound sequence without attending to each dimension explicitly. Event-related potentials (ERPs) have been used to examine the processes of auditory deviance detection. Previous research has shown that music-syntactic anomalies elicit early right anterior negativity (ERAN), while more general acoustic irregularities elicit mismatch negativity (MMN). Although these ERP components occur in a similar latency range with a similar scalp topography, the relationship between the detection processes they reflect remains unclear. This study compared these components by manipulating music-syntactic (chord progression) and acoustic (intensity) irregularities orthogonally in two experiments. Non-musicians (Experiment 1: $N = 39$; Experiment 2: $N = 24$) were asked to listen to chord sequences, each consisting of 5 four-voice chords, as they watched a silent video clip. Standard, harmonic-deviant, intensity-deviant, and double-deviant chords occurred at the final position in each sequence. Deviant stimuli were presented infrequently ($p = .10$) in Experiment 1 and equiprobably ($p = .25$) in Experiment 2. Regardless of deviance probability, both harmonic and intensity deviants elicited similar negativities, which were indistinguishable in terms of latency or scalp distribution. When the two deviant types occurred simultaneously, the negativity increased in an additive manner; that is, the amplitude of the double-deviant ERP was as large as the sum of the single-deviant ERPs. These findings suggest that the detection of music syntactic and acoustic irregularities works independently, based on different regularity representations.

INTRODUCTION

In Western tonal music, the representation of the relationship of chords is hierarchical; this structure is governed by harmonic functions of chords described in the theory of harmony (Krumhansl, 1983). The term “syntax,” which is defined broadly as a set of rules governing the combination of discrete structural elements into larger units, is often used for music as well as for language (Asano & Boeckx, 2015; Patel et al., 1998). The regularities that are found in chord sequences and create harmonic structures are regarded as a form of musical syntax (Koelsch, 2005; Koelsch et al., 2007).

Music-syntactic processing has been examined through an event-related potential (ERP) component called early right anterior negativity (ERAN), which occurs around 150–250 ms after the onset of a harmonically irregular chord (Koelsch et al., 2000; Koelsch & Sammler, 2008; Pagès-Portabella & Toro, 2020). Koelsch et al. (2000) found that the ERAN occurs when a regular chord progression, from dominant to tonic, is disrupted by a harmonic irregularity—e.g., a chord progression from dominant to a Neapolitan sixth (in C major, *D♭–F–A♭*). After the ERAN, a harmonically irregular chord often elicits another negativity, N5, which occurs around 400–850 ms after stimulus onset (Koelsch et al., 2007, 2013; Ma et al., 2018). Some studies have proposed that the N5 component reflects the process of harmonic integration (Koelsch et al., 2013; Zhang et al., 2018).

In addition to anomalies in musical structures, irregularities in acoustic dimensions (e.g., frequency, intensity, duration, or location) elicit a mismatch negativity (MMN) around 100–250 ms after stimulus onset (Fishman, 2014; Näätänen et al., 2007). The MMN is usually recorded in the auditory oddball paradigm (Paavilainen, Simola et al., 2001; Tervaniemi et al., 1994; for a review, see Sussman et al., 2014), in which two types of sounds are randomly presented at high and low probabilities while participants are passively listening to the sounds. The infrequent sound is the rarity or deviation that elicits the MMN in contrast to the standard or frequent sound. Traditionally, the MMN is thought to reflect an automatic change-detection process that detects discrepancies between the input from the deviant auditory event and the sensory memory representations of the regular aspects of the previously presented auditory event (Näätänen et al., 2005).

The ERAN and MMN, which both reflect auditory deviant detection, have been experimentally distinguished by their responsiveness to the degree of violation of the harmonic expectation based on the rules of chord progression. For example, Leino et al. (2007) presented a harmonically irregular chord, the Neapolitan sixth, at one of three positions infrequently (p = .14): one at a pre-dominant position and the other two at post-dominant positions. The Neapolitan sixth chord contains out-of-key notes (in C major, $D\flat$, and $A\flat$) and is classified as a subdominant function. Given the strong expectation of a dominant to tonic succession, a post-dominant Neapolitan sixth elicited a larger ERAN than a pre-dominant Neapolitan sixth. This is evidence that the ERAN reflects the processing of an irregularity in chord progression. In contrast, when a mistuned chord containing a deviant tone from the musical scale was presented at the same three positions, MMN amplitude was not modulated by the position. Moreover, in their study, the latencies of MMN (peaking on average 270 ms poststimulus) and ERAN (peaking on average 236 ms poststimulus) differed. These results suggest that the brain's responses that reflect the processing of chord-progression rules and other auditory regularities are functionally and temporally distinguishable (see also Garza-Villarreal et al., 2011).

Furthermore, Koelsch et al. (2007) used a supertonic chord as the harmonically irregular chord to control the effect of sensory dissonance. In their Experiment 2, a syntactically irregular supertonic chord (in C major, *D–F–A*) that contained only one new pitch elicited an ERAN compared to a syntactically regular tonic chord (in C major, *C–E–G*) that contained two new pitches. This result indicates that the ERAN is elicited by syntactic irregularity but not by sensory dissonance or pitch irregularity (see also Koelsch & Sammler, 2008). Moreover, because harmonically regular and irregular chords were presented with equal probability in their experiment, the ERAN was thought to reflect irregularity detection that was based on the long-term representation of musical syntax. This is different from the eliciting condition of the typical MMN, which is thought to reflect irregularity detection based on the online auditory context.

The previous studies have functionally distinguished the ERAN from the MMN in terms of what types of regularities are processed (Koelsch, 2009). However, it has been argued that these negativities belong to the family of perisylvian negativities that mediate the processing of auditory irregularities (Koelsch et al., 2001; Koelsch & Friederici, 2003; Koelsch, Schmidt et al., 2002). Namely, the ERAN is a special kind of abstract-feature MMN elicited by music-syntactic irregularity (Koelsch, Schröger et al., 2002), or music-syntactic MMN (Koelsch, 2009; Koelsch, Gunter et al., 2003). Although previous studies have compared the ERAN and MMN in a single experiment (Koelsch et al., 2001; Leino et al., 2007), none of the studies have examined the case in which the ERAN and MMN are elicited at the same time by presenting both music-syntactic and acoustic irregularities simultaneously. The present study is the first to address the issue.

Several studies have shown that auditory irregularity dimensions are detected independently with additivity (Paavilainen et al., 2003; Paavilinen, Valppu et al., 2001) or dependently with subadditivity (Lidji et al., 2009; Wolff & Schröger, 2001), respectively. With additivity, the amplitude of the double-deviant MMN that was elicited simultaneously by the two deviant dimensions should be equal to the sum of the single-deviant MMNs that were elicited independently (e.g., frequency and duration dimensions: Wolff & Schröger, 2001), suggesting that both dimensions are separately processed (Caclin et al., 2006). With subadditivity, the amplitude of double-deviant MMN should be smaller than the sum of the single-deviant MMNs (e.g., frequency and intensity dimensions: Wolff & Schröger, 2001), reflecting dependent processing with overlapping processing of each dimension (Hansen et al., 2019).

Present study

The current study examined the relationship and possible interactions between the detection processes of music-syntactic irregularities and acoustic irregularities. In line with previous studies (Koelsch et al., 2007), a short chord sequence that followed harmonic rules was used as a stimulus. Deviant stimuli were presented at the final position. ERPs associated with music-syntactic irregularity and acoustic irregularity were recorded in a passive-listening task in which harmonic deviance and intensity deviance were manipulated orthogonally.

The ERAN and MMN were observed in the context of a violation of chord progression (Koelsch et al., 2000) and an infrequent intensity change (Althen et al., 2011; Todd et al., 2008), respectively. To avoid sensory dissonance in the frequency dimension of the harmonically irregular chord, the supertonic chord, which appeared in the third position of the chord sequence and consisted of in-key notes, was selected as the harmonic deviant (Koelsch et al., 2007; Koelsch & Jentshcke, 2008). In the intensity deviant, the intensity was infrequently decremented, because an intensity decrement elicits the MMN while inhibiting the N1 (Jacobsen et al., 2003; Rinne et al., 2006). Thus, the detection processes of the present harmonic deviant and intensity deviant can be expected to elicit the endogenous ERAN and MMN, controlling for the exogenous N1, so that the fresh-afferent activity caused by a rare stimulus in the adaptation and inhibition states of the neural population for repetitive stimuli would be ruled out (May & Tiitinen, 2010; Näätänen & Picton, 1987; Wang et al., 2008).

