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Reducing preferred listening levels in headphones through coherent audiotactile stimulation

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Abstract: Using headphones may expose the listener to potentially harmful levels of sound. This study examines whether introducing tactile vibrations to the listening experience would encourage them to reduce their headphone volume. Fifteen participants adjusted their preferred listening levels for four diverse music tracks under audio-only and audiotactile conditions. Results indicated a significant decrease in preferred audio levels with added tactile stimulation. This effect was particularly significant in songs featuring a strong beat. In contrast, only a minimal effect was observed for genres such as classical music, which typically lack a pronounced beat, at higher vibration intensities. These findings suggest that integrating tactile feedback could be a viable strategy for lowering sound exposure risk. *© 2024 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).*

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1. Introduction

The act of listening to music through headphones has become an integral part of daily life for millions worldwide. However, this widespread practice has risks, particularly concerning hearing health, as sound levels can reach potentially harmful levels (Epstein *et al.*, 2010). Prolonged exposure to high-volume sound through headphones can lead to various auditory issues, including temporary or permanent hearing loss (Sliwinska-Kowalska and Davis, 2012). This concern is not limited to professional environments, such as DJs and sound engineers, but extends to the general public, especially frequent headphone users.

Recent advancements in audio technology have introduced an intriguing possibility: the integration of vibration into headphone design. Studies have shown that adding tactile vibration to audio experiences can enhance the overall listening experience (Marozeau, 2023; Merchel and Altinsoy, 2018; Remache-Vinueza *et al.*, 2021) and potentially alter the perception of loudness (Schürmann *et al.*, 2004). Consequently, the same level of acoustic energy can be perceived as louder and more immersive by incorporating vibration, thereby enriching the auditory experience while decreasing the sound level.

Several companies have begun exploring this concept, proposing headphones or wearables that integrate vibration technology (for example, Nuraphone, Woojer, Hypersense). This innovation opens a new avenue for research, particularly in understanding its implications for hearing health. We hypothesize that by adding vibration to headphones, listeners will instinctively lower the volume needed to achieve a pleasant and comfortable listening level. This behavior could potentially lead to a safer listening environment, reducing the risk of hearing damage associated with high-level sound exposure.

To test this hypothesis, we have examined how adding vibration to headphones influences volume preferences. However, it is important to note that adding vibration to headphones could lead to two distinct consequences. First, it creates a perceivable vibration, which could benefit the listening experience. Second, it could enhance the energy sent to the cochlea via bone conduction. This latter effect is potentially problematic; if the reduction in energy transmitted through air conduction is entirely compensated for by increased bone conduction, then the overall exposure level remains unchanged.

To address this complexity, we introduced an additional condition in our experiment where vibrations were transmitted to the chest, akin to the experience of being at a concert. This condition was designed to induce only the sensation of vibration while minimizing the impact of bone conduction and helped us to disentangle the effects of air-conducted and bone-conducted sound transmission created by the actuator.

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2. Methods

2.1 Participants

Fifteen normal-hearing participants, aged between 22 and 37 (11 females and 4 males), were recruited among Danish Technical University (DTU) students. All the participants performed pure tone audiometry before participating in the experiment. They all reported no hearing difficulties.

2.2 Stimuli

Four distinct music tracks were selected to represent different music styles. The songs were selected from a genre familiar to the participants, yet the specific tracks were unknown to them.

