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Bass amplification impacts emotional, neural and physiological responses to music

Nicolas Epain [a,*], Samuel Moulin [a], Camille Mingam [a], Mérové Wallerich [a], Etienne Corteel [a], Luc H. Arnal [b]

[a] L-Acoustics, 13 Rue Levacher Cintrat, 91460, Marcoussis, France
[b] Université Paris Cité, Institut Pasteur, AP-HP, INSERM, CNRS, Fondation Pour l'Audition, Institut de l'Audition, IHU reConnect, 75012, Paris, France

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ABSTRACT

Live music is highly appreciated for its emotional impact, often enhanced by louder sound levels to boost audience arousal and engagement. As high sound levels cause hearing damage and disturb nearby residents, focusing on audio quality offers a safer way to enhance emotional responses to music. However, how quality parameters, such as the balance between low and high frequencies, impact and link emotional, neural and physiological responses is unclear.

This study examines how low-frequency amplification affects listeners' arousal and its connection to neural and physiological responses during music listening. Two experiments were conducted: (i) in controlled laboratory conditions and (ii) in more ecological, live settings.

Subjective reports indicate that amplified bass significantly increases arousal, with a lesser but noticeable effect on valence. Electroencephalography (EEG) recordings show that early auditory components are unaffected by bass amplification, but the arousing effect is linked to enhanced oscillatory features in the low delta (2-5 Hz) frequency range, suggesting active, predictive tracking of music.

In natural music-listening settings, portable electrodermal activity (EDA) sensors were used to measure emotional and physiological responses. Results confirm that bass amplification increases arousal and that EDA better captures emotional integration in response to bass amplification than EEG. This suggests that low frequencies engage additional sensory or emotional circuits beyond traditional auditory pathways, and that EDA provides a more objective and practical measure of emotional responses in naturalistic environments.

Overall, bass amplification effectively enhances the emotional music experience, and EDA is a valuable tool for objectively capturing emotional responses in live settings.

1. Introduction

Music is a universal human experience which evokes a wide range of emotional, cognitive, and physiological responses and plays a major role in our affective and social lives. Beyond musicological considerations regarding musical structures, styles, or interpretations, how music is conveyed notably contributes to influence our experience. On the one hand, the quality of sound itself is crucial, with many individuals investing heavily in sound systems to enhance auditory musical experience. Also important is the context in which music is heard, as in live music performances for instance, which are often perceived as more emotionally engaging [1], emphasizing the role of social and environmental factors in shaping our musical experiences.

Music amplification plays a crucial role in enhancing the audience's engagement, especially for live music. However, the way music sounds can be reinforced goes way beyond the mere increase of sound level. Furthermore, as high sound levels pose the risks of hearing damage for the audience and noise disturbance for nearby residents, focusing on audio quality is essential to enhance the emotional response and audience's engagement to music in a safer manner [2,3].

Recent research has begun to explore the role of low frequencies in music-listening [4,5]. Low-frequency sounds, particularly those below 150 Hz, can exert remarkable effects on listeners, amplifying emotional but also physical engagement and sensations [6]. According to recent findings, amplified bass can engage sensory mechanisms that go beyond typical auditory processing even when non-noticeable, suggesting that

* Corresponding author.
E-mail addresses: nicolas.epain@l-acoustics.com (N. Epain), luc.arnal@pasteur.fr (L.H. Arnal).

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low-frequency vibrations may activate non primarily auditory functions such as the vestibular system [6,7]. This may contribute to the immersive feeling of music and intensify emotional responses, an effect that is particularly evident in environments where sound is both heard and felt, such as concerts and clubs.

Despite its wide use, the ways low frequency amplification shapes our subjective perception of music but also our bodily and emotional states remain underexplored. Recent evidence suggests that low-frequency sounds, even when undetectable, can influence brain responses and enhance the desire to move [8], particularly in social or live settings [6], possibly by modulating physiological arousal. At the neural level, many works have suggested that musical emotions are linked to the predictive processing of music in brain regions associated with reward and emotional processing [9–12]. However, our current understanding of why and how bass amplification may interact with these processes to enhance emotions remains limited, notably by various experimental factors.

Capturing emotions during music listening is complex. At the subjective level, research on music and emotion often focuses on consciously accessible dimensions of pleasure and activation, referred to as valence and arousal. These dimensions form the basis of the circumplex model of affect [13–15], which has been widely used to study emotional responses to music [16,17]. Studies have shown that acoustic features of music can predict perceived arousal more reliably than valence [18]. While subjective self-reports are useful for assessing perceived emotional intensity and valence, they are limited in capturing subtle, dynamic mood shifts in real time. In this study, we aimed to determine whether physiological and neural signals, measured through electroencephalography (EEG) and electrodermal activity (EDA), could provide more continuous and objective markers of these affective dimensions.

Prior research has increasingly explored the neural and physiological correlates of music-evoked emotions using EEG and EDA, particularly along the dimensions of valence and arousal. EEG studies have shown that tempo and rhythmic structure in music modulate brain oscillations and emotional states [19,20]. Additional evidence indicates that specific frequency bands and functional connectivity patterns are associated with discrete music-induced emotions [21]. On the peripheral side, EDA has been widely used as an index of emotional arousal during music listening, showing sensitivity to both dimensional ratings (e.g., energy and tension arousal) and discrete emotions [22–24]. Arousing music tends to generate higher EDA responses, suggesting that EDA may serve as a reliable physiological correlate of arousal. Together, these findings support the use of EEG and EDA as complementary methods to capture how emotional responses unfold during music listening.

Another crucial factor pertains to the context in which experiments are conducted. While laboratory settings ensure experimental control, it may alter how emotions are generated by live music, which involves social bonding and a shared artistic experience within and between the audience and performers [25–27]. To address this, we applied the same music-listening experimental paradigm across different contexts, aiming to test whether the emotional and physiological effects of bass amplification can be reliably tracked in both controlled lab environments and in more natural, real-world settings.