The harmonic deviant and intensity deviant were presented separately (single deviant) or simultaneously (double deviant). The aim of the single-deviant conditions was to examine differences in irregularity-detection processes by comparing the latency and scalp topography of each single-deviant ERP. Previous studies have shown similar topographies but incomplete overlap latencies of the ERAN and MMN (Koelsch et al., 2001; Koelsch, Gunter, et al., 2005; Leino et al., 2007). Considering that the elicitation of ERAN involves higher cognitive processing than MMN, ERAN could have a longer latency than MMN (Koelsch et al., 2001).

In the double-deviant condition, two hypotheses were examined. The first hypothesis is that the detection processes of music-syntactic and acoustic irregularities are mutually independent and have no interaction. According to this hypothesis, both deviant dimensions will be detected independently, and the double-deviant ERP will not differ from the sum of the single-deviant ERPs. The second hypothesis is that the detection processes of the two types of irregularities are mutually dependent and interact with each other. In this case, the double-deviant ERP will be smaller than the sum of the single-deviant ERPs.

EXPERIMENT 1

Method

Participants

Forty-six university students (25 women and 21 men, 18–29 years old, $M = 22.5$ years old) participated in the experiment. Due to technical failure and excessive artifacts, the data of seven participants were excluded; the remaining data ($N = 39$, 21 women and 18 men, 18–29 years old, $M = 22.7$) were used for hypothesis testing. Thirty-eight of the 39 participants were right-handed, and one was left-handed, according to the Edinburgh Handedness Inventory (Oldfield, 1971). None of the participants had hearing impairments or a history of neurological disease. All participants were non-musicians and had no professional musical training or explicit knowledge of music theory, although they have received musical lessons at primary and junior high schools as part of compulsory education. The protocol was approved by the Behavioral Research Ethics Committee of the Osaka University School of Human Sciences, Japan (HB020-058), and written informed consent was obtained from all participants. Participants received a cash voucher of 2,000 Japanese yen as an honorarium. The sample size ($N = 39$) was determined to ensure the detection of a medium effect size ($dz = 0.5$) with a power of .80 (minimal $N = 34$).

Materials and procedure

Figure 1 shows the chord sequence used in the experiment. A sequence consisting of 5 four-voice (soprano, alto, tenor, and bass) chords was composed and played with a piano timbre. The chord sequence followed the rules of Western harmony (I→IV→II→V→I). The duration of each of the first four chords and that of the final chord were 600 ms and 1,200 ms, respectively, such that the overall duration of each sequence was 3,600 ms. The final chord of the sequence was experimentally manipulated in a 2 × 2 design: absence or presence of harmonic deviance and absence or presence of intensity deviance. In other words, standard (p = .7), harmonic-deviant (p = .1), intensity-deviant (p = .1), and double-deviant (p = .1) chords were presented randomly. In the standard sequence, the final chord (I: tonic chord) followed the fourth chord (V: dominant chord): In the rule of chord progression, dominant-to-tonic succession is a natural motion in the final position of a sequence. In the harmonic deviant condition, the final chord was altered to be a supertonic chord (II), violating the dominant-to-tonic succession, because supertonic chords cannot substitute for the function of the tonic chord. In the intensity-deviant condition, the intensity of the final chord was decreased by 6 dB (half amplitude) from the standard condition. In the double-deviant condition, the final chord was altered to be the supertonic chord, and its intensity was decreased by 6 dB. The stimuli were generated using Studio One Prime (Version 4.6.2; PreSonus Audio Electronics, Baton Rouge, LA, USA) and edited using Adobe Audition (version 13.0.12; Adobe Systems Incorporated, San Jose, CA, USA). The four types of sequences were transposed into seven major keys (C major, C# major, D major, D# major, E major, F major, F# major). The stimulus set is available at https://osf.io/r9cg6/. The sound materials were produced in stereo. Musical stimuli were recorded monoaurally on the first channel (music), and a stimulus marker indicating the onset of the final chord was added to the second channel (marker). These channels were outputted separately via a stereo-to-monoaural splitter cable. The stimuli on the music channel were presented through left and right headphones (DR-531; ELEGA ACOUS, Tokyo, Japan) at 60 dB SPL (excluding intensity deviants). The marker channel was connected to an auditory signal detector (StimTrak; Brain Products, Gilching, Germany), which immediately (<1 ms) sent a trigger to an electroencephalography

(EEG) amplifier.

A total of 1,000 stimuli (700 standard, 100 harmony-deviant, 100 intensity-deviant, and 100 double-deviant stimuli) were presented with an interstimulus interval of 50 ms. Thus, the interval between the onset of the final chord and the onset of the first chord of the next sequence was 1,250 ms. The session was separated into two blocks, with a short break between blocks. The order of stimuli was pseudorandomized, with the constraints that at least one standard sequence was inserted between the deviant sequences and that sequences in the same key or deviance type were not repeated more than three times in succession. Participants sat in a comfortable chair and were told to passively listen to musical stimuli while watching a subtitled silent movie on an LCD screen in front of them. They were not informed about deviant stimuli. The total duration of the experiment was about 2 h, including the electrode preparation.

EEG recording

EEG data were recorded using a QuickAmp (Brain Products) with Ag/AgCl electrodes. Thirty-four scalp electrodes were applied according to the 10–20 system (Fp1/2, F3/4, F7/8, Fz, FC1/2, FC5/6, FT9/10, C3/4, T7/8, Cz, CP1/2, CP5/6, TP9/10, P3/4, P7/8, Pz, O1/2, Oz, PO9/10). Additional electrodes were placed on the left and right mastoids, the left and right outer canthi of the eyes, and above and below the right eye. The data were referenced offline to the nose. The sampling rate was 1,000 Hz. The online filter was DC–200 Hz. Electrode impedances were kept below 10 kΩ.

Data reduction

EEG data were analyzed using Brain Vision Analyzer (Brain Products). First, a digital filter of 0.25 Hz (6 dB/oct)–25 Hz (48 dB/oct) was applied to the data (Koelsch et al., 2007). Ocular artifact correction based on independent component analysis was then applied. A 1,200-ms period (200 ms before and 1,000 ms after the final chord) was averaged after removing trials in which voltages exceeded ±80 μV on any channel. On average, 662 (range = 535–700), 95 (74–100), 94 (76–100), and 95 (80–100) trials were retained in the standard, harmonic-deviant, intensity-deviant, and double-deviant conditions, respectively. No significant differences in the proportions of averaged trials were found among the four conditions ($F_{3,114} = 1.23$, $p = .300$, $\varepsilon = .826$, $\eta_p^2 = .031$). Baseline correction was applied by subtracting the mean amplitude of the prestimulus 200-ms period from each point of the waveform.

Based on previous reports (ERAN: Koelsch et al., 2000, 2007; MMN: Fisher et al., 2011; Näätänen et al., 2007; N5: Koelsch et al., 2007, 2013; Ma et al., 2018), the epochs of 140–200 ms and 400–600 ms were selected as the time windows for analyzing ERAN/MMN and N5/late negativity, respectively. Because the N5 has been examined exclusively in the study of harmonic deviance in music, the more descriptive term "late negativity" is used here. To extract the deviance-related ERP responses, ERP waveforms in the standard condition were subtracted from ERP waveforms in each deviant condition (difference waveforms). Because both ERAN/MMN and N5/late negativity have a frontal scalp distribution, ERP waveforms were calculated as the mean of five frontal electrodes (F7, F3, Fz, F4, and F8). For the ERAN/MMN, peak latency was determined individually for each deviant condition as the most negative peak occurring in the frontal region at 140–200 ms poststimulus onset. The peak latency of the N5/late negativity was not analyzed because no clear peaks were observed.

