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Technical note

Neural activity and sound impression induced by virtual bass for individuals who prefer bass-heavy audio

Kaori Asakawa [a,*], Jin Hirano [a], Takashi Yamazaki [a], Masaru Kimura [a], Yoichi Yamazaki [b], Kenji Katahira [b,1], Noriko Nagata [b]

[a] Information Technology R&D Center, Mitsubishi Electric Corporation, Kamakura, Kanagawa 247-8501, Japan
[b] School of Engineering, Kwansei Gakuin University, Sanda, Hyogo 669-1330, Japan

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ABSTRACT

This study aimed to examine the impact of virtual bass technology on sound perception and its potential effects on the electroencephalogram (EEG) of individuals who prefer bass-heavy audio. A group of eleven participants was exposed to nine jazz music excerpts, with added harmonics generated from low-frequency components to enhance the bass sound virtually. The participants then evaluated the sound impression of these excerpts. The findings revealed that the inclusion of bass harmonics in the sound sources led to a more pronounced "powerful" impression compared to the absence of such enhancements. Furthermore, the study observed that the lower alpha1 band power in the frontal and right centro-parietal regions increased when moderate harmonics were added, in contrast to the conditions without added harmonics or with excess harmonics. These results suggest that virtual bass sound not only influences perceptual aspects but also induces physiological modulation.

1. Introduction

In recent years, advancements in technology have led to the development of smaller digital media devices, including audio-visual monitors and portable audio sets. However, these compact sizes often result in compromised sound quality, particularly the bass frequency output of small loudspeakers tends to be weak.

One approach to address this problem is the use of "virtual bass" [10,17,16] technology. Virtual bass technology amplifies the feeling of bass by adding bass harmonics to sound using signal processing. The technology is based on the phenomenon wherein humans perceive the pitch corresponding to the fundamental frequency upon hearing a complex tone that lacks the fundamental frequency [15]. Previous studies revealed that virtual bass technology can enhance the bass feeling of a bass guitar solo having a stable frequency structure by adding a certain amount of bass harmonics, but its sound quality decreased [17,16]. However, it is unclear whether virtual bass modulates the acoustic perception of a musical track.

Recent studies on musical perception have focused on the correlation between listener emotions and their physiological responses such as brain activity. Sammler et al. [22] reported that there exists a correlation between listening to pleasant music and prefrontal midline theta power. Some studies have demonstrated music-induced emotional frontal asymmetry in the alpha (8–13 Hz), beta (18–22 Hz), and gamma (35–39 Hz) bands [23,6]. These studies have suggested that music-induced negative or positive emotion is associated with the electroencephalogram (EEG) power spectrum. While virtual bass sound, also known as missing fundamental sound, has been used to investigate the neural basis for pitch perception [24,3,31] and the neural encoding of sound frequency [5,32,11,33], it has been reported that virtual bass can alter the timber and sound quality [15,17,16]. Given that it has been suggested that differences in sound quality affect brain activity [13], brain states caused by differences in the quality of virtual bass should be observed. However, it is unclear whether virtual bass, which provides a subtle but significant difference to the feeling of a sound, affects neural responses.

This study aimed to examine the effect of virtual bass on sound impression and brain activity. To this end, subjective rating experiments

* Corresponding author.
E-mail addresses: Asakawa.Kaori@ab.MitsubishiElectric.co.jp, kaori.h.asakawa@gmail.com (K. Asakawa), Hirano.Jin@ah.mitsubishielectric.co.jp (J. Hirano), Yamazaki.Takashi@ab.mitsubishielectric.co.jp (T. Yamazaki), Kimura.Masaru@ah.MitsubishiElectric.co.jp (M. Kimura), y-yamazaki@kwansei.ac.jp (Y. Yamazaki), katahira@waseda.jp (K. Katahira), nagata@kwansei.ac.jp (N. Nagata).
[1] Current address: Waseda University, Shinjyuku, Tokyo 162-8644, Japan.

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were conducted. The participants evaluated their emotion and impression of music containing virtual bass. Moreover, we measured EEG power while the participants were listening to music to determine the effects of the added bass harmonics on brain activity.

2. Materials and methods

The virtual bass technology caters to individuals with a keen perception of bass sound. To select these participants, a preliminary experiment was conducted with 31 individuals (17 males and 14 females, average age 20.7 years) from Kwansei Gakuin University, who provided informed consent. All participants were native Japanese speakers. In the preliminary experiment, three jazz music pieces ("Lullaby for Rabbit" by Makoto Ozone, "Never Let Me Go" by Junko Onishi Trio, and "So What" by Miles Davis) were presented three times under three different conditions: bass frequencies below 100 Hz were filtered out using a fourth-order infinite impulse response (IIR) filter or an eighth-order IIR filter, or left non-filtered. The task was the same as the one in the subjective evaluation experiment explained in detail later. The results revealed that 17 participants reported higher valence scores for the music excerpts that retained their original low frequencies compared to those with the bass frequencies filtered out in the cases of using fourth- and eighth-order IIR. These participants were then selected for the subsequent experiments.