(1) "SuckerPunch" by FLETCHER (stylized in capital letters), released in 2022 from Capitol Records: A mainstream, commercially appealing composition was selected for its prominent low-frequency bass, fast tempo set at 142 beats/min (BPM), resembling typical nightclub tracks. Because of its recent release, participants were unlikely to have heard it before the experiment. The song opens with a standard introduction, showcasing female vocals and keyboard. It then shifts to a more dynamic rhythm, marked by a pronounced snare drum hitting on beats 2 and 4, as shown in Fig. 1(A). Alongside this, a bass line rhythmically plays on the eighth notes, filling the space with a dense texture.
(2) "The Sails of Charon" by Scorpions, released in 1977 by RCA Records: A representative rock composition from that area. The track, set at a tempo of 110 BPM, embodies key aspects of the prevalent music styles of the era, notably featuring riffs from distorted guitars. In the introduction, the drum pattern draws inspiration from a disco shuffle, marked by the bass drum striking on each beat, as depicted in Fig. 1(B). Additionally, an open high-hat is played on every eighth note, adding a distinctive rhythmic layer to the composition. The chosen track was one of the band's comparatively less recognized pieces, likely unfamiliar to most participants.
(3) "Conquest of Paradise" by Vangelis, released in 1992 from the label East-West: Selected for its orchestration approach. A film soundtrack within the classical music genre, characterized by vocal layering and percussion. Set at a measured pace of 74 BPM in a 3/4 time signature, the piece features strings and percussion instruments executing an ostinato rhythm on each beat, as well as on the "and" of the third beat, as illustrated in Fig. 1(C). This arrangement creates an ethereal quality, balancing minimalism and pronounced rhythmic intensity.
(4) "Haitian Fight Song" by Charlie Mingus, released in 1957: This composition is a solo performance featuring the double bass. The solo is marked by a subtle yet powerful rhythmic foundation, primarily focusing on lower frequencies with minimal high-frequency elements. Serving as the introduction to an orchestral masterpiece by Mingus, it unfolds at a tempo of approximately 154 BPM. This solo is a fusion of diverse musical styles, blending blues, gospel, and classical influences. It traverses a broad dynamic range, shifting seamlessly from gentle, introspective segments to intense, forceful sections [see Fig. 1(D)].

All tracks were reduced to a mono format. Two frequency ranges were isolated: High-frequency components passed through a one-pole high-pass filter with a cutoff at 1000 kHz, and low-frequency components passed through a one-pole low-pass filter with a cutoff at the same frequency.

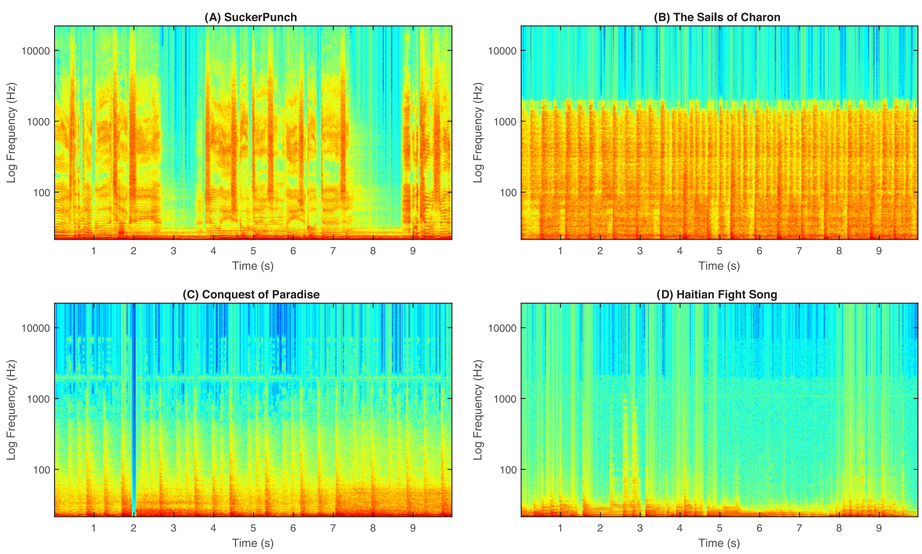

Fig. 1. Spectogram of the first 10 s of the songs: (A) "SuckerPunch"; (B) "The Sails of Charon"; (C) "Conquest of Paradise"; (D) "Haitian Fight Song."

2.3 Test setup

Participants were seated in an audiometric booth equipped with an EVOLVE 80 MS stereo headset (Jabra, Copenhagen, Denmark) and an L5 (Lofelt GmbH, Berlin, Germany), a wideband voice coil actuator designed for high-definition haptic feedback, housed in a $5 \times 5 \times 3\,\text{cm}^3$ wooden case (see Fig. 2). It has a resonance frequency of 60 Hz, functioning thereafter as a low-pass filter with a slope of 10 dB per octave. This actuator delivered vibrotactile stimulation and was positioned between the headphone band and the scalp or held against the chest. The vibrations were oriented parallel to the skin and had an input voltage of approximately 860 mV, equating to a root mean square (RMS) vibration velocity of roughly 0.063 m/s. Both channels were triggered simultaneously with a click and a test sample to assess any temporal misalignment between audio and tactile stimuli due to mechanical inertia. An average delay of 0.024 s was observed. Given the negligible impact of this delay on the study (Fujisaki and Nishida, 2009), no correction was implemented. Participants used a USB-connected infinite rotary knob to adjust the audio levels. The knob featured 30 discrete steps encompassing its full rotation, with each step altering the volume by 1 dB within a range from 0 to 50 dB of attenuation.