Statistical analysis

Statistical analyses were carried out using the statistical software package SPSS version 27 (SPSS Inc., Chicago, IL, USA). A two-way repeated-measures analysis of variance (ANOVA) with harmonic deviance (absent vs. present) and intensity deviance (absent vs. present) as the factors was conducted on the five frontal mean amplitudes of 140–200 ms or 400–600 ms. For the difference waveforms, the peak latencies of the ERAN/MMN were submitted to a one-way repeated-measures ANOVA with the factor of deviance type (harmonic vs. intensity vs. double). Furthermore, topographic differences of ERPs were analyzed by a topographic ANOVA (TANOVA) using the Randomization Graphical User Interface (RAGU, version 2020-11-24; Habermann et al., 2018; Koenig et al., 2011). The TANOVA tests whether the differences in scalp electric field, which is calculated for each ERP component from the global field power of the whole head electrodes, are due to the effect of an experimental condition or random noise. By randomly shuffling the condition assignments in each subject and recomputing the scalp field differences many times, the estimated distribution of the scalp field difference under the null hypothesis is calculated. The *p*-value indicates the probability that the observed topographical difference is obtained under the null hypothesis that there is no real difference. The topographies of deviant-related ERPs (deviant − standard) were compared at the 140–200 ms and 400–600 ms latency ranges. The iteration of randomization was 5,000. To examine the relationship between the types of deviant detection, the additive or subadditive effect was evaluated by comparing the sum of the single-deviant difference waveform amplitudes and the double-deviant difference waveform amplitude using paired *t*-tests (Paavilinen, Valppu et al., 2001). Greenhouse-Geisser ε correction was applied when the degrees of freedom were more than one. In all statistical tests including the TANOVA, the significance levels were set to $\alpha = .05$. In post-hoc testing, the Bonferroni correction was applied to multiple comparisons. To assess the absence of an interaction between harmonic deviance and intensity deviance, the Bayes factor (BF_{01}) for the model with the main effects only (null hypothesis) versus the model with the main effects and the interaction term (alternative hypothesis) was computed using a Bayesian two-way repeated-measures ANOVA. For the calculation, JASP 0.13 (JASP Team, 2020) was used. As the prior distribution, multivariate Cauchy distribution (fixed effect: scale parameter r = 0.5; random effect: scale parameter r = 1), which is the default of JASP, was used. Moreover, the additivity of the deviances was examined using a Bayesian paired *t*-test to assess whether the difference between the sum of the single-deviant difference waveform amplitudes and the double-deviant difference waveform amplitude was zero (effect size $\delta = 0$, null hypothesis) or not (effect size $\delta \neq 0$, alternative hypothesis). As the prior distribution for δ, the Cauchy distribution, with a scale parameter r of 0.707, was used. According to the classification scheme of Wagenmakers et al. (2018), a BF_{01} greater than 3 provides moderate evidence for the null hypothesis. The data set is available at https://osf.io/r9cg6/.

Results and Discussion

Figure 2A shows the grand average waveforms and scalp topographies of the ERPs elicited by the final chords. All types of deviants were presented infrequently (p = .10 each) and elicited the ERAN/MMN and N5/late negativity in the frontal area at the 140–200 ms and 400–600 ms time windows, respectively. The ERAN and MMN showed indistinguishable latency and scalp distribution. The upper section of Table 1 provides the mean amplitudes and results of the *t*-tests for the comparisons of the standard and each deviant. All negativities were significantly greater than baseline.

Early negativities in the 140–200 ms time window

The bottom panel of Figure 2A shows that ERPs elicited by the three types of deviance were spread similarly over the frontal region. A two-way repeated-measures ANOVA revealed significant main effects of harmonic deviance and intensity deviance ($F_{1,38} = 21.60$, $p < .001$, $\eta_p^2 = .362$ and $F_{1,38} = 29.62$, $p < .001$, $\eta_p^2 = .438$). However, the interaction of harmonic and intensity deviances was not significant ($F_{1,38} = 1.90$, $p = .177$, $\eta_p^2 = .048$), suggesting that each deviance factor independently affected the ERP components. However, the absence of the interaction was not strongly supported by the results of the Bayesian two-way repeated ANOVA ($BF_{01} = 2.59$). The alternative hypothesis was not supported, either.

The mean peak latencies (*SD*s) of the ERAN/MMN were 169.3 (22.4), 168.2 (17.1), and 166.1 (15.4) ms for the harmonic-deviant, intensity-deviant, and double-deviant stimuli, respectively. A one-way ANOVA on peak latency did not show a difference in latency (deviance type: $F_{2,76} = 0.39$, $p = .625$, $\varepsilon = .766$, $\eta_p^2 = .010$). According to the TANOVA, the topographic difference between ERAN and MMN at 140–200 ms was not significant ($p = .858$). These results suggest that each deviant elicited a similar ERP response.

Late negativities in the 400–600 ms time window

The bottom panel of Figure 2A shows that N5/late negativity was distributed over the frontal region in all deviant conditions. A two-way repeated ANOVA revealed significant main effects of harmonic deviance and intensity deviance ($F_{1,38} = 9.93$, $p = .003$, $\eta_p^2 = .207$ and $F_{1,38} = 17.70$, $p < .001$, $\eta_p^2 = .318$). As in the earlier time window, the interaction of harmonic and intensity deviances was not significant, suggesting that each deviance factor independently affected the ERP components ($F_{1,38} = 0.83$, $p = .369$, $\eta_p^2 = .021$). Again, the absence of the interaction was not strongly supported by the result of the Bayesian two-way repeated ANOVA ($BF_{01} = 2.93$).

The TANOVA did not reveal a significant difference in scalp topography between N5 and late negativity at 400–600 ms (p = .357). Again, the ERP responses were indistinguishable between harmonic-deviant and acoustic-deviant stimuli.

Additive effects for double deviant

Figure 3A shows the additive effects at the 140–200 ms and 400–600 ms time windows. This additivity was confirmed by the lack of statistical amplitude differences between the sum of single-deviant ERPs and the double-deviant ERP in the 140–200 ms and 400–600 ms time windows ($t_{38} = -1.69$, p = .099, dz = 0.27, and $t_{38} = -0.94$, p = .353, dz = 0.15). The Bayesian paired t-test provided moderate evidence for the null hypothesis only in the N5/late negativity (ERAN/MMN: BF_{01} = 2.42; N5/late negativity: BF_{01} = 3.94). Taken together, these findings suggest that music-syntactic and acoustic irregularities are detected independently in early auditory processing (Caclin et al., 2006).

Experiment 1 showed the additive effect of ERP responses elicited by harmonic and intensity deviances. However, it is possible that the harmonic deviant was detected as a pitch-interval deviant because it was presented infrequently. More specifically, the pitch interval between the fourth and fifth chords of the harmonic deviant (i.e., three semitones in the soprano part) was different from that of the standard (i.e., one semitones). Several studies have reported that the MMN is elicited by an infrequent change in pitch intervals in a melody (Fujioka et al., 2004) and in chords (Bergelson & Idsardi, 2009). In Experiment 2, this possibility of pitch-interval deviance was addressed by presenting all stimulus types with equal probability. By presenting the sequences with equal probability, no template for frequent standard chords would be formed, and the pitch-interval of one condition would not become dominant over the other (Koelsch et al., 2000). Thus, the presentation with equal probability can also prevent the pitch-interval deviance.

EXPERIMENT 2

The goal of Experiment 2 was to replicate Experiment 1's finding that harmonic and intensity deviances additively affected the ERP amplitude when the stimuli were presented with equal probability. The ERAN occurs even if harmonically irregular and regular chords are presented equiprobably (Kolsch et al., 2007: Koelsch & Jentschke, 2008). The neural response to equiprobable harmonic deviants reflects the detection of harmonic irregularity based on knowledge rather than on a sensory memory-based template (frequency or pitch interval) of the standard sequence (Koelsch, 2009; Koelsch et al., 2000, 2007). If an equiprobable harmonic deviant were to elicit a negativity, it would provide evidence that the chord is processed in terms of musical syntax.