For the subjective rating and EEG experiments, of the 17 participants, a total of eleven individuals (seven males and four females, averaging 20.8 years of age) with normal hearing and right-handedness were able to attend the subsequent experiments. The Research Ethics Committee of Kwansei Gakuin University approved this study.

Stimuli for the experiments comprised nine jazz music pieces ("Beyond the Summer II" by Cro-magnon, "Blue Lights" by Art Farmer, "Cry Me A River" by Dexter Gordon, "Django" by Modern Jazz Quartet, "Home" by Makoto Ozone, "If…" by Hiromi Uehara, "Iqbal" by Yusef Lateef, "Round Midnight" by Donald Byrd, and "Satin Doll" by Dave Grusin). These differed from the ones used in the preliminary study. These music sources were selected based on their rich low frequencies, particularly below 100 Hz, such as pizzicato for double bass. Sixty-second instrumental excerpts without vocals were extracted from uncompressed files (44, 100 Hz sampling, 16 bits, 2 channels) of the original sound sources for signal processing.

To create the "virtual bass" sound, a signal processing algorithm utilizing quarter cycle detection [30] was employed. The algorithm introduces harmonic distortion to the original sound by detecting quarter-period intervals from the bass component and setting them to zero. This approach enables the smooth generation of odd- and even-order harmonics regardless of the bass component's amplitude, minimizing sound quality degradation [29]. Fig. 1 illustrates the framework for generating virtual bass sound. In this study, harmonics generated from low-frequency components in the range of 50–100 Hz were added to the input signal, and components below 100 Hz were subsequently removed. The harmonics were low-pass filtered at 150 Hz to preserve the sound quality, and then high-pass filtered at 100 Hz to eliminate the fundamental frequency range. We used a finite impulse response (FIR) filter designed using the Kaiser window, except for a 150 Hz low pass filter, which was a second-order IIR filter ($Q = 0.707$), designed to make the attenuation slope 12 dB/oct. Each music piece was played under three conditions: 0 %, 10 %, and 50 % harmonic distortion. The ratio of the squares of the harmonics to the sum of squares of the input signal from the original music was calculated.

Participants rated the musical excerpts on nine adjectives. These adjectives were determined using following the steps. (1) The words used for the description of sound representation quality by seven sound engineers were collected. (2) Six sound engineers evaluated the appropriateness of 245 words obtained in the first step using four scores–from 1 ("inappropriate") to 4 ("appropriate"). (3) Two authors (one had experience with sound quality evaluation) sorted them into three groups based on the evaluation objective: physical quantity (e.g., "exist low/high frequency"), impressions (e.g., "gentle"), and representation (e.g., "realistic-feeling") on sound. Accordingly, 32, 32, and 31 words were selected based on the appropriate score in each group, resulting in average appropriate scores of 3.49, 3.58, and 3.59, minimum scores were 3.00, 2.67, and 3.33 respectively. (4) Six sound engineers evaluated the similarity of all pairs of 32 words (i.e., 32 words $\times$ (32–1) words $\div$ 2 = 496 pairs) in the impression group using six scores from 1 ("very similar") to 6 ("very not similar"). (5) Hierarchical cluster analysis using Ward's method was performed based on the similarity score, which resulted in seven clusters. (6) One representative word and two subsidiary words were extracted based on the closeness from the center of the cluster with higher appropriate ratings by clusters. Finally, we obtained the following adjectives[2]: "heavy feeling (punchy, weighty)," "have a spatial depth (fine, transparent)," "sharply defined (clear, chiseled)," "have a core (not get thin even though low-volume, carefree)," "harsh (hurtful, hard)," "thin (skinny, light)," and "cloudy (blurry, muffled)." In addition to these, we adopted "muddy" to evaluate for sound with distortion [9], and "preference" as a word to indicate how participants like the sound quality [19,28].

The participants were asked to rate the musical excerpts using the nine adjectives mentioned above on a scale ranging from 0 to 100. These ratings were provided using the corresponding adjective words in Japanese. Throughout the experiment, participants listened to nine music excerpts under each of the three conditions, presented in a pseudo-random order. In the subjective evaluation experiment, each music excerpt was played three times within a condition. The sequencing was organized to ensure that the same condition or piece of music was not played consecutively. After each music excerpt, participants were required to rate it on a scale of 0–100 and indicate their level of affective response (valence and arousal) while listening to the piece of music using the same scale. The stimuli were normalized using Adobe Audition 3.0 and presented at A-weighted sound pressure level of 76 dB through a headphone amplifier (iFI nano iDSD) and a headphone (Sennheiser HD 650). The stimuli were adjusted to the average amplitude of all the files, and a cosine window of 500 ms was applied to the beginning and end portions. Fig. 2 illustrates an example of the final spectrum and original spectrum for a sound stimulus, averaged over 60 s. According to the product specifications, the headphone had a reproduction frequency range of 10–41,000 Hz, which covered the required frequency range for the experiment.