Each song was split into two frequency ranges: high-pass and low-pass. The high-pass version was consistently played through the headphones at a fixed volume level, determined to be comfortable by the authors. In contrast, the low-pass version was delivered through the headphones and the tactile actuator. Participants were given the ability to adjust the volume of the low-pass component in the headphones using a USB knob, which served as the dependent variable in our experiment. The intensity level of the low-pass version sent to the tactile actuator was set at a fixed level for each trial but varied across different trials, acting as the study's independent variable. The experimental interface was developed and run using Pure Data.

2.4 Procedure

Vibrations were calibrated at four distinct levels: 4, 8, 12, and 16 dB above an average tactile threshold. This threshold was established through previous studies using the same equipment (same actuator and amplifier) (Aker *et al.*, 2022; Verma *et al.*, 2023). In a preliminary pilot study conducted by the authors, it was confirmed that a level of 4 dB above the threshold was subtly perceptible, whereas a level of 16 dB approached the edge of discomfort.

The tactile actuator was tested in two locations: on the head and the chest. Although the head location was more convenient for headphone integration, this placement risked additional sound sensations due to bone conduction. To mitigate this, the actuator was tested on the chest as well. The chest was chosen because it is commonly recognized as the primary area where vibrations are felt in live music environments.

The experiment was structured into six distinct blocks. Within each block, participants underwent 20 trials, encompassing every possible combination of four songs and four levels of tactile stimulation intensity. A baseline condition featuring only audio was included for the four songs. The sequence of these trials was randomized to reduce the order effect. For each block, the position of the tactile actuator remained constant, either on the head or the chest, but this location alternated between blocks. The sequence in which these locations were tested varied randomly among participants.

Before each trial, the low-pass volume of the signal sent to the headphones was set to a maximum attenuation of 50 dB. Participants were instructed to adjust the volume of the music using an infinite rotary knob. They were encouraged to set the volume to a comfortable level as if they were listening at home. Once satisfied with their chosen level, they pressed the knob to initiate the subsequent trial. There was no time limit for this adjustment other than the song's duration. On average, the participants spent just less than 1 min per trial. Consequently, the entire experiment, comprising 120 trials, took around 2 h to complete.

3. Results

Figure 3 displays the results, with each panel dedicated to a specific song. The data represent the change in sound level relative to the audio-only condition. A negative value supports our hypothesis that the presence of tactile vibration leads

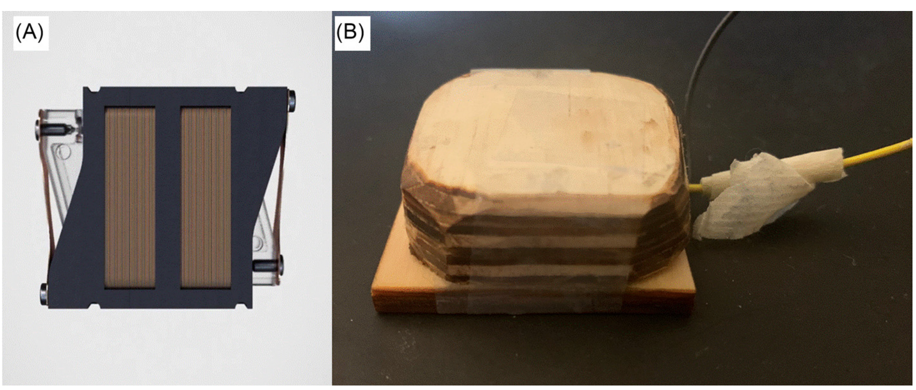

Fig. 2. (A) Lofelt L5 actuator; (B) encapsulation case.