In this study, we explore how varying bass levels affect listeners' emotional experiences, neural activity, and physiological responses. The study was conducted in two phases: the first phase (Experiment 1) occurred in a controlled laboratory setting to assess the relationship between bass levels and emotional and neural responses to music. The second phase (Experiment 2) took place in real-world indoor and outdoor environments, where we investigated whether physiological (EDA) recordings could effectively capture how bass amplification modulates emotional responses in more natural listening conditions.

2. Methods

2.1. Experiment 1

Participants 20 volunteers (11 females, aged from 18 to 53 years old, mean = 36.5; std = 11.5; 17 right-handed) participated in the experiment. All participants reported no history of hearing impairments or neurological disorders. Participants were informed of their rights in the experiment and expressed their non-opposition to the study's parameters. They were compensated at a rate of 20€. The study was approved by the Comité de Protection des Personnes Tours OUEST 1 on 10/09/2020 (project identification number 2020T317 RIPH3 HPS). The experiment was conducted at the EEG lab at Institut de l'Audition (Hearing institute) In Paris.

Musical track selection To study the influence of acoustic parameters on the emotional response to music, we first focused on qualifying the musical extracts from an emotional point of view. We first selected 24 pieces of music, which featured low-frequency content, and with different musical styles and moods. We selected one 20-second excerpt within each musical piece, which gave the listener enough time to appreciate the mood of the tracks, while avoiding excessive EEG artifacts due to movements. A total of 39 listeners were then asked to report their emotional response to the 24 excerpts by pointing to a computer's graphical user interface (GUI) representing Russel's circumplex model of affect [13]. In other words, recorded valence and arousal values were determined by the x and y coordinates of the point clicked by the participants. Based on the reported valence and arousal values, we selected the eight tracks that best span the emotional space, i.e. we selected one track with mostly positive valence and high-arousal reports, one with neutral valence and high-arousal reports, etc (see list of tracks in suppl. mat.). The selection was done by visually inspecting valence/arousal distributions for the different tracks. Note that we chose not to use tracks from an annotated database because we wanted participants to listen to tracks that were popular and representative of the music they listened to, while databases typically consist of relatively confidential royalty-free music.

Stimuli Each of the eight selected tracks was then filtered such that, combined with the in-ear monitor's (Contour XO, L-Acoustics) response, the resulting frequency response reflected three different listening condition archetypes: 1- In condition LF-low, a high-pass filter was applied to cut off low-frequencies below about 80 Hz, which corresponds to standard domestic conditions (no subwoofer). 2- In LF-mid condition, a high-pass filter was applied to cut off frequencies below 40 Hz, corresponding to a mid-scale sound reinforcement system with subwoofers. 3- In LF-high condition, no filtering was applied, resulting in bass-heavy response representative of a large-scale sound system. Hence, the test material consisted in $3 \times 8 = 24$ different audio stimuli. The playback system's frequency responses (filtering plus in-ear monitors), measured using a manikin, are presented in Fig. 4A. The stimuli were equalized in level so as not to involve the influence of loudness in the participants' emotional response. The level was set to be comfortable and was not changed between participants.

Experiment The experimental setup is illustrated in Fig. 1. Participants sat comfortably in a shielded room and were equipped with the EEG cap and in-ear monitors (Contour XO, L-Acoustics) to avoid unwanted artifacts due to headphones pressure on the EEG electrodes and participants' head. Listeners were asked to report their subjective emotional response (valence and arousal) after listening to each stimulus by pointing to a computer's GUI representing Russel's circumplex model [13]. The experiment started with a short training phase, during which participants used the test interface to report arousal and valence for three music tracks presented in the three different LF conditions (see the supplementary material for the list of the tracks used in the training phase).

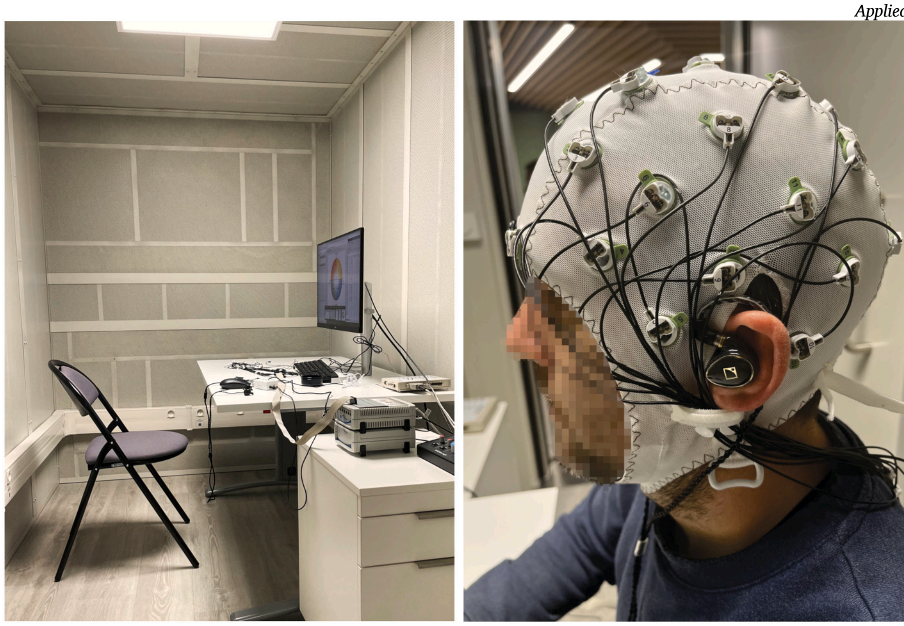

Fig. 1. Setup for Experiment 1. Left: shielded room and test interface; Right: participant equipped with in-ear monitors and the EEG cap.

Sound stimuli were presented in three consecutive sequences using PsychoPy v2022.2.4 [28]. Each of the three sequences consisted of the 24 test stimuli played in a random order. No constraint was implemented to prevent a music track from being repeated twice in a row; however it happened only once per participant on average.