Method

Participants

Twenty-eight university students (7 women and 21 men, 18–31 years old, M = 22.1 years old) participated in Experiment 2. None of them had participated in Experiment 1. Due to technical failure and excessive artifacts, the data of four participants were excluded; the remaining data (N = 24, 6 women and 18 men, 18–31 years old, M = 22.1) were used for hypothesis testing. Twenty-three of the 24 participants were right-handed, and one was left-handed, according to the Edinburgh Handedness Inventory (Oldfield, 1971). None of the participants had hearing impairments or a history of neurological disease. All participants were non-musicians, and all had less than one year of extracurricular musical training (five participants had extracurricular musical experience for 1–10 months, M = 6.4 months) and no explicit knowledge of music theory. They have received musical lessons at primary and junior high schools as part of compulsory education. The protocol was approved by the Behavioral Research Ethics Committee of the Osaka University School of Human Sciences, Japan (HB021-021), and written informed consent was obtained from all participants. Participants received a cash voucher of 2,000 Japanese yen as an honorarium. The sample size ($N = 24$) was determined to ensure the detection of the effect size calculated from the harmonic deviant of Experiment 1 ($dz = 0.90$) with a power of .95 (minimal $N = 19$).

Materials and procedure

The sound materials were the same as those used in Experiment 1. However, the probabilities of presentation were different: the four types of chord sequences (standard, harmonic deviant, intensity deviant, and double deviant) were presented with equal probability (ps = .25). A total of 624 stimuli (156 per chord sequence type) were presented. The session was separated into three blocks, with a short break between blocks. The order of stimuli was pseudorandomized, with the constraint that sequences in the same key and condition were not repeated more than three times in succession. All other procedures were the same as in Experiment 1.

EEG processing and statistical analysis

The methods of recording and data reduction of EEG were the same as in Experiment 1. One bad channel (FT 10) for one participant was spline interpolated. In Experiment 2, on average, 152 (range = 121–156), 151 (121–156), 150 (123–156), and 151 (124–156) trials were retained in the standard, harmonic-deviant, intensity-deviant, and double-deviant conditions, respectively. No significant differences in the proportions of averaged trials were found among the four conditions ($F_{3,69} = 2.83$, $p = .061$, $\varepsilon = .758$, $\eta_p^2 = .110$). The method of statistical testing was the same as in

Experiment 1.

Results and Discussion

In Experiment 2, all types of sequences were presented with equal probability. Figure 2B shows the grand average waveforms and scalp topographies of the ERPs elicited by the final chords. All types of deviants elicited the ERAN/MMN and the N5/late negativity in the frontal area in the 140–200 ms and 400–600 ms time windows, respectively. The bottom section of Table 1 shows the mean amplitudes and the results of the *t*-tests for the comparison of the standard and each deviant. All negativities were significantly greater than baseline, except for the late negativity for the harmonic deviant condition.

Early negativities in the 140–200 ms time window

The bottom panel of Figure 2B shows that the ERPs elicited by the three types of deviance were similarly spread over the frontal region, and the results were almost the same as in Experiment 1. A two-way repeated-measures ANOVA revealed significant main effects of harmonic deviance and intensity deviance ($F_{1,23} = 7.28$, $p = .013$, $\eta_p^2 = .240$ and $F_{1,23} = 41.08$, $p < .001$, $\eta_p^2 = .641$). The interaction of harmonic and intensity deviance was not significant, suggesting that the two deviance factors independently affected the ERP components ($F_{1,23} = 0.17$, $p = .684$, $\eta_p^2 = .007$). The lack of interaction between harmonic and intensity deviance was supported by the Bayesian two-way repeated ANOVA ($BF_{01} = 3.15$), which provided moderate evidence for the null hypothesis.

The mean peak latencies (*SD*s) of the ERAN/MMN were 164.2 (19.6), 171.2 (18.0), and 168.4 (20.3) ms for the harmonic-deviant, intensity-deviant, and double-deviant stimuli, respectively. A one-way ANOVA on peak latency did not reveal a difference in latency (deviance type: $F_{2,46} = 1.17$, $p = .320$, $\varepsilon = .981$, $\eta_p^2 = .048$). Similarly to Experiment 1, the TANOVA did not reveal a significant difference in scalp topography between ERAN and MMN at 140–200 ms ($p = .282$).

Late negativities in the 400–600 ms time window

The bottom panel of Figure 2B shows that late negativity was distributed over the frontal region in all deviant conditions. A two-way repeated-measures ANOVA revealed a significant main effect of intensity deviance ($F_{1,23} = 18.63$, $p < .001$, $\eta_p^2 = .448$), but the main effect of harmonic deviance was not significant ($F_{1,23} = 4.12$, $p = .054$, $\eta_p^2 = .152$). As with the earlier time window, the interaction of harmonic and intensity deviances was not significant, suggesting the independence of each deviance factor, with only intensity deviance affecting the late negativity ($F_{1,23} = 0.27$, $p = .611$, $\eta_p^2 = .011$). The absence of the interaction of harmonic and intensity deviance was supported by the Bayesian two-way repeated ANOVA ($BF_{01} = 3.31$), providing moderate evidence for the null hypothesis. The TANOVA did not show a significant topographic difference between N5 and late negativity ($p = .815$).

Additive effects of double deviant

Figure 3B shows the additive effects in the 140–200 ms and 400–600 ms time windows; these were similar to those in Experiment 1. Again, this additivity was confirmed by the lack of significant amplitude differences between the sum of single-deviant ERPs and the double-deviant ERP in the 140–200 ms and 400–600 ms time windows ($t_{23} = -0.41$, $p = .684$, $dz = -0.08$ and $t_{23} = 0.52$, $p = .611$, $dz = 0.11$). The Bayesian paired *t*-test also provided moderate evidence for the null hypothesis (ERAN/MMN: $BF_{01} = 4.31$; N5/late negativity: $BF_{01} = 4.13$). Again, the evidence suggests independent neural processing for the music-syntactic and acoustic irregularity dimensions, even if harmonically irregular chords occur equiprobably with regular chords.

Effects of Deviance Probability

To examine possible differences between the two experiments, a three-way mixed ANOVA with factors of harmonic deviance (absent vs. present), intensity deviance (absent vs. present), and deviance probability (rare vs. equiprobable) was conducted on the mean amplitudes in the 140–200 ms and 400–600 ms time windows. The significance levels were set at $\alpha = .05$.

For both early (140–200 ms) and late (400–600 ms) time windows, a three-way mixed ANOVA revealed significant main effects of harmonic deviance and intensity deviance (early time window: $F_{1,61} = 23.65$, $p < .001$, $\eta_p^2 = .279$ and $F_{1,61} = 57.55$, $p < .001$, $\eta_p^2 = .485$; late time window: $F_{1,61} = 12.35$, $p < .001$, $\eta_p^2 = .168$ and $F_{1,61} = 27.82$, $p < .001$, $\eta_p^2 = .313$). However, the main effect of deviance probability was not significant (early time window: $F_{1,61} = 0.15$, $p = .699$, $\eta_p^2 = .002$; late time window: $F_{1,61} = 2.05$, $p = .157$, $\eta_p^2 = .033$) and none of the interactions involving deviance probability were significant (early time window: ps > .146; late time window: ps > .358).

GENERAL DISCUSSION

The present study examined the relationship between the detection processes of music-syntactic and acoustic irregularities by manipulating these two factors orthogonally. In the experimental sessions, the harmonic and intensity deviants were presented independently (single deviant) or simultaneously (double deviant). All stimuli elicited negativities around 140–200 ms after the stimulus onset. Both single-deviant ERPs were indistinguishable in terms of latency and scalp distribution. The double-deviant ERP demonstrated an additive effect and was equivalent to the sum of the effects of the harmonic deviance and the intensity deviance. Although the absence of an interaction effect was not supported by Bayesian analysis in Experiment 1, the Bayesian analysis in Experiment 2 and the ANOVA conducted on data from both experiments clearly supported the additivity of the deviance factors. Taken together, these findings suggest that in these specific conditions, music-syntactic irregularities that elicit a similar neural response as acoustic irregularities are detected independently in early auditory processing.