In the EEG experiment, the participants, stimuli, and apparatus used were the same as those in the subjective evaluation experiment. EEG data were recorded using the BioSemi Active-Two system (BioSemi Inc., The Netherlands). An EEG array containing 64 active electrodes that cover the entire scalp (according to the International 10/20 EEG system), along with an additional six channels of electrodes placed on the face, collected EEG data at a sampling rate of 1,024 Hz. Participants wore the headphones over an EEG headcap. Prior to the experiment, a trained experimenter confirmed that there was no interference to the EEG waveform from the headphones. During each trial, the music excerpt was played following a 1-minute period of silence. The silence and music started 1 s after the participants pressed a button. Participants were instructed to keep their eyes closed both during the silence and while listening to the music. After the music ended, participants were asked to open their eyes and evaluate the excerpt to investigate the correlation between subjective evaluation and EEG power. Auditory cues, such as a beep, were used to indicate the start of the trial, when to listen to the excerpt, and when to subjectively evaluate it. During the EEG experiment, each music excerpt within a condition was played only once.

EEG data analysis was conducted in a similar manner to that of

[2] The words in parentheses were subsidiary words. For simplicity, only representative words were described in the following.

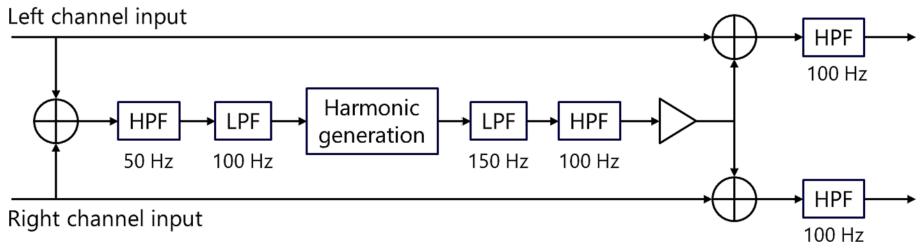

Fig. 1. Framework of creating virtual bass sound stimuli. HPF: high-pass filter, LPF: low-pass filter. The numbers indicate cut-off frequency.