Data acquisition and preprocessing Electroencephalography (EEG) data was continuously acquired using BrainVision Recorder (Brain Products GmbH, Gilching, Germany). Electrode placement followed the standard 10-20 international system using the Brain Products actiCap headcap with 32 electrodes. The sampling rate during recording was set to 1000 Hz. To ensure correct timing between the recorded EEG data and the auditory stimulation, TTL triggers were sent from the stimulation computer to the recording device marking the timing of auditory stimulus in the EEG recording. Subsequent offline preprocessing of EEG data was carried out with the FieldTrip Toolbox [29] in MATLAB (R2024a, Mathworks Inc., Natick, MA, USA). The data was re-referenced to the average across all channels. To eliminate low-frequency drifts, a fourth-order Butterworth high-pass filter with a 0.5 Hz cutoff was applied. Additionally, a notch filter at 50 Hz and its five harmonics was used to remove line noise. The continuous EEG data was then segmented into epochs, each spanning from one second before the sequence onset to 18 seconds after the target tone onset. These epochs underwent visual inspection, and those containing artifacts such as muscle activity were discarded. Any channel identified as bad during this process was also removed. Subsequently, an independent components analysis (ICA) was employed to identify and remove ocular artifacts, specifically blinks and horizontal eye movements. For each trial, we then converted the data into z-scores using the pre-stimulus baseline activity (from 200 ms before to stimulus onset) for each electrode. We then calculated event related potentials (ERPs) and computed time-frequency analysis for each trial before averaging per condition.

Time–frequency analysis on auditory sensors A time–frequency wavelet transform was applied to each trial (one second pre- to 20 seconds post-onset, zero-padded) at each EEG sensor using a wavelet ($m = 7$) analysis (0.5 Hz resolution from 1 to 12 Hz; 1 Hz resolution from 13 to 30 Hz). This analysis resulted in an estimate of oscillatory power at each time sample and at each frequency between 1 and 30 Hz. Data were distributed normally, which allowed us to use standard parametric repeated-measures analysis of variance (ANOVA) to assess the statistical significance of observed effects on our experimental factors. To assess the strength of the observed effects and correct for type I errors potentially arising from multiple comparisons performed at single frequency points we used non-parametric cluster statistics according to the procedure described in [30].

2.2. Experiment 2

In this section we describe the methods of Experiment 2, whereby we investigated the relationship between bass amplification and the emotional response to music, as measured by EDA.

Participants A total of 62 listeners, 29 females and 33 males, participated in the experiment. The age of the participants ranged from 20 to 80 and they all reported having normal hearing abilities. Twenty-one listeners (8F, 13M) took part in the first phase of the experiment (indoor environment) and 41 (21F, 20M) in the second phase (outdoor environment). All participants explicitly agreed to take part in the experiment by signing an explanatory consent form.

Musical track selection We used eight musical pieces with diverse genres to generate test stimuli. The tracks used for Experiment 2 were different from those used in Experiment 1. The reason why we used different tracks is that we wanted to maximize the listener's EDA response to music. As EDA is generally considered as a psychophysiological indicator of emotional arousal, we selected tracks that featured a "drop", a crescendo or other musical characteristics that could lead to arousal. The duration of the excerpts ranged from 38 to 46 seconds, so that the participants had sufficient time to experience important musical structures such as chord progressions, loops, etc. In the following, we refer to the eight musical excerpts used to generate the test stimuli as the tracks (see list of tracks in suppl. mat.).

Stimuli The 32 test stimuli were generated by filtering the eight musical tracks with four different sets of filters, featuring different amounts of low-frequency amplification. In the following, we refer to the different versions of the stimuli as "LF condition 1–4", where 1 represents the condition with the smallest amount of bass and 4 represents the one with the largest amount of bass. The frequency responses of the filters used to stimulate the stimuli are illustrated in Fig. 6. Note that, in condition 3, no filtering was applied to the original tracks and the sound system

Fig. 2. Setup for the indoor phase of Experiment 2 (artistic depiction).

was set to its standard configuration, which features plenty of bass. In condition 4 low frequencies below 80 Hz had an additional 3 dB boost. On the other hand, in conditions 1 and 2 high-pass filters were applied to reduce the amount of bass compared to the sound system's standard configuration, with the overall playback system's response being relatively flat in condition 4. The stimuli were then equalized in loudness using the ITU loudness measurement standard [31]. The playback level at the listening position was set at about 90 dBA on average.

Experiment The experiment was run in two successive phases. The first phase took place in an acoustically treated room used for multichannel audio listening. The setup is illustrated in Fig. 2. Participants sat comfortably in an armchair, facing a professional grade stereo sound system, in a setup resembling that of music-listening in a domestic environment. They were instructed to remain seated and focus on the music playing on the stereo in front of them. Only one listener took the test at one time. The listening test was divided into two measurement sessions, separated by a short pause. Each measurement session started with one minute of silence, followed by 1 min 30 s of introductory easy listening music. The purpose of the introductory music was for the participants to have a bit of time to relax and to get used to the playback level. A series of 16 of the 32 stimuli, consisting of exactly two versions of each track was then presented. The order in which the tracks were presented was picked at random, with the constraint that at least four other stimuli be played between two versions of a given track. The order in which the different versions of a given track were played was also selected at random.

The second phase of the experiment was conducted in an outdoor environment typically used to test loudspeakers. The setup is illustrated in Fig. 3. In this phase, three participants sat side by side, facing a mono sound system of the kind used at a music festival. The aim of this second phase was to mimic the listening conditions encountered in outdoor concerts. Unlike the indoor phase, the outdoor phase was divided into four measurement sessions to prevent listener fatigue. Indeed, when analyzing the data acquired during the indoor phase, we observed that the participant's EDA response was lesser when a track had been played earlier during the same measurement session (see Section 3.3). Thus, during each measurement session of the outdoor phase, only one version of each music track was played, and the different tracks were played in a random order. Also, the order in which the different versions of a given track were played was picked at random.

Data acquisition and preprocessing Test participants were equipped with a Shimmer3 GSR+ sensor [32], which was used to record skin conductance for the entire duration of the experiment. The sensor's electrodes were positioned on the index and middle finger of the participant's non-dominant hand. During the indoor phase, they were handed a buzzer-type joystick to provide feedback whenever they experienced chills or felt aroused by the music. However, due to technical constraints, the joystick was not available to the participants during the outdoor phase.