Additivity of similar neural responses to independent irregularities

Two independent factors elicited ERPs that showed similar latency and scalp distribution. This finding supports the suggestion of Koelsch et al. (2001) that "both MMN and ERAN belong to a family of perisylvian negativities that mediate the processing of irregularities of auditory input" (p. 1389). The MMN is known to be elicited by various deviant dimensions: the deviation of abstract features (Paavilainen et al., 2013) and statistical regularities (Tsogli et al., 2019). Similarly, music-syntactic irregularity may elicit a special kind of abstract-feature MMN (Koelsch, Schröger, et al., 2002).

The current finding of ERP amplitude additivity suggests that the responses to harmonic and intensity deviances were based on different and independent representations of regularities. When mutually independent dimensions deviate simultaneously, different representations for each dimension elicit the MMN in an additive manner; the additivity reflects the independent detection of the deviant dimensions (Caclin et al., 2006). In the present study, the representation of the music-syntactic regularity already exists in a long-term format, and the acoustic regularity is extracted online from the current auditory stream (Koelsch, 2009). Thus, the additivity suggests that music-syntactic and acoustic irregularities are detected independently in a similar latency range based on different types of regularity representations that are related to long-term music knowledge and the short-term auditory context. Another possibility is that the brain reacted to the music-syntactic and acoustic irregularities similarly and both types of irregularities elicited a general non-specific response.

N5 and late negativity

After early negativities, all deviants elicited a late negative potential around 400–600 ms after the stimulus onset, although the amplitude of the response to the harmonic deviant in Experiment 2 did not achieve significance. Although the N5 has been thought to reflect the process of harmonic integration (Koelsch, Gunter, et al., 2003) or the processing of musical meaning (Koelsch, 2011), its functional significance is not fully understood. In this study, however, the intensity deviant elicited similar negativity, with the same latency and scalp distribution. When the harmonic and intensity deviants occurred simultaneously, the deviant factor additively affected the amplitude of this negativity. Therefore, the N5/late negativity in this study may not have been a response specific to music-syntactic irregularity. Several studies have measured the late discriminative negativity (LDN) that follows the MMN, and have found that the latency overlaps with the N5 (Honbolygó et al., 2017; Peter et al., 2012). Although the LDN is considered to reflect cognitive-level processing of deviant stimuli (Čeponiene et al., 2004), its functional significance remains unclear (David et al., 2020). It is necessary to closely examine the functional significance of the late negativities elicited by music-syntactic irregularities and acoustic irregularities in future research.

Several studies have reported that a late positive potential, P600, is elicited after the ERAN when participants are asked to detect out-of-key or out-of-tune notes (Lagrois et al., 2018; Peretz et al., 2009; Zendel et al., 2022; Zendel & Alexander, 2020). Similarly to the N5, the P600 is also thought to reflect the integration of a violated tone into the tonal context, and both potentials are observed around 400–600 ms (N5: Koelsch et al., 2007; Zhang et al., 2018; P600: Lagrois et al., 2018; Zendel et al., 2022; Zendel & Alexander, 2020). Although both components may have a similar function, Koelsch (2011) discussed that the N5 may also reflect the processing of intramusical meaning. As far as we know, similarities and differences between N5 and P600 are poorly understood. Detailed discussion on this issue goes beyond the scope of this paper. Future research is needed to elucidate the relationship between the two components.

Limitations

The present study has several limitations. First, the current study used a short chord sequence with a simple harmonic structure. Several studies have stated that the ERAN reflects more structural processing than the MMN (Koelsch, 2009; Garza-Villarreal et al., 2011). The neural response to the current harmonic deviant may have reflected the local dependency of chords, but not the processing of the hierarchical syntactic structure (Koelsch et al., 2013). By manipulating the structure of the musical context and positions of presentation that differ in harmonic inappropriateness, differences in latency between the ERAN and the MMN might be observed (Koelsch et al., 2001).

Second, in the present study, all participants were non-musicians. Hansen et al. (2019) reported that musicians showed more subadditive effects in the MMN elicited by the multidimensional deviant than non-musicians, suggesting that shared neural resources are used to process multidimensional features. Musicians have greater sensitivity in harmonic irregularity detection (Koelsch, Schmidt, et al., 2002; Pagès-Portabella & Toro, 2020) and acoustic irregularity detection (Tervaniemi et al., 2009) than non-musicians. Thus, the subadditive effect of music-syntactic irregularities and acoustic irregularities might be found in musicians. Pagès-Portabella and Toro (2020) suggested that musicians have not only the ability to detect music-syntactic irregularities, but also dissonance of chords. Using the double-deviant paradigm of the present study, it should be possible to investigate how each regularity dimension of the music is processed both integratively and separately, and how musical expertise affects the detection of music-syntactic irregularities and other auditory irregularities.

CONCLUSION

The current results indicate that music-syntactic irregularity elicits a similar neural response as acoustic irregularity, and both irregularities elicited additive neural responses. These findings suggest that each deviance can be independently detected in early auditory processing based on different representations of regularities. This study provides further evidence for the notion that the ERAN and MMN are family, but have distinct functional significance. How responsiveness to experimental variables overlaps in the ERAN and MMN, and how the factor of musical training affects the detection of each deviant, are topics for future research.

References

Althen, H., Grimm, S., & Escera, C. (2011). Fast detection of unexpected sound intensity decrements as revealed by human evoked potentials. *PLOS ONE, 6*(12). https://doi.org/10.1371/journal.pone.0028522

Asano, R., & Boeckx, C. (2015). Syntax in language and music: What is the right level of comparison? *Frontiers in Psychology, 6,* 1–16. https://doi.org/10.3389/fpsyg.2015.00942

Bergelson, E., & Idsardi, W. J. (2009). A neurophysiological study into the foundations of tonal harmony. *NeuroReport, 20*(3), 239–244. https://doi.org/10.1097/WNR.0b013e32831ddebf

Caclin, A., Brattico, E., Tervaniemi, M., Näätänen, R., Morlet, D., Giard, M. H., & McAdams, S. (2006). Separate neural processing of timbre dimensions in auditory sensory memory. *Journal of Cognitive Neuroscience, 18*(12), 1959–1972. https://doi.org/10.1162/jocn.2006.18.12.1959

Čeponiene, R., Lepistö, T., Soininen, M., Aronen, E., Alku, P., & Näätänen, R. (2004). Event-related potentials associated with sound discrimination versus novelty detection in children. *Psychophysiology, 41*(1), 130–141. https://doi.org/10.1111/j.1469-8986.2003.00138.x

David, C., Roux, S., Bonnet-Brilhault, F., Ferré, S., & Gomot, M. (2020). Brain responses to change in phonological structures of varying complexity in children and adults. *Psychophysiology, 57*(9), 1–13. https://doi.org/10.1111/psyp.13621

Fisher, D. J., Grant, B., Smith, D. M., & Knott, V. J. (2011). Effects of deviant probability on the "optimal" multi-feature mismatch negativity (MMN) paradigm.

International Journal of Psychophysiology, 79(2), 311–315. https://doi.org/10.1016/j.ijpsycho.2010.11.006

Fishman, Y. I. (2014). The mechanisms and meaning of the mismatch negativity. *Brain Topography, 27*(4), 500–526. https://doi.org/10.1007/s10548-013-0337-3

Fujioka, T., Trainor, L. J., Ross, B., Kakigi, R., & Pantev, C. (2004). Musical training enhances automatic encoding of melodic contour and interval structure. *Journal of Cognitive Neuroscience, 16*(6), 1010–1021. https://doi.org/10.1162/0898929041502706

Garza-Villarreal, E. A., Brattico, E., Leino, S., Østergaard, L., & Vuust, P. (2011). Distinct neural responses to chord violations: A multiple source analysis study. *Brain Research, 1389,* 103–114. https://doi.org/10.1016/j.brainres.2011.02.089

Habermann, M., Weusmann, D., Stein, M., & Koenig, T. (2018). A student's guide to randomization statistics for multichannel event-related potentials using Ragu. *Frontiers in Neuroscience, 12,* 1–20. https://doi.org/10.3389/fnins.2018.00355

Hansen, N. C., Højlund, A., Møller, C., Pearce, M., & Vuust, P. (2019). Domain-relevant auditory expertise modulates the additivity of neural mismatch responses in humans. *BioRxiv, 61*. https://doi.org/10.1101/541037

Honbolygó, F., Kolozsvári, O., & Csépe, V. (2017). Processing of word stress related acoustic information: A multi-feature MMN study. *International Journal of Psychophysiology, 118,* 9–17. https://doi.org/10.1016/j.ijpsycho.2017.05.009

Jacobsen, T., Horenkamp, T., & Schröger, E. (2003). Preattentive memory-based comparison of sound intensity. *Audiology and Neuro-Otology, 8*(6), 338–346. https://doi.org/10.1159/000073518

JASP Team (2020). JASP (version 0.13) [computer software] https://jasp-stats.org/.