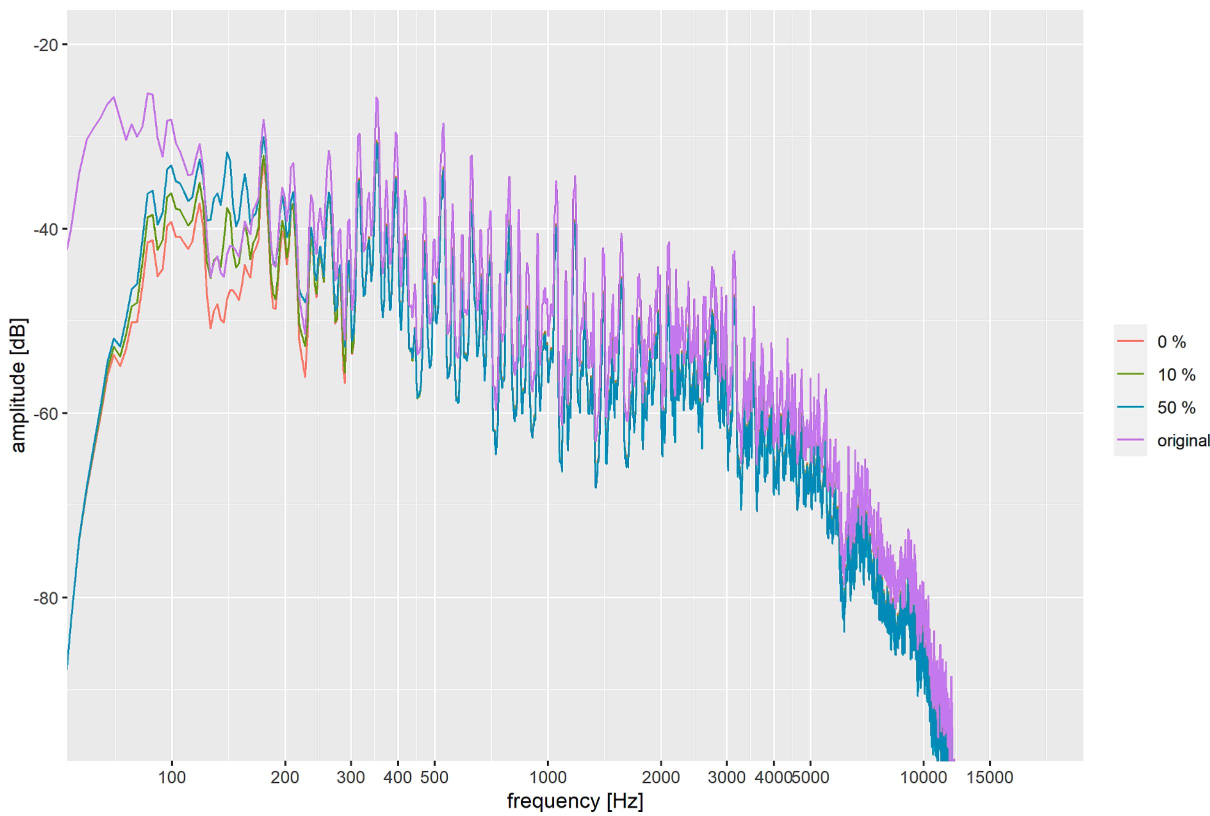

Fig. 2. Example of average sound spectrum for a sound file ("Cry Me A River") for 60 s.

Katahira et al. [12]. The data was analyzed using EEGLAB (Version 13.4.4b) and FieldTrip (Build 20140522) working on MATLAB (Version R2013b, MathWorks, Inc., Massachusetts, USA). The EEG data were down-sampled to 256 Hz and filtered using 1 and 100 Hz bandpass. An independent component analysis was performed on the EEG data to identify independent components that correspond to noises that were to be manually rejected using visual inspection. Additionally, the Laplacian filter was applied. Each trial was extracted from the preprocessed data, and the trials, including eye blinks and noisy channels, where potentials exceeded ±100 μV, were discarded.

The power spectrum analysis followed a setup similar to that of a previous study conducted by Sammler et al. [22]. Welch's method with a window width of 2 s and a 50 % overlap was used to estimate the power spectrum. The individual alpha frequency (IAF) was calculated by averaging the peak frequency in the range of 8–13 Hz at three electrodes (CPz, Pz, and POz) from the individual power spectra during the silent period in each trial. The mean IAF was 10.0 Hz (SD: 0.78 Hz; IAF range: 8.7–11.5 Hz). The relative frequency bands were defined individually by multiplying the IAF with the following ranges: lower limit 0.4 to upper limit 0.6 as theta, similarly, 0.6–0.8 as lower alpha1, 0.8–1.0 as lower alpha2, 1.0–1.2 as upper alpha, and beta 1.2–30 Hz (only beta upper limit was fixed frequency) [8]. These individual band power values were normalized using Eq. (1) for each participant. For each condition (C), electrode (*e*), and frequency band (*f*), the individual band power was divided by the average band power across $N = 64$ electrodes measured in the 0 % condition, which served as a baseline (B) for the same participant and frequency band. The EEG power spectra in each frequency band in each condition (0, 10, 50 %) were calculated using Eq. (1) and denoted as $P_C^{(0\%)}$, $P_C^{(10\%)}$, and $P_C^{(50\%)}$, respectively. In this study, each EEG power value was normalized using $P_C{}^{(0\%)}$ as the baseline.

$$\widehat{P}_C(e,f) = \frac{P_C(e,f)}{1/N * \sum_{e=1}^{N} P_B(e,f)} \qquad (1)$$

For the statistical analysis, the electrodes were grouped into seven regions of interest (ROI) as follows: fronto-central (AFz, Fz, FCz), left frontal (AF3, F3, F7, FC3), right frontal (AF4, F4, F8, FC4), left centro-parietal (C3, C5, CP3, CP5), right centro-parietal (C4, C6, CP4, CP6), left parieto-occipital (P3, P5, PO3, PO7), and right parieto-occipital (P4, P6, PO4, PO8).

3. Results

Regarding data in the subjective evaluation experiment, rating scores were averaged across repetitions. The data for each participant in each distortion condition averaged for music excerpts were used for analysis to examine the pure effect of the virtual bass, i.e., analyses of variance (ANOVAs) for subjective ratings and factor score, and correlation analysis in the EEG experiment. In the analysis aimed at investigating the psychological evaluation structure or naive EEG response to the virtual bass, i.e., factor analysis for subjective ratings and ROI analysis for EEG data, the data that were not averaged for music excerpts were used.

3.1. Subjective evaluation

Fig. 3 shows the average subjective ratings for all music excerpts across each condition of the subjective evaluation experiment. To examine the effect of the conditions, separate one-way ANOVAs with repeated measures on data averaged repetition and music excerpts were performed for each adjective and affective response. Post hoc multiple comparisons of means within each harmonic condition were conducted using the Bonferroni method at a significance level of 0.05.