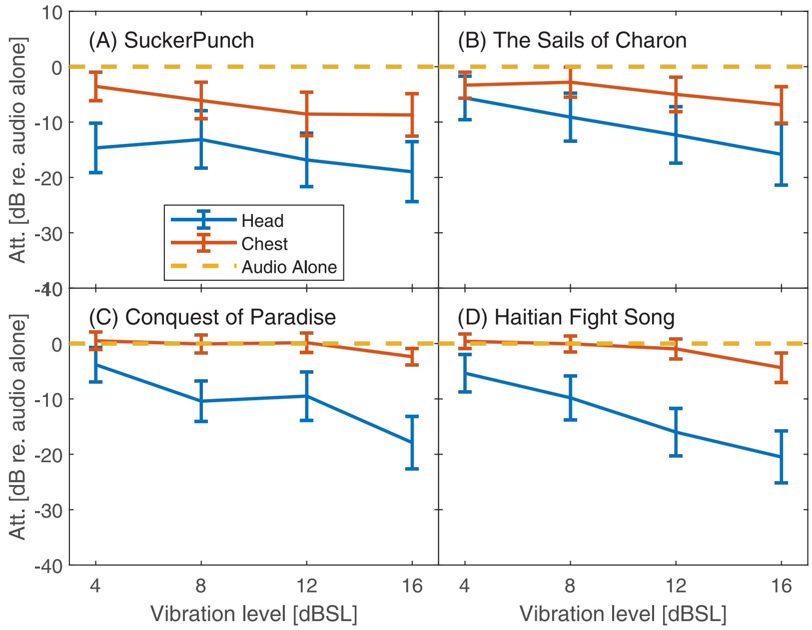

Fig. 3. Experimental results for each song, comparing audiotactile conditions to audio-only. Negative values indicate a reduced volume in the presence of vibration. Actuator locations (head and chest) are differentiated by color. The error bars represent the standard error.

participants to decrease the volume level. Across the board, participants either retained the same level as in the audio-only scenario (zero attenuation) or reduced the volume in the audiotactile conditions (negative value). Strikingly, conditions with the actuator on the head resulted in substantial reductions in volume for all songs and at all vibration levels. Additionally, we observed a monotonic relationship between the level of vibration and the extent of attenuation: Higher vibrations led to greater reductions in volume. A repeated-measures analysis of variance (ANOVA) was conducted on the attenuation level, involving three main factors: song ($df = 3$), vibration level ($df = 3$), and actuator location ($df = 1$). According to the results of the Anderson–Darling test, the studentized residuals of the model were found to conform to a normal distribution, as indicated by a highly significant p-value ($p < 0.0001$). All main factors showed significance [song: $F(3, 42) = 3.6586, p = 0.0198$; level: $F(3, 42) = 7.8787, p = 0.0003$; location: $F(1, 14) = 11.3436, p = 0.0046$], along with a significant three-way interaction [$F(9, 126) = 2.5228, p = 0.0227$]. Selected *post hoc* analyses were then conducted on a song-by-song basis to examine specific features.

In the song "SuckerPunch," a volume reduction can be observed for all tactile conditions, reaching an attenuation close to 20 dB when the actuator was placed on the head with maximum vibration. The ANOVA analysis of this song demonstrated a significant effect exclusively related to location [$F(1, 14) = 7.9141, p = 0.0138$], with no significant effects detected for the level. The data from the chest area significantly differed from zero [$t(14) = -2.53, p = 0.024$], indicating that vibrations, even in the absence of bone conduction, played a role in reducing the preferred listening level. For "Sail of Charon," the ANOVA revealed a significant effect only for the vibration level factor [$F(3, 42) = 3.68, p = 0.0193$]. When analyzing the level as a continuous variable, a regression line revealed a slope of –0.58. This suggests that, on average, there was a decrease in 0.58 dB in the preferred volume level for every additional dB of vibration. In the case of "Conquest of Paradise," the analysis showed significant effects for both location [$F(1, 14) = 9.0033, p = 0.0095$] and level [$F(3, 42) = 7.7403, p = 0.0003$], as well as a notable interaction between these two factors [$F(3, 42) = 5.0126, p = 0.0046$]. This interaction implies that the effect of the vibration level is dependent on location. Focusing solely on chest data, the level effect remains significant [$F(3, 42) = 3.6466, p = 0.022$], but this is driven exclusively by vibration 16 dBSL, which is the only level significantly different from zero ($t < 0.05$). A regression analysis conducted on the data from the head revealed a model as $-1.03 * Level - 0.08$. This indicates that there was a corresponding attenuation of approximately the same magnitude for each additional dB of vibration. A similar pattern emerged with "Haitian Fight Song." The analysis revealed a significant interaction between level and location [$F(3, 42) = 4.6965, p = 0.0065$]. Additionally, examining only the chest data showed a significant level effect [$F(3, 42) = 4.5189, p = 0.0078$], attributed to vibration at 16 dBSL ($t < 0.05$). Similar to the previous song, the regression analysis of the data from the head yielded a slope close to 1, specifically $-1.29 * Level - 0.01$.