Koelsch, S. (2005). Neural substrates of processing syntax and semantics in music. *Current Opinion in Neurobiology, 15*(2), 207–212. https://doi.org/10.1016/j.conb.2005.03.005

Koelsch, S. (2009). Music-syntactic processing and auditory memory: Similarities and differences between ERAN and MMN. *Psychophysiology, 46*(1), 179–190. https://doi.org/10.1111/j.1469-8986.2008.00752.x

Koelsch, S. (2011). Towards a neural basis of processing musical semantics. *Physics of Life Reviews, 8*(2), 89–105. https://doi.org/10.1016/j.plrev.2011.04.004

Koelsch, S., & Friederici, A. D. (2003). Toward the neural basis of processing structure in music. *Annals of the New York Academy of Sciences, 999*(1), 15–28. https://doi.org/10.1196/annals.1284.002

Koelsch, S., Gunter, T., Friederici, A. D., & Schröger, E. (2000). Brain indices of music processing: "Nonmusicians" are musical. *Journal of Cognitive Neuroscience, 12*(3), 520–541. https://doi.org/10.1162/089892900562183

Koelsch, S., Gunter, T., Schröger, E., & Friederici, A. D. (2003). Processing tonal modulations: An ERP study. *Journal of Cognitive Neuroscience, 15*(8), 1149–1159. https://doi.org/10.1162/089892903322598111

Koelsch, S., Gunter, T. C., Schröger, E., Tervaniemi, M., Sammler, D., & Friederici, A. D. (2001). Differentiating ERAN and MMN: An ERP study. *NeuroReport, 12*(7), 1385–1389. https://doi.org/10.1097/00001756-200105250-00019

Koelsch, S., Gunter, T. C., Wittfoth, M., & Sammler, D. (2005). Interaction between syntax processing in language and in music: An ERP study. *Journal of Cognitive Neuroscience, 17*(10), 1565–1577. https://doi.org/10.1162/089892905774597290

Koelsch, S., & Jentschke, S. (2008). Short-term effects of processing musical syntax: An ERP study. *Brain Research, 1212,* 55–62. https://doi.org/10.1016/j.brainres.2007.10.078

Koelsch, S., Jentschke, S., Sammler, D., & Mietchen, D. (2007). Untangling syntactic and sensory processing: An ERP study of music perception. *Psychophysiology, 44*(3), 476–490. https://doi.org/10.1111/j.1469-8986.2007.00517.x

Koelsch, S., Rohrmeier, M., Torrecuso, R., & Jentschke, S. (2013). Processing of hierarchical syntactic structure in music. *Proceedings of the National Academy of Sciences of the United States of America, 110*(38), 15443–15448. https://doi.org/10.1073/pnas.1300272110

Koelsch, S., & Sammler, D. (2008). Cognitive components of regularity processing in the auditory domain. *PLOS ONE, 3*(7), e2650. https://doi.org/10.1371/journal.pone.0002650

Koelsch, S., Schmidt, B. H., & Kansok, J. (2002). Effects of musical expertise on the early right anterior negativity: An event-related brain potential study. *Psychophysiology, 39*(5), 657–663. https://doi.org/10.1017/S0048577202010508

Koelsch, S., Schröger, E., & Gunter, T. C. (2002). Music matters: Preattentive musicality of the human brain. *Psychophysiology, 39*(1), 38–48. https://doi.org/10.1111/1469-8986.3910038

Koenig, T., Kottlow, M., Stein, M., & Melie-García, L. (2011). Ragu: A free tool for the analysis of EEG and MEG event-related scalp field data using global randomization statistics. *Computational Intelligence and Neuroscience, 2011,* 1–15. https://doi.org/10.1155/2011/938925

Krumhansl, C. L. (1983). Perceptual structures for tonal music. *Music Perception, 1*(1), 28-62. https://doi.org/10.2307/40285249

Lagrois, M. É., Peretz, I., & Zendel, B. R. (2018). Neurophysiological and behavioral differences between older and younger adults when processing violations of tonal structure in music. *Frontiers in Neuroscience, 12,* 54. https://doi.org/10.3389/fnins.2018.00054

Leino, S., Brattico, E., Tervaniemi, M., & Vuust, P. (2007). Representation of harmony rules in the human brain: Further evidence from event-related potentials. *Brain Research, 1142*(1), 169–177. https://doi.org/10.1016/j.brainres.2007.01.049

Lidji, P., Jolicœur, P., Moreau, P., Kolinsky, R., & Peretz, I. (2009). Integrated preattentive processing of vowel and pitch: A mismatch negativity study. *Annals of the New York Academy of Sciences, 1169*(1)*,* 481–484. https://doi.org/10.1111/j.1749-6632.2009.04770.x

Ma, X., Ding, N., Tao, Y., & Yang, Y. F. (2018). Syntactic complexity and musical proficiency modulate neural processing of non-native music. *Neuropsychologia, 121,* 164–174. https://doi.org/10.1016/j.neuropsychologia.2018.10.005

May, P. J. C., & Tiitinen, H. (2010). Mismatch negativity (MMN), the deviance-elicited auditory deflection, explained. *Psychophysiology, 47*(1), 66–122. https://doi.org/10.1111/j.1469-8986.2009.00856.x

Näätänen, R., Jacobsen, T., & Winkler, I. (2005). Memory-based or afferent processes in mismatch negativity (MMN): A review of the evidence. *Psychophysiology, 42*(1), 25–32. https://doi.org/10.1111/j.1469-8986.2005.00256.x

Näätänen, R., Paavilainen, P., Rinne, T., & Alho, K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: A review. *Clinical*

Neurophysiology, 118(12), 2544–2590. https://doi.org/10.1016/j.clinph.2007.04.026

Näätänen, R., & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: A review and an analysis of the component structure. *Psychophysiology, 24*(4), 375–425. https://doi.org/10.1111/j.1469-8986.1987.tb00311.x

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*(1), 97-113. https://psycnet.apa.org/doi/10.1016/0028-3932(71)90067-4

Paavilainen, P. (2013). The mismatch-negativity (MMN) component of the auditory event-related potential to violations of abstract regularities: A review. *International Journal of Psychophysiology, 88*(2), 109–123. https://doi.org/10.1016/j.ijpsycho.2013.03.015

Paavilainen, P., Mikkonen, M., Kilpeläinen, M., Lehtinen, R., Saarela, M., & Tapola, L. (2003). Evidence for the different additivity of the temporal and frontal generators of mismatch negativity: A human auditory event-related potential study. *Neuroscience Letters, 349*(2), 79–82. https://doi.org/10.1016/S0304-3940(03)00787-0

Paavilainen, P., Simola, J., Jaramillo, M., Näätänen, R., & Winkler, I. (2001). Preattentive extraction of abstract feature conjunctions from auditory stimulation as reflected by the mismatch negativity (MMN). *Psychophysiology, 38*(2), 359–365. https://doi.org/10.1017/S0048577201000920

Paavilainen, P., Valppu, S., & Näätänen, R. (2001). The additivity of the auditory feature analysis in the human brain as indexed by the mismatch negativity: 1+1≈2 but

1+1+1<3. *Neuroscience Letters, 301*(3), 179–182. https://doi.org/10.1016/S0304-3940(01)01635-4