The analysis revealed significant main effects and differences between the conditions for “heavy feeling” [$F\,(2, 20) = 9.84$, $p < 0.01$, 0 % < 10 %, 0 % < 50 %], “have a core” [$F\,(2, 20) = 7.84$, $p < 0.01$, 0 % < 10 %], and “thin” [$F\,(2, 20) = 10.99$, $p < 0.01$, 0 % > 10 %, 0 % > 50 %].

“Cloudy” showed a significant main effect [F (2, 20) = 3.74, $p < 0.05$] but no significant differences between conditions. “Preference” showed only a significant tendency of the main effect [$F\,(2, 20) = 3.48$, $p = 0.051$].

The perception of “heavy feeling” and “have a core” was greater at the 10 % condition compared to the 0 % condition. Although the p-value ($p = 0.051$) did not reach the significance level of 0.05, the “preference” was higher only at the 10 % condition compared to the other conditions.

Additionally, a factor analysis on data averaged repetition was conducted to explore the underlying common factors among the nine adjectives. Using the maximum-likelihood method and promax rotation, a factor analysis revealed two factors based on parallel analysis, which accounted for 59.49 % of the total variance.

As listed in Table 1, the first factor could be interpreted as a factor of “clarity” and included “cloudy,” “sharply defined,” “have a spatial depth,” “muddy,” and “preference.” The second factor was a factor of “powerful,” and included “thin,” “heavy feeling,” “have a core,” and “harsh.”

To examine whether these two factors were affected by the addition of bass harmonics, the factor score for each participant was calculated for each condition and music excerpt. The regression method was used to obtain the factor scores with IBM SPSS Statistics 24. Subsequently, one-way ANOVAs with repeated measures on data averaged music excerpts were conducted separately for each factor.

The analysis revealed significant main effects and differences between conditions for the factor scores of “powerful” [$F\,(2, 20) = 9.91$, $p < 0.01$, 0 % < 10 %, 0 % < 50 %]. The “clarity” factor scores showed no significant differences between the conditions [F (2, 20) = 1.26, p = 0.30] (Fig. 4).

3.2. EEG data

To examine the impact of adding harmonics on the EEG data, the Kruskal–Wallis test was conducted for the data of each participant in each distortion condition and music excerpts followed by a Steel–Dwass

Table 1
Result of factor analysis of subjective ratings for adjectives.

	Factor 1	Factor 2
Cloudy	−0.89	0.01
Sharply defined	0.86	−0.08
Have a spatial depth	0.81	0.04
Muddy	−0.71	−0.09
Preference	0.69	0.08
Thin	0.09	−1.05
Heavy feeling	0.03	0.69
Have a core	0.23	0.58
Harsh	−0.03	−0.18
Contribution ratio (%)	32.99	26.50

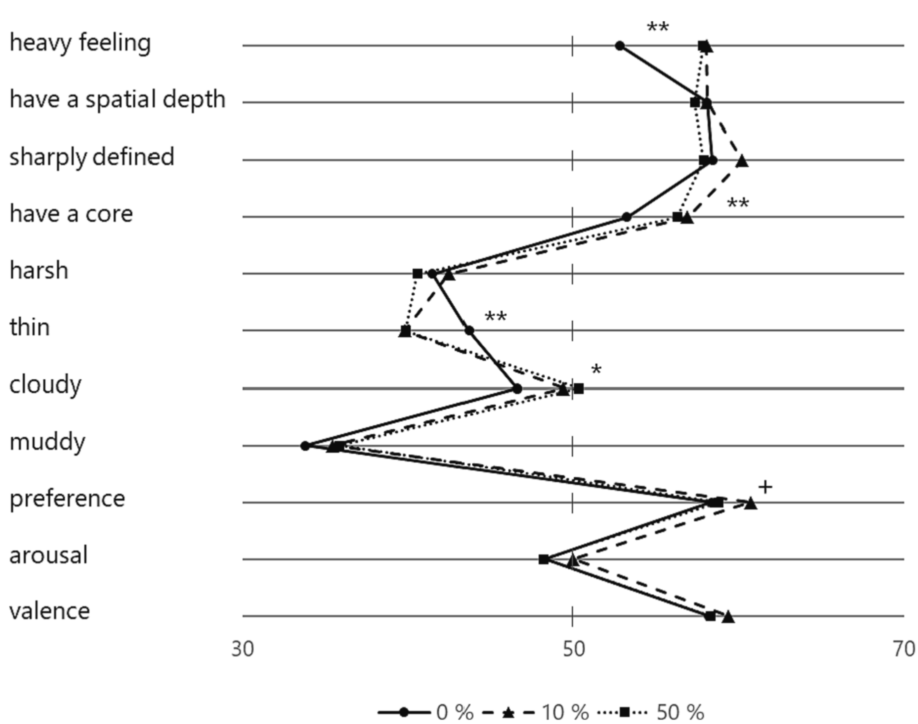

Fig. 3. Mean subjective ratings for 9 music excerpts in 0 %, 10 %, and 50 % added harmonics to high-pass filtered signal ratio. The marks (+$p < 0.10$, *$p < 0.05$, **$p < 0.01$) indicate the main effect of conditions for each word.