We applied the EDA positive change method (EPC) [33] to calculate a single score for each listener and stimulus. This method consists in accumulating positive variations in skin conductance over a period, hence summing any occurring peak. A log function was then applied to increase the normality of the distribution of EPC values. Lastly, to account for individual differences among participants, the EPC values for each stimulus were z-scored for each participant. In the following, we refer to the resulting electrodermal activity values as EDA scores.

The data gathered from the feedback button was processed as follows. For each participant and each stimulus, we counted the number of times the feedback button was pressed to obtain one value. To account for individual differences between participants, these values were z-scored for each participant. In the following, we refer to these scores as FBP (feedback button presses) scores.

Participant screening A screening of the data revealed that four participants of the indoor phase and three participants of the outdoor phase were EDA "non-responders", meaning that very little activity was measurable at the surface of their skin. Consequently, data from these participants was excluded from further analysis. To identify non-responders, we first z-scored the skin conductance signals for each participant. We then calculated the variance of the z-scored signals over 10 s time windows and averaged these values over all windows. The four non-responders exhibited variances lower than one standard deviation below the average over all participants. The proportion of non-responders identified in this study aligns with values reported in the literature [34].

3. Results

3.1. Experiment 1: behavioral results

We first assessed the effect of bass amplification (3 levels: LF-low, LF-med and LF-high; Fig. 4A) on self-reported, subjective emotional re-

Fig. 3. Setup for the outdoor phase of Experiment 2.

sponses to music using Russell's circumplex model. Fig. 4B presents the behavioral data measured for two exemplar tracks from Experiment 1, for all participants and LF conditions. For both tracks, ratings are relatively scattered across the emotional space, with listeners reporting negative and positive values for both valence and arousal. However, the points corresponding to Track 3 and Track 1 are predominantly distributed in the lower-left and upper-right quadrant of the emotional space, respectively, as expected based on the music track selection process. Track 3 is a sad and relatively slow pop-rock song, while Track 1 is a funky, upbeat track (please refer to the additional material for music track information).

We now focus on the reported arousal values as a function of the track and LF condition, as shown in Fig. 4C. On the one hand, reported arousal values vary significantly amongst musical tracks, reflecting differences in their mood. This was confirmed by a Bonferroni multiple comparison post-hoc test, which revealed five distinct groups: in descending arousal order, a) Tracks 1 & 2; b) Track 6; c) Track 5; d) Tracks 3 & 7; e) Tracks 4 & 8. A Bonferroni multiple comparison test gave the same result. On the other hand, for a given track, arousal values obtained for the three LF conditions show minimal variation. Nonetheless, for most tracks, arousal values appear to increase slightly as the LF condition progresses from low to high. We then performed a repeated analysis of variance (ANOVA) of the reported arousal values for factors track, LF condition, and their interaction. The ANOVA reveals that there is a significant impact of both the music track ($F(7, 476) = 107.708$, $p < 10 - 4$) and LF condition ($F(2, 136) = 11.284$, $p = 10^{-4}$), while the influence of their interaction is non-significant ($F(14, 952) = 1.175$, $p = 0.3025$). However, the effect size obtained for the LF condition ($\eta^2 = 1.36\%$) is about 23 times smaller than that observed for the track ($\eta^2 = 31.60\%$). Fig. 4D shows the reported arousal values as a function of the LF condition, on average for every track. Although the values distributions seem almost identical, a closer look reveals that the arousal is slightly larger for the LF condition "high" than for conditions "low" and "medium" ($\mu_{\text{low}} = -0.011$; $\mu_{\text{med}} = 0.000$; $\mu_{\text{high}} = 0.054$). A Bonferroni multiple comparison post-hoc test indicated that this difference is statistically significant.

Regarding valence, the analysis provided similar results as that obtained for arousal, as illustrated in Fig. 4E. As is the case for arousal, a two-way repeated ANOVA shows that both the music track ($F(7, 476) = 70.609$, $p < 10^{-4}$) and LF condition ($F(2, 136) = 6.159$, $p = 0.0032$) have a significant impact on reported valence values, whereas their interaction has no significant effect ($F(14, 952) = 0.751$, $p = 0.6780$). The effect size for the LF condition ($\eta^2 = 0.75\%$) is about 31 times smaller than that of the track ($\eta^2 = 23.25\%$). A Bonferroni multiple comparison post-hoc test indicated that the valence reported for LF condition "high" is significantly larger than that reported for LF condition "low" ($\mu_{\text{low}} = -0.036$; $\mu_{\text{med}} = 0.008$; $\mu_{\text{high}} = 0.015$).

In summary, we observed a significant impact of the lower end of the playback system's frequency response on both the arousal and valence reported by the participants, but this impact is 20 to 30 times smaller than that of the music track.

3.2. Experiment 1: EEG results

To test the effects of low-frequency amplification on auditory brain responses, we first focused on early evoked electrophysiological components during the first second following the onset of each musical excerpt. By applying a repeated measure ANOVA at each time point, we observed no significant effect of the low-frequency condition, with all F values remaining below the significance threshold (Fig. 5A), both