Pagès-Portabella, C., & Toro, J. M. (2020). Dissonant endings of chord progressions elicit a larger ERAN than ambiguous endings in musicians. *Psychophysiology, 57*(2), 1–11. https://doi.org/10.1111/psyp.13476

Patel, A. D., Gibson, E., Ratner, J., Besson, M., & Holcomb, P. J. (1998). Processing syntactic relations in language and music: An event-related potential study. *Journal of Cognitive Neuroscience 10*(6), 717–733. https://doi.org/10.1162/089892998563121

Peretz, I., Brattico, E., Jrvenp, M., & Tervaniemi, M. (2009). The amusic brain: In tune, out of key, and unaware. *Brain, 132*(5), 1277–1286. https://doi.org/10.1093/brain/awp055

Peter, V., McArthur, G., & Thompson, W. F. (2012). Discrimination of stress in speech and music: A mismatch negativity (MMN) study. *Psychophysiology, 49*(12), 1590–1600. https://doi.org/10.1111/j.1469-8986.2012.01472.x

Rinne, T., Särkkä, A., Degerman, A., Schröger, E., & Alho, K. (2006). Two separate mechanisms underlie auditory change detection and involuntary control of attention. *Brain Research, 1077*(1), 135–143. https://doi.org/10.1016/j.brainres.2006.01.043

Sussman, E. S., Chen, S., Sussman-Fort, J., & Dinces, E. (2014). The five myths of MMN: Redefining how to use MMN in basic and clinical research. *Brain Topography, 27(*4), 553–564. https://doi.org/10.1007/s10548-013-0326-6

Tervaniemi, M., Kruck, S., De Baene, W., Schröger, E., Alter, K., & Friederici, A. D. (2009). Top-down modulation of auditory processing: Effects of sound context, musical expertise and attentional focus. *European Journal of Neuroscience, 30*(8), 1636–1642. https://doi.org/10.1111/j.1460-9568.2009.06955.x

Tervaniemi, M., Maury, S., & Näätänen, R. (1994). Neural representations of abstract stimulus features in the human brain as reflected by the mismatch negativity. *NeuroReport 5*(7), 844–846. https://doi.org/10.1097/00001756-199403000-00027

Todd, J., Michie, P. T., Schall, U., Karayanidis, F., Yabe, H., & Näätänen, R. (2008). Deviant matters: Duration, frequency, and intensity deviants reveal different patterns of mismatch negativity reduction in early and late schizophrenia. *Biological Psychiatry, 63*(1), 58–64. https://doi.org/10.1016/j.biopsych.2007.02.016

Tsogli, V., Jentschke, S., Daikoku, T., & Koelsch, S. (2019). When the statistical MMN meets the physical MMN. *Scientific Reports, 9*(1), 1–12. https://doi.org/10.1038/s41598-019-42066-4

Wagenmakers, E. J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., Selker, R., Gronau, Q. F., Dropmann, D., Boutin, B., Meerhoff, F., Knight, P., Raj, A., van Kesteren, E. J., van Doorn, J., Šmíra, M., Epskamp, S., Etz, A., Matzke, D., … Morey, R. D. (2018). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin and Review, 25*(1), 58–76. https://doi.org/10.3758/s13423-017-1323-7

Wang, A. L., Mouraux, A., Liang, M., & Iannetti, G. D. (2008). The enhancement of the N1 wave elicited by sensory stimuli presented at very short inter-stimulus intervals is a general feature across sensory system. *PLOS ONE, 3*(12), e3929. https://doi.org/10.1371/journal.pone.0003929

Wolff, C., & Schröger, E. (2001). Human pre-attentive auditory change-detection with single, double, and triple deviations as revealed by mismatch negativity additivity. *Neuroscience Letters, 311*(1), 37–40. https://doi.org/10.1016/S0304-3940(01)02135-8

Zendel, B. R., & Alexander, E. J. (2020). Autodidacticism and Music: Do Self-Taught Musicians Exhibit the Same Auditory Processing Advantages as Formally Trained Musicians? *Frontiers in Neuroscience, 14*, 752. https://doi.org/10.3389/fnins.2020.00752

Zendel, B. R., Demirkaplan, Ö., Mignault‐Goulet, G., & Peretz, I. (2022). The relationship between acoustic and musical pitch processing in adolescents. *International Journal of Developmental Neuroscience, 82*(4), 314‐330. https://doi.org/10.1002/jdn.10181

Zhang, J., Zhou, X., Chang, R., & Yang, Y. (2018). Effects of global and local contexts on chord processing: An ERP study. *Neuropsychologia, 109*, 149–154. https://doi.org/10.1016/j.neuropsychologia.2017.12.016

Table 1

Mean amplitudes (μV) of early and late time windows in the difference waveforms of three types of deviants.

	Experiment 1					
	140–200 ms			400–600 ms		
Deviants	*M (SD)*	*t*(38)	*p*	*M (SD)*	*t*(38)	*p*
Harmonic deviant	−0.99 (1.09)	5.63	<.001	−0.53 (0.86)	3.85	<.001
Intensity deviant	−0.82 (0.79)	6.49	<.001	−0.66 (1.10)	3.76	< .001
Double deviant	−1.49 (1.46)	6.38	<.001	−0.98 (1.07)	5.68	<.001
	Experiment 2					
	140–200 ms			400–600 ms		
Deviants	*M (SD)*	*t*(23)	*p*	*M (SD)*	*t*(23)	*p*
Harmonic deviant	−0.49 (0.90)	2.67	.014	−0.27 (0.85)	1.54	.138
Intensity deviant	−0.72 (0.67)	5.27	<.001	−0.37 (0.54)	3.36	.003
Double deviant	−1.12 (1.05)	5.19	<.001	−0.74 (0.90)	4.02	< .001

Note: Two-tailed one-sample t-tests were conducted to evaluate significant deviations from the baseline.

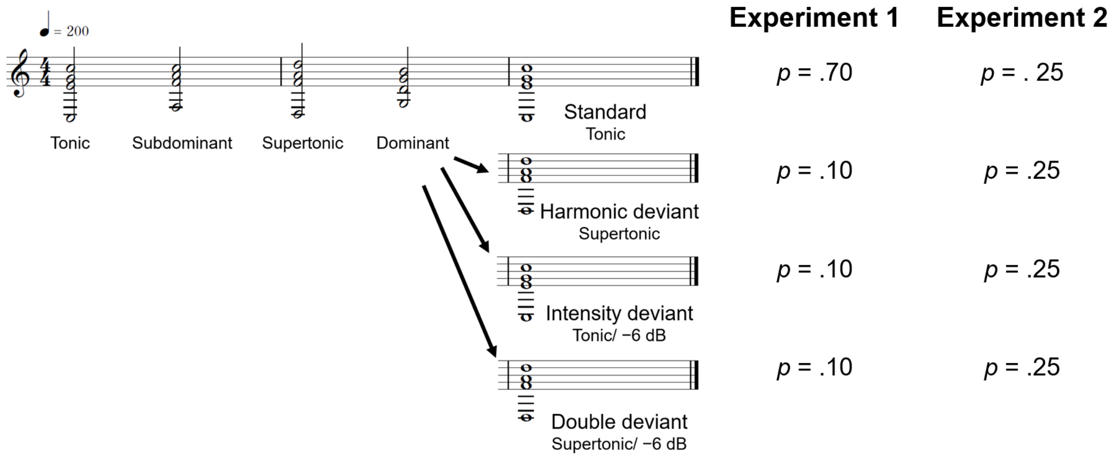

Figure 1. Four types of chord sequences were used in this experiment. Each sequence was transposed into seven major keys. Deviant stimuli were presented with a low probability (Experiment 1) or with equal probability (Experiment 2).