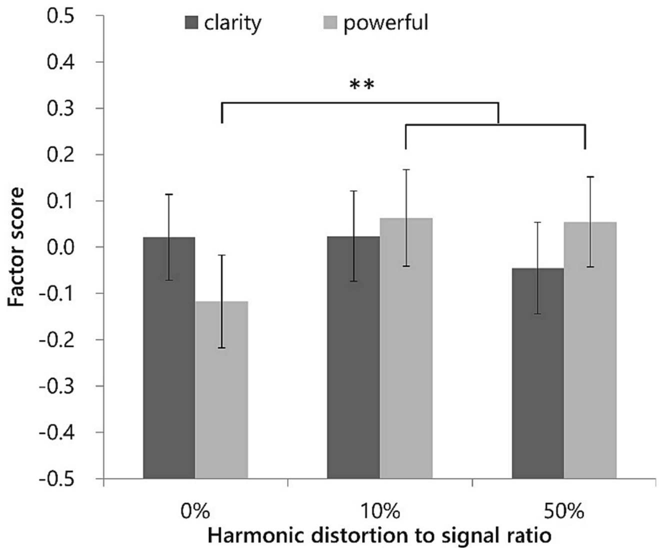

Fig. 4. The "clarity'" and "powerful" factor scores in 0 %, 10 %, and 50 % added harmonics to signal ratio. The error bars show standard error. $^{**}p < 0.01$.

multiple comparison ($p < 0.05$) for the five EEG rhythms, i.e., the relative frequency band of IAF, in each of the seven areas, individually.

The results showed significant main effects for lower alpha1 in the fronto-central [χ^2 (2) = 7.26, 10 % > 50 %], left frontal [χ^2 (2) = 10.25, 0 % < 10 %, 10 % > 50 %], right frontal [χ^2 (2) = 7.10, 0 % < 10 %], and right centro-parietal [χ^2 (2) = 6.62, 0 % < 10 %] (Fig. 5). Additionally, upper alpha [χ^2 (2) = 6.01] and beta [χ^2 (2) = 6.06] in the left frontal were significantly affected by the addition of bass harmonics; however, the differences between conditions were not significant.

A factor analysis was conducted on the subjective rating data obtained from the EEG experiment. Two factors, namely the clarity factor and the powerful factor, were extracted using the same adjectives, explaining a total variance of 57.35 % and 8.75 %, respectively. The fact that the same factors were obtained in both experiments suggests that the evaluation construction for the virtual bass sound is consistent within participants. The contribution ratio of the clarity factor in the EEG experiment was higher than that in the subjective evaluation experiment. This could be because each excerpt was not repeated in the EEG experiment.

Correlations between EEG power, which exhibited significant differences between conditions, and factor scores were examined. To calculate the correlation coefficients, subjective evaluation data were pooled across individuals and the values at the 0 % condition were subtracted from those at the 10 % or 50 % condition to account for individual differences. Subjective evaluation data above 2SD were