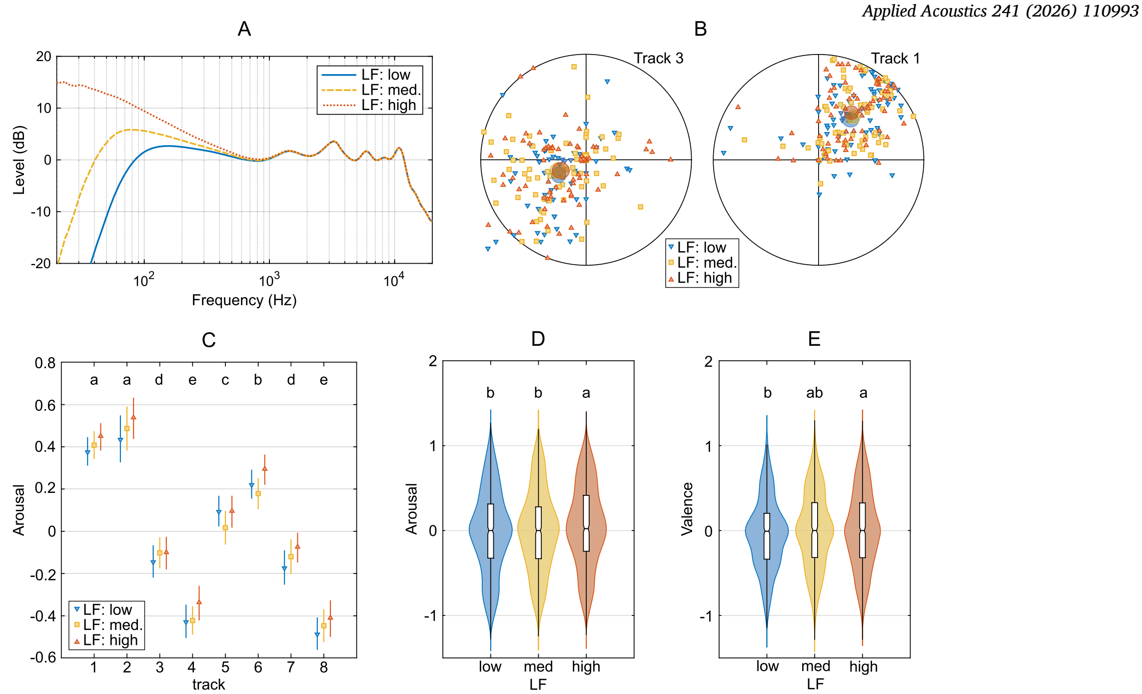

Fig. 4. Impact of the amount of bass on the listener's emotional response to music. A) Measured frequency response of the playback system (ear buds + filtering) in the three listening conditions: LF-low, LF-med. and LF-high. B) Individual reports of valence and arousal on Russell's circumplex model for Tracks 1 and 3 and for the three listening conditions. C) Reported arousal values for the eight tracks and three listening conditions, on average for all test participants and repeats (markers: mean value; vertical lines: 95% confidence intervals). An ANOVA suggests that the impact of the LF condition is statistically significant, but small relative to that of the track. D) Reported arousals as a function of the listening conditions, averaged for every participant, repeat and track. A Bonferroni post-hoc multiple comparison test indicates that the arousal for LF condition "high" is higher than that reported for conditions "low" and "med". Note: the letters above the boxes illustrate statistical significance in pairwise comparisons, i.e., two groups sharing one letter are not significantly different. E) Reported valences as a function of the listening conditions, averaged for every participant, repeat and track. A Bonferroni test indicates that the valence for LF condition "high" is higher than that reported for condition "low". Note: in plots C, D and E letters above the boxes illustrate statistical significance in pairwise comparisons, i.e., two groups sharing one letter are not significantly different.

during this time window and across the full peri-stimulus period (1–20 seconds post-onset; data not shown). Using a similar regression procedure as used for behavioral reports (see Section 3.1), we also tested for a linear effect of bass levels on early auditory ERPs and did not find any significant effect. This suggests that even if it modulates affective reports, bass amplification cannot be registered in early auditory cortical responses.

To explore the effects of bass amplification on brain responses over the entire peri-stimulus duration, we applied the same statistical approach to the time-frequency spectrum of EEG data across all channels. First a qualitative observation shows that as expected, music listening induces an early increase, followed by sustained neural entrainment in the theta (4-8 Hz) range (Fig. 2A). To measure a sustained effect of bass amplification, we then applied a repeated-measure ANOVA at each frequency of the spectrally resolved data averaged across time over the peristimulus time course (from 1 to 19 seconds to avoid unwanted edge artifacts at onset and offset). This analysis reveals that brain entrainment to the musical excerpts is significantly modulated by the bass, particularly in the delta (2-5 Hz) range (see Fig. 5B; ANOVA $p_{\text{cluster}} = 0.048$) and more marginally in the beta (15-22 Hz) band (see Fig. 5B, ANOVA $p_{\text{cluster}} = 0.089$), both mostly visible in anterior central sensors (Fig. 5B).

To test whether this effect depended on specific LF conditions, we performed post-hoc t-tests (see violin plots in Fig. 2B). Focusing the post-hoc analysis specifically on the averaged spectrum in delta and beta frequency bands across all channels and during the whole peristimulus time-course, we observed that the condition in which the bass is strongest seems to dominate this effect: in the delta band, post-hoc t-tests show that the LF-high condition induces a stronger drive than LF-med. ($t = 3$, $p = 8 \cdot 10^{-3}$) but not LF-low ($t = -.3$, $p = .7$) conditions. In the beta band, the post-hoc t-tests show a similar effect: the power is slightly greater in the LF-high condition than in the LF-med. ($t = 1.9$, $p = .07$) and LF-low ($t = 1.6$, $p = .12$) conditions, although non-significant. Thus, although relatively weak, the EEG results indicate that while early auditory responses are not affected by bass amplification, the latter would be represented in the power of the responses sustained over time while listening to the musical extracts. Statistical analysis using a two-factor bass vs song ANOVA did not reveal any additional significant difference, nor any interaction with the song effect. While it seems to capture a weak cerebral bass entrainment effect, the electrophysiological recordings did not permit to discover more subtle effects, related to the subjectivity or affective responses of the participants.

3.3. Experiment 2: physiological results

Effect of track repetition indoors We first examined how the EDA scores evolved during the indoor phase of Experiment 2. In Fig. 6B, the EDA scores are plotted as a function of time (stimulus index), on average for every participant and measurement session. The EDA decreases during the experiment, which may indicate that the participants reacted less and less as they listened to the series of stimuli. One possible explanation is that each track was played twice during a measurement session. The response to a given track is likely lessened if it already has been played a few minutes earlier. To observe this effect, we compared the EDA scores measured when tracks were played for the first or second time during a session (Fig. 6C). A t-test revealed that the value of the EDA score is indeed significantly larger when a track is heard for the first time in a measurement session ($t = 3.11$, $p = 2 \cdot 10^{-3}$). In the following we do not consider the effect of time or repetition on the EDA, as it seemed independent from the track or condition.