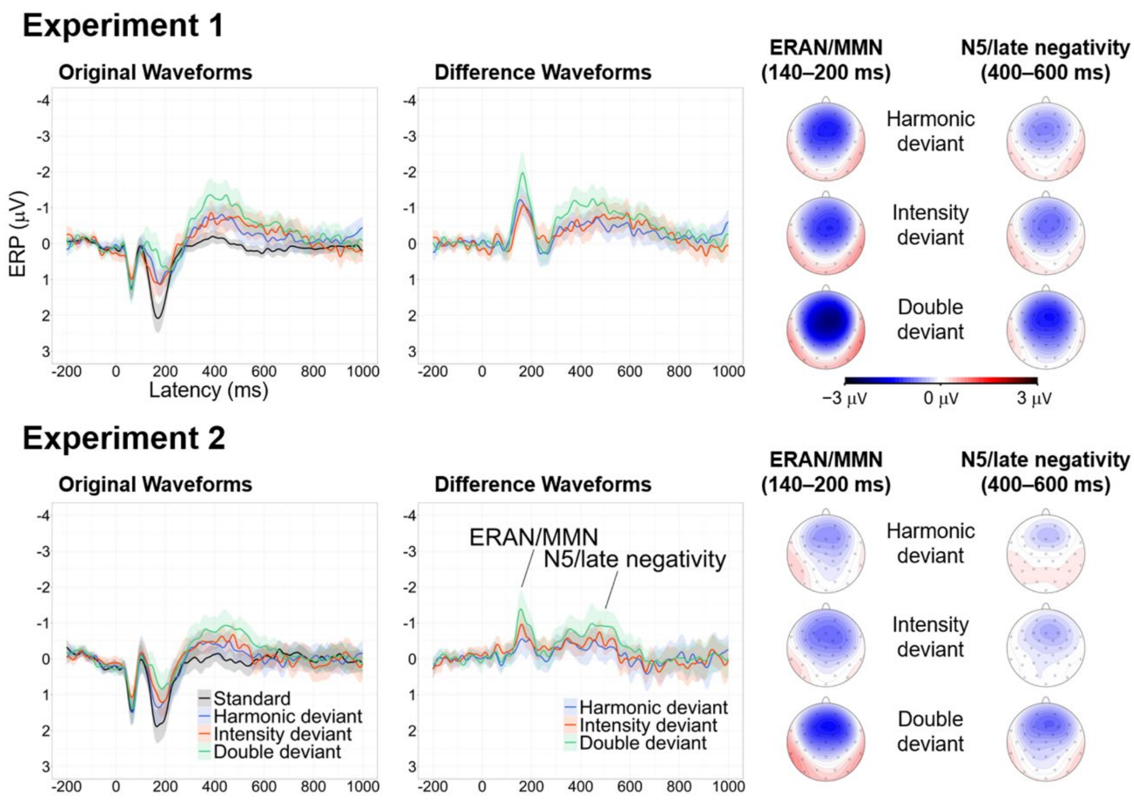

Figure 2. Grand average waveforms (means of the five frontal electrodes: F7, F3, Fz, F4, and F8) with 95% confidence intervals and topographic maps of the ERPs elicited by the four types of final chords (standard, harmonic deviant, intensity deviant, and double deviant). In each experiment, the left panel shows the original waveforms elicited by the four types of final chords; the middle panel shows the deviant minus standard difference waveforms elicited by the three types of deviant chords. The right panel shows the topographic maps of the ERAN/MMN (140–200 ms) and the N5/late negativity (400–600 ms).

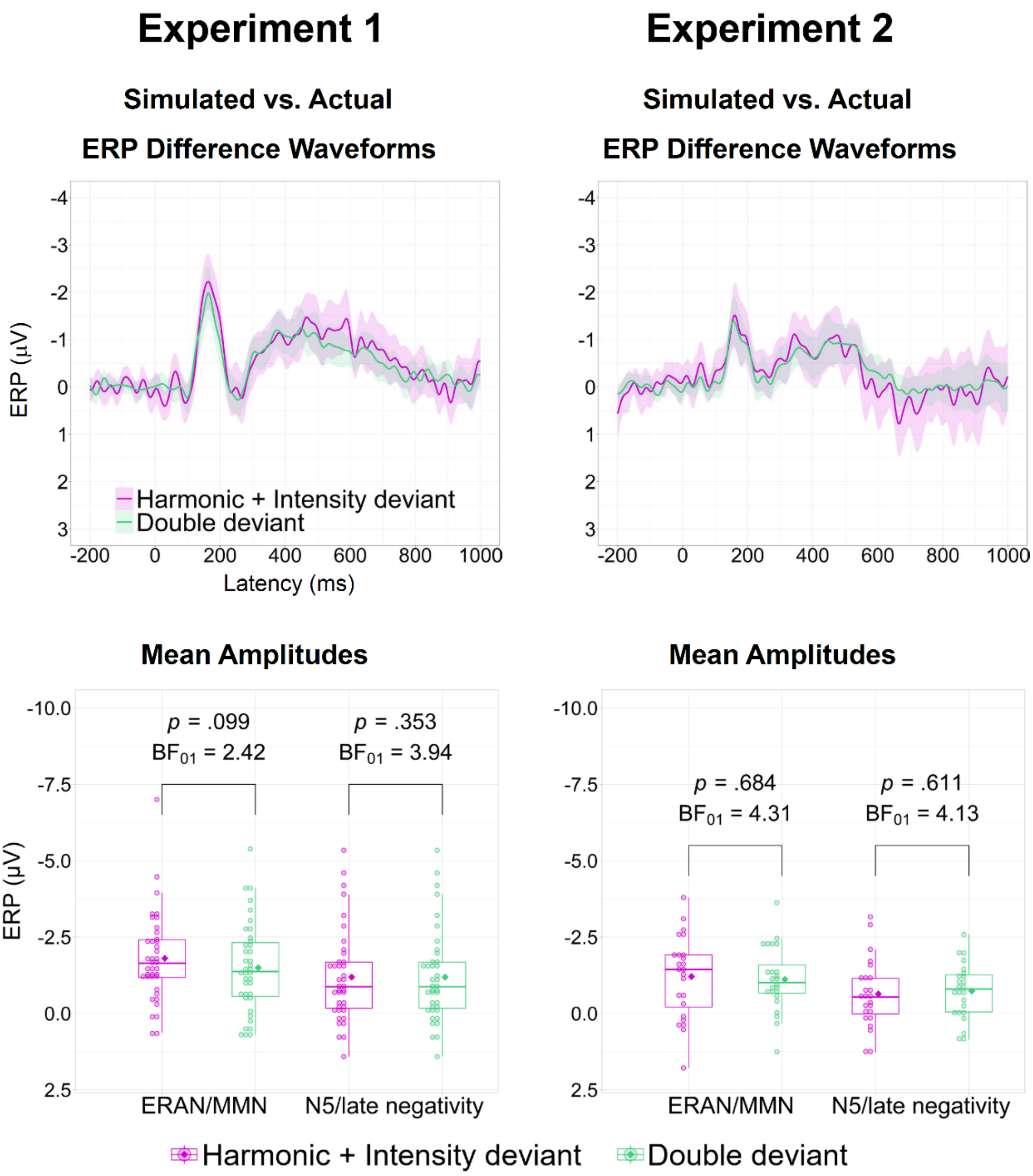

Figure 3. Comparison of single-deviant and double-deviant ERP responses in each experiment. The magenta line indicates a simulated summation of ERP responses elicited by the harmonic deviant and by the intensity deviant, whereas the green line indicates the actual ERP responses elicited by the double deviant. Filled areas indicate 95% confidence intervals. The means of the five frontal electrodes are shown. The bottom panel shows the summed amplitude of the two single-deviant ERPs and the

amplitude of the double-deviant ERP at the time windows of ERAN/MMN (140–200 ms) and N5/late negativity (400–600 ms). The rhombuses and dots indicate the mean amplitudes and individuals’ amplitudes, respectively.

Graphical abstract:

In two passive-listening experiments, the relationship between the detection processes of music-syntactic and acoustic regularities was examined by presenting instances of harmonic and intensity deviants independently (single deviant) or simultaneously (double deviant). The harmonic and intensity deviants elicited early negativity with similar latency and topography; an additive effect was observed when both deviants co-occurred. The results suggest that music-syntactic and acoustic irregularities are detected independently, based on different and independent representations.