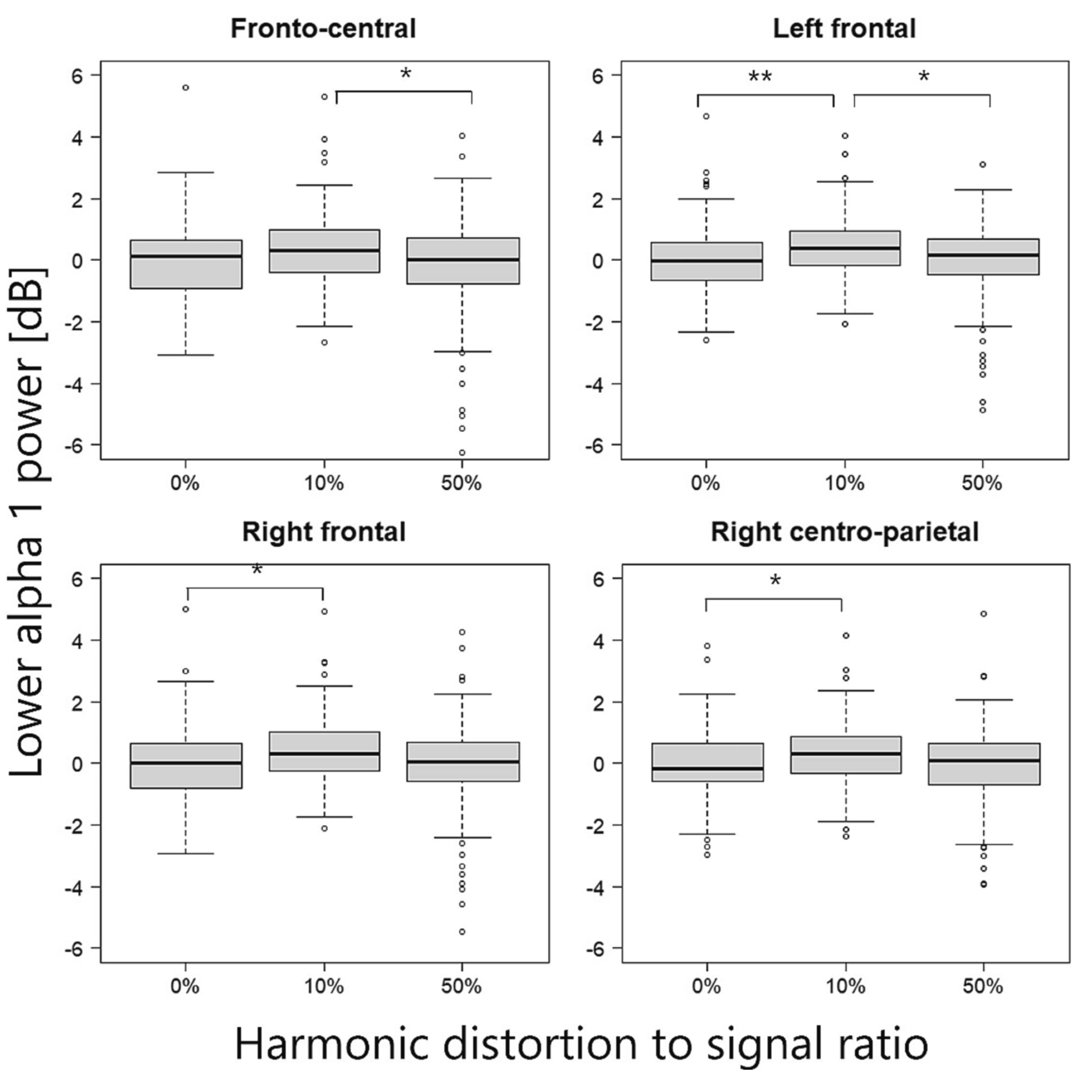

Fig. 5. Lower alpha1 power in 0 %, 10 %, and 50 % added harmonics to signal ratio. $^{*}p < 0.05$, $^{**}p < 0.01$.

excluded as outliers. EEG data in the 10 % and 50 % conditions were directly used as they were already normalized to the 0 % condition. The subjective ratings of affect (valence and arousal) and factor scores showed no significant correlations with these EEG rhythms.

4. Discussion

In this study, we investigated the impact of virtual bass on subjective impression of music excerpts and their brain activity involving participants who preferred bass-heavy audio.

The findings revealed that the inclusion of bass harmonics using virtual bass resulted in a more powerful impression of the music compared to excerpts without the harmonics. Moreover, participants tended to prefer the music excerpt with an additional 10 % harmonics of the total power over the other conditions.

Furthermore, our study unveiled the influence of virtual bass on brain activity. Specifically, the lower alpha1 band power in the frontal and right centro-parietal regions increased when 10 % harmonics were added, in contrast to the conditions without added harmonics or with 50 % harmonics.

The results that state that adding harmonics enhances powerful impression are consistent with those of a previous study by Mu et al. [17]. They reported that adding harmonics impaired sound quality, that is, noise and distortion, increased by the addition of virtual bass. Meanwhile, our results indicate that the clarity of sound does not decrease significantly when harmonics are added. This difference may be attributed to some procedural factors such as the stimuli used or the algorithms employed for creating the virtual bass sound.

EEG activities in the low frequency band (lower alpha1, 6–8 Hz) in the frontal region were higher in the 10 % condition than in the others. Virtual bass sound increased the powerful impression and did not reduce the impression of clarity in the subjective rating experiment. Interestingly, it has been reported that the context of perception in concert halls, the strength of bass (i.e., powerful impression) and clarity are considered the critical components for sound quality [26]. Accordingly, it is implied that the sound with a high score in both powerful and clear impression in virtual bass could be regarded as high-quality sound compared to the sound with a low powerful impression in the 0 % condition. Alpha power has been understood to be relaxed and comfortable, that is, a rest state in the brain [25,21]. Previous studies showed that the frontal alpha power increases during meditation [1,27], listening to preferred music [18] or consonant compared to dissonant chords [20]. Hence, the participants in this study can be considered to have experienced positive emotion while listening to virtual bass sound with high quality compared to no virtual bass.