Multifactorial analysis of indoor data We ran two-way repeated ANOVAs with factors "track", "LF condition" and their interaction on the EDA and

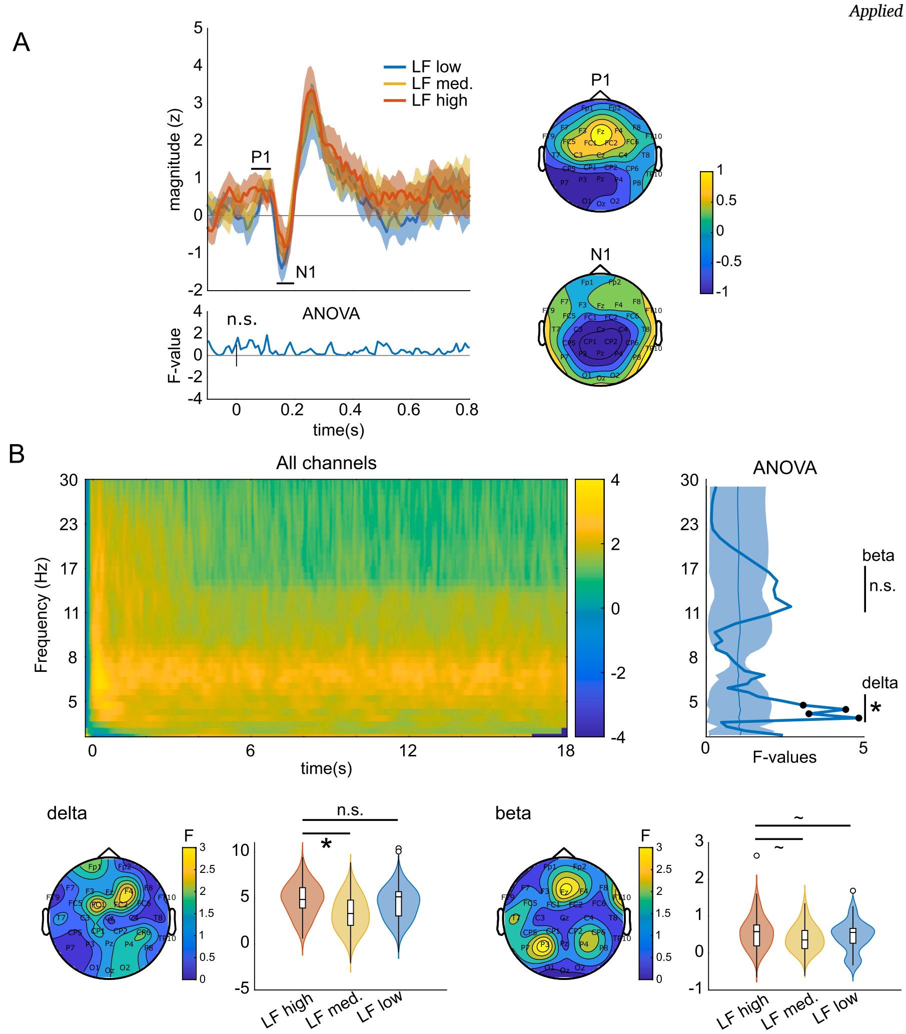

Fig. 5. Impact of the amount of bass on electroencephalographic responses to music. A. Event-Related Potential (ERP) responses following the onset of musical excerpts. Top: Topographical renderings of ERP component P1 and N1 averaged. Center: ERPs measured on central electrode Cz as a function of experimental conditions. Repeated measures ANOVA, main effect of low-frequency profile (3-levels: low, med., high) on ERP responses across time. B. Time-frequency analysis. Top left panel: spectral power of brain responses averaged across all EEG channels and participants. Top right panel: ANOVA main effect of low-frequency profile on EEG spectral power (averaged across the entire peristimulus timecourse). Black dots indicate statistical significance (cluster corrected for multiple comparisons) across time in the delta range [3–5 Hz]. Blue shading, mean and s.d. of the corresponding null distributions across 1,000 permutations. Bottom left: topographical renderings of ANOVA main effect of LF conditions in the delta [3–5 Hz]. Violin plots: delta power averaged across all channels as a function of LF experimental conditions. Bottom right: topographical renderings of ANOVA main effect of LF conditions in the beta [15–22 Hz]. Violin plots: beta power averaged across all channels as a function of LF experimental conditions. * statistical significance at $p < 0.05$; merely significant. n.s.: non significant.

FBP (feedback button presses) scores measured indoors. Regarding FBP scores, both the main effects of the track ($F(7, 512) = 4.723$, $p = 10^{-4}$) and LF condition ($F(3, 512) = 10.643$, $p < 10^{-4}$) are statistically significant, but not the interaction between these two factors. In addition, the track has a slightly larger effect size ($\eta^2 = 9.37\%$) than that of the LF condition ($\eta^2 = 6.03\%$). As is the case for the FBP, ANOVA on EDA data reveal that both the track ($F(7, 512) = 2.806$, $p = 9.1 \cdot 10^{-3}$) and LF condition ($F(3, 512) = 3.917$, $p = 1.4 \cdot 10^{-2}$) have a significant impact on the EDA, while the impact of the track-condition interaction is not significant. Also, the effect size is slightly larger for the track ($\eta^2 = 3.19\%$) than for the LF condition ($\eta^2 = 2.07\%$).

Effect of the musical content indoors The effect of the music track on the FBP and EDA are illustrated in Figs. 6D and 6G. Comparing the data obtained for the two modalities, we observe larger variations for the FBP than the EDA. This was expected given the size of the effects determined by the ANOVAs. Regarding the participants' feedback, Track 3 was the most arousing track, while Tracks 5 and 7 were the least arousing. On the other hand, the largest EDA scores were obtained for Track 4 while the smallest were obtained for Tracks 2, 5 and 7. Therefore, the least arousing tracks were the same from the viewpoints of both the FBP and the EDA, but the most arousing tracks differed.