However, the effects of virtual bass were not identical in the amount of distortion, particularly in EEG data. The lower alpha1 power in the 50 % condition significantly decreased compared to the 10 % condition in the fronto-central and left frontal regions. Moreover, although it was only a statistical tendency, participants preferred the sound in the 10 % condition over the other conditions. Collectively, it could be inferred that sound with too much harmonic distortions undermine the benefit of virtual bass.

Our results did not show a simultaneous increase in pleasant ratings and frontal midline (Fm) theta power while listening to virtual bass, although Sammler et al. [22] reported an association between pleasant music and Fm theta rhythm. This can be attributed to the difference in the extent of valence emotion induced by the stimuli (i.e., consonant and dissonant music) or whether the same excerpts add some harmonics.

The correlation analysis in this study between subjective ratings and lower alpha 1 power, which differed significantly between conditions, showed no significant effects. Previous studies have reported that EEG in the frontal area in the lower frequency range, such as the lower alpha1 and theta bands, are closely associated with listening to music that elicits pleasant emotions. The sound stimuli used in these studies produced strong and distinct positive or negative emotions. For example, the consonant chords vs. the dissonant chords [20], the joyful consonant dance music vs. the pitch-shifted dissonant versions of the same excerpts [22], the film soundtracks that many people rated as joy and pleasure vs. angry and sad [14], the pleasurable chill-inducing music chosen by the participants themselves vs. the neutral music chosen by the experimenter [4]. The sound stimuli in this study comprised various jazz music with harmonics vs. low-pass filtered of the same excerpts, and there were no significant differences in pleasantness ratings between the amount of harmonics. This could result in no correlation with emotion ratings. On the other hand, when participants who prefer bass listen to music with enhanced or no bass, they could feel pleasure in a more moderate level of bass that does not detract from the sound quality. Although the correlation was not significant, as discussed above, the results of this study suggested that the virtual bass sound improved sound quality based on subjective evaluation. Furthermore, EEG activities in the low frequency band in the frontal region were higher when a medium amount of harmonics was added than in the other conditions. Our results could be influenced by individual preferences for the music or advanced sound impression, and it remains to be investigated. This is the first study to address the relationship between factor scores of virtual bass sound impressions and EEG, future studies could provide suggestions in this perspective.

An increase of lower alpha1 in the right centro-parietal at the 10 % condition may be related to tension arousal [7]. Although the right centro-parietal alpha was not statistically correlated to the subjective arousal score, the powerful impression of sound may lead to tension arousal.

In this study, virtual bass technology was employed as a means to modify sound quality and examine its effect on EEG. Future studies can explore other aspects of sound, such as reality, powerful impressions, and the clarity factor of 3D sound, to gain further insights into the impact of modifying sound quality and impressions on human perception.

Moreover, as this study could be influenced by individual preference in terms of sound quality and impression [2], future studies can explore the degree of change in the EEG. Such investigations would be useful in exploring the neural basis of the perception of sound impressions.

5. Conclusion

In this study, two experiments were conducted: a subjective rating experiment, where listeners evaluated their emotions and sound impressions of music excerpts with virtual bass, and an EEG measurement experiment while listening to the same excerpts.

The results demonstrated that the addition of bass harmonics using virtual bass resulted in a heightened powerful impression retaining a clear impression compared to excerpts without bass harmonics. Moreover, excerpts with a moderate (10 %) addition of harmonics tended to be preferred over those with either too little (0 %) or too much (50 %) harmonics added. Additionally, the analysis revealed an increase in lower alpha1 band power in the frontal and right centro-parietal regions under the added harmonics conditions.

The key findings of this study are as follows: First, the inclusion of moderate harmonics in virtual bass technology enhances not only the perception of bass, but also the impressions of power leaving clarity. Second, virtual bass that induces significant differences in sound impressions without causing drastic emotional changes can influence brain activity, particularly in the lower frequency band power. Accordingly, our findings suggest that virtual bass technology has the potential to enhance sound quality and elicit positive experiences in listeners who prefer bass sounds, from both psychological and physiological perspectives. While this study focused on individuals with a preference for bass sounds, future research could explore the relationship between sound quality preferences and brain activity by considering various types of listener preferences to reach more generalized conclusions.

CRediT authorship contribution statement

Kaori Asakawa: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **Jin Hirano:** Methodology, Resources. **Takashi Yamazaki:** Methodology, Resources, Software. **Masaru Kimura:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Software, Writing – review & editing. **Yoichi Yamazaki:** Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – review & editing. **Kenji Katahira:** Formal analysis, Investigation, Methodology, Resources. **Noriko Nagata:** Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: 'Noriko Nagata reports financial support was provided by Japan Science and Technology Agency (JST). Takashi Yamazaki, Masaru Kimura has patent #Harmonic generator. Patent JP 2009-216797. licensed to Mitsubishielectric corp.1'.

Data availability

Data will be made available on request.

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