Effect of the LF condition indoors We now focus on the effect of the LF condition on the emotional response. Figs. 6E and 6H present the effect of the LF condition on the FBP and EDA, respectively, on average for every track. As is the case for the effect of the track, variations related to the LF condition are larger for the FBP than for the EDA. This is in line with the effect sizes calculated by the ANOVAs. Further, the FBP appears to increase with the relative amount of low-frequencies: the FBP values for condition 4 are significantly higher than that obtained for conditions 1 and 2, as indicated by a Bonferroni multiple comparison post-hoc test. Conversely, FBPs obtained for condition 1 are significantly lower than that obtained for conditions 3 and 4 ($\mu_1 = -0.242$, $\mu_2 = -0.081$, $\mu_3 = 0.159$, $\mu_4 = 0.369$). However, a Bonferroni test conducted on the EDA data revealed less contrast: EDA values obtained for condition 4 are significantly higher than those obtained for condition 2 only ($\mu_4 = 0.131$, $\mu_2 = -0.258$). Examining the data for individual tracks

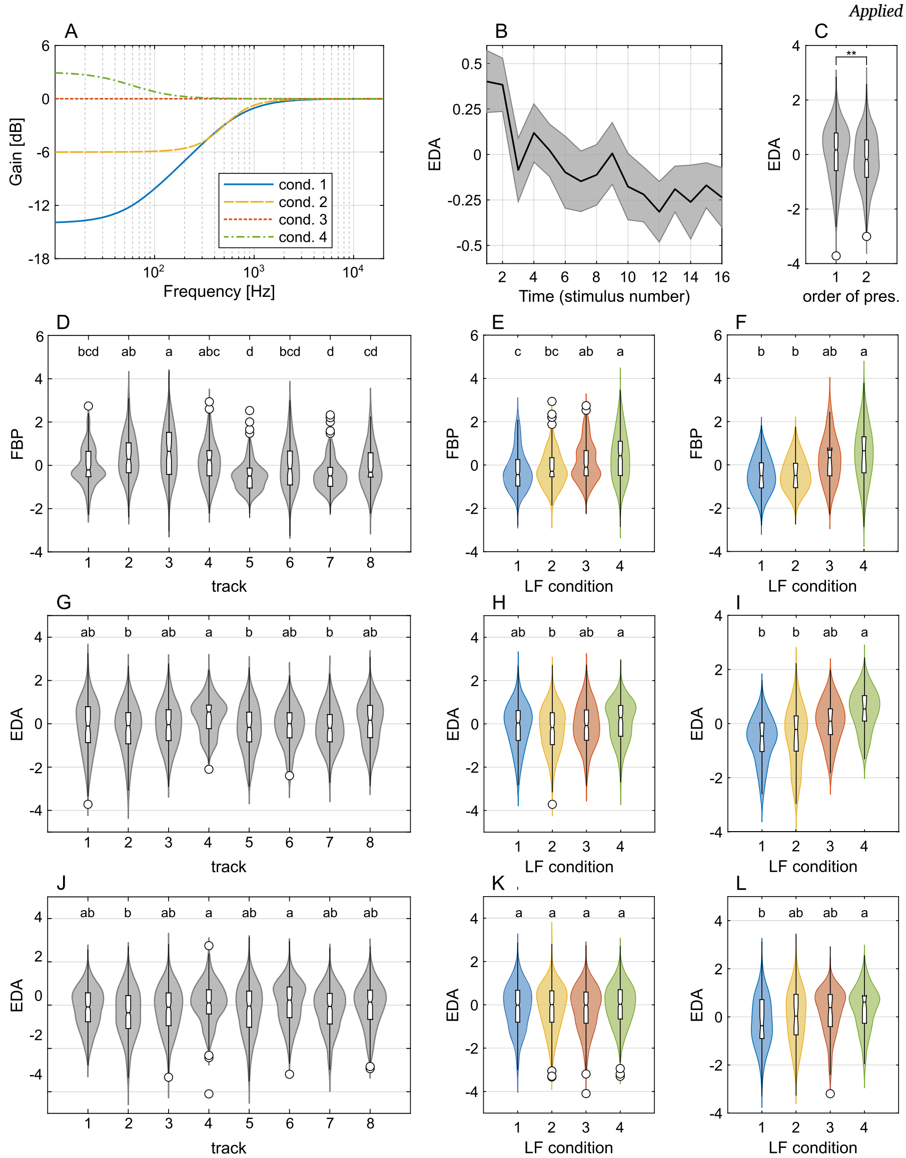

Fig. 6. Results of Experiment 2. A) Equalization gains applied to the stimuli. B) Indoor, electrodermal activity (EDA) as a function of time, averaged over every participant and measurement session (black line: mean; grey area: std. err. of the mean). C) Indoor, EDA as a function of the stimulus order of presentation. D) Indoor, occurrences of feedback button presses (FBP) as a function of the track. E) Indoor, FBP as a function of the LF condition. F) Indoor, FBP as a function of the LF condition for Track 6. G) Indoor, EDA as a function of the track. H) Indoor, EDA as a function of the LF condition. I) Indoor, EDA as a function of the LF condition for Track 6. G) Outdoor, EDA as a function of the track. H) Outdoor, EDA as a function of the LF condition. I) Outdoor, EDA as a function of the LF condition for Track 6. Note: in plots D-L, letters above the boxes illustrate statistical significance in pairwise comparisons, i.e., two groups sharing one letter are not significantly different.

using a one-way ANOVA for factor LF condition, a significant effect is detected for Track 6 for EDA and FBP ($p = 7 \cdot 10^{-4}$ and $p = 0.0024$, respectively) and Track 5 for EDA only ($p = 0.0370$). The data corresponding to Track 6 is plotted in Figs. 6F and 6I for the two measurement modalities: in both cases the values obtained with LF condition 4 are significantly larger than that obtained for conditions 1 and 2, as indicated by a Bonferroni post-hoc multiple comparison test.

Multifactorial analysis of outdoor data We now examine the data measured during the outdoor phase of Experiment 2. Contrary to the indoor case, only the track seems to impact the EDA significantly ($F(7, 1184) = 3.762$, $p = 7 \cdot 10^{-4}$). On the contrary the impact of the LF condition is not significant ($F(3, 1184) = 1.643$, $p = 0.1836$), and likewise there seems to be no impact of the track-LF interaction ($F(21, 1184) = 1.400$, $p = 0.1093$). The corresponding effect size is also smaller than that observed indoors ($\eta^2 = 0.0205$).

Effect of the musical content outdoors The impact of the music track on EDA scores is illustrated in Fig. 6J. The EDA varies as a function of the track in a similar way to that observed in the indoor data: Track 4 is one of the most arousing tracks, while Track 2 is one of the least arousing.

Effect of the LF condition outdoors On average for every track, there is no observable impact of the amount of bass on the EDA outdoors, as illustrated in Fig. 6K. Nevertheless, considering the responses measured for Track 6 alone, there seems to be an impact of the LF condition on the EDA: EDA scores are significantly larger with LF condition 4 than with LF condition 1, as revealed by a Bonferroni post-hoc multiple comparison test ($\mu_1 = -0.203$, $\mu_4 = 0.371$). This is illustrated in Fig. 6L.

4. Discussion

In this study, we investigated the impact of bass amplification on the emotional response to music through subjective reports, electroencephalography (EEG), and electrodermal activity (EDA). Our findings suggest that while bass amplification enhances emotional responses, its effects are generally smaller than those driven by the musical content. However, physiological measures, particularly EDA, appear to capture emotional modulation by bass more reliably than EEG or self-report.

Subjective emotional responses to bass amplification Here, we show that bass amplification enhances self-reported emotional arousal and, to a lesser extent, valence. However, the size of this effect varied between Experiment 1 (laboratory setting) and Experiment 2 (ecological setting). In Experiment 1, bass had a smaller effect on reported valence and arousal compared to the emotional quality of the music tracks. In Experiment 2, the effect of bass, while still secondary to the musical content, was of a similar order of magnitude. One possible explanation for this discrepancy lies in the response format. In Experiment 1, participants used a graphical user interface (GUI) to rate their emotions, which may have biased them toward judging the mood of the tracks rather than their own subjective emotional experience. This could explain why valence ratings were rather inconsistent, whereas arousal ratings—closer to physiological measures—showed clearer modulation by bass. Additionally, listening conditions differed between experiments: in Experiment 1, participants wore in-ear monitors, whereas in Experiment 2, a high-powered sound system allowed for the tactile perception of low-frequency vibrations. This component may contribute to heightened arousal, consistent with previous findings showing that even subliminal low-frequency sounds can influence listener behavior [6].

Neural and physiological responses to bass amplification Our EEG findings indicate that early auditory event-related potentials (ERPs) were largely unaffected by bass manipulation. Unlike behavioral responses, which showed a clear relationship between bass levels and emotional engagement, cortical auditory responses did not exhibit strong modulations. However, spectral analysis of EEG data revealed a weak but significant effect of bass amplification on sustained oscillatory activity in the low delta (2–5 Hz) and, to a lesser extent, beta frequency ranges. Given previous research linking these bands to temporal tracking of music (e.g., [35]), these results may suggest that bass modulates endogenous, predictive processes rather than exogenous auditory entrainment in the theta range. However, these results highlight a key limitation of EEG in capturing deeper, subcortical processes that may mediate physiological responses to bass. The neural circuits driving these responses may extend beyond the auditory cortex to involve deeper structures, such as the brainstem, vestibular system, or limbic areas, which are not optimally captured by EEG. This could explain why EDA may provide a clearer indication of arousal changes than EEG.

Compared to EEG, EDA responses were more sensitive to changes in bass levels, potentially suggesting that low-frequency sounds engage emotional and autonomic mechanisms that extend beyond auditory cortical processing. This discrepancy may be due to the recording conditions—EEG was measured with in-ear monitors, whereas EDA was collected in a setting with loudspeakers. Additionally, EDA reflects autonomic nervous system activity, which integrates sensory and emotional responses at a more systemic level, potentially explaining its greater sensitivity to bass modulation. This raises the possibility that fMRI, which offers higher spatial resolution and tracks slower, integrated fluctuations in neural activity, could provide more detailed insights into the neural mechanisms underlying bass-induced emotional modulation. However, fMRI constraints make it difficult to study music perception in naturalistic settings. In contrast, EDA presents a more practical and ecologically valid tool for measuring emotional responses in real-world listening environments.

Implications for measuring emotional responses to music Overall, our results suggest that EDA may be a more reliable and ecologically valid measure of emotional responses to music than EEG or self-report. EDA captures real-time physiological changes while allowing participants to remain fully immersed in the music without the need for explicit responses. Moreover, EDA can be used in environments that better approximate natural listening conditions, unlike EEG, which typically requires laboratory constraints. However, replicating the sensory experience of a live concert posed challenges, particularly in the outdoor experiment. EDA responses in the outdoor setting showed less contrast than in the indoor experiment, likely due to external environmental factors. Distractions such as overhead planes, birdsong, and wind may have introduced variability in physiological responses. Additionally, social context may have played a role, as participants in the outdoor setting were seated side by side, potentially influencing their emotional engagement. Importantly, while our sample size is consistent with prior EEG studies using similar within-subject designs [19,36], future work should aim to replicate these findings in larger groups to strengthen generalizability.

Conclusions Our study highlights the role of bass amplification in enhancing emotional responses to music and emphasizes the importance of using multimodal approaches to assess music-induced emotions. While EEG provides insights into neural correlates of music perception, it may be less sensitive to the emotional impact of bass than EDA, which appears to be a more robust and ecologically valid tool for capturing real-time emotional engagement in naturalistic settings. These observations are also relevant for optimizing sound design in live performances, demonstrating that enhancing bass levels can enrich the listener's emotional experience without necessarily increasing overall loudness. Future studies should further explore the vibrotactile contributions of bass and investigate how social and environmental factors interact with low-frequency perception to shape musical emotions.

CRediT authorship contribution statement

Nicolas Epain: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Samuel Moulin:** Supervision, Methodology, Conceptualization. **Camille Mingam:** Software, Investigation, Data curation. **Mérové Wallerich:** Software, Investigation, Formal analysis, Data curation. **Etienne Corteel:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Luc H. Arnal:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Luc H. Arnal reports financial support was provided by L-Acoustics. Luc H. Arnal reports a relationship with L-Acoustics that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.apacoust.2025.110993.

Data availability

Data will be made available on request.

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