4. Discussion

In this study, when the actuators were positioned on the headphones, they elicited both tactile vibrations on the skin and cochlear vibrations through bone conduction. While the former was perceived as a direct tactile sensation, the latter translated into an augmented energy within the cochlea, subsequently leading to an apparent increase in loudness. Quantifying the specific increase in energy within the cochlea attributable solely to the actuator is a complex task (Stenfelt, 2016). Nevertheless, considering that the vibration of the actuator was oriented parallel to the skin, as opposed to the perpendicular alignment commonly seen in standard bone conduction devices, it can be reasonably suggested that this approach might be less effective in energy transmission compared to conventional bone conduction techniques.

Comparing the results when the actuator is placed on the chest with the results on the head can help us disentangle the effects of vibration from bone conduction. If the attenuation were solely due to bone conduction, we would expect (1) no effect when the actuator is located on the chest and (2) an equivalent attenuation and vibration level when the actuator is on the head, indicated by a regression line with a slope of -1 and an intercept at 0, assuming an ideal bone conduction transfer function. However, as Stenfelt and Håkansson (2002) showed that for every 10 dB increase in airborne auditory stimuli, there is a corresponding rise of 8–9 dB in bone conduction to achieve a similar loudness, a shallower slope around –0.85 could also be expected. Conversely, if the attenuation were due to a combination of vibration and bone conduction, we would anticipate (1) a larger effect on the head than the chest, as vibrations are more strongly felt on the head (Corniani and Saal, 2020), and (2) for both locations, an increase in attenuation with vibration level, with the slope potentially being any negative value.

Based on our results, the songs "Conquest of Paradise" and "Haitian Fight Song" almost entirely exhibit the behavior expected for attenuation caused purely by bone conduction, although a small but significant attenuation is observed at maximum vibration levels. On the other hand, for songs with a strong rhythm like "SuckerPunch" and "The Sails of Charon," the pattern of results clearly suggests at least a contribution from vibration, showing an effect of cross-modal enhancement. Specifically, when considering only the data for the chest on these two songs, we found an attenuation that could reach up to 8.7 dB. This is a relatively large effect compared to the effect of loudness enhancement found in previous studies (Schürmann *et al.*, 2004) that showed the loudness level of sound can be enhanced by about two phons when presented with a congruent vibration. This result suggests that the influence of vibration on the preferred listening level may be attributed to factors beyond mere amplification of loudness, potentially including enhanced musical immersion.

5. Limitations of the study

Our perception of vibration is limited to a range of up to 1 kHz (Prsa *et al.*, 2021). As a consequence, only low-frequency sounds can be effectively conveyed through vibrations. In our experimental design, the levels of high-frequency components were predefined, leaving participants with the exclusive capacity to manipulate the low-frequency aspect. This manipulation resembles an equalization (EQ) task, where participants increase low frequencies until satisfactory sound quality is achieved.

When comparing results obtained with the actuator placed on the head vs on the chest, it is important to consider the varying density of mechanoreceptors, specifically Meissner's and Pacinian corpuscles, which are responsible for encoding vibration sensations across different body parts. Given that the facial area has approximately seven times higher innervation density than the upper trunk (Corniani and Saal, 2020), the observed differences in results between the chest and the head could be attributed to a relatively less sensitive response in the chest area.

6. Conclusion

This study explored the impact of audiotactile feedback on preferred listening levels across various musical genres. Our findings corroborate the hypothesis that incorporating tactile vibrations can effectively reduce preferred listening levels, potentially mitigating the risk of noise-induced hearing loss. This effect is particularly strong for songs with pronounced beats. It persists even when the actuator is positioned on the chest, thus, eliminating the possible influence of bone conduction. On the other hand, for songs without strong beats, only a marginal effect is found when the actuator is placed on the chest, and the vibration level is high.

Overall, this finding is relevant for practical applications, such as designing headphones with integrated actuators, where an optimized vibration level could lead to safer listening practices. For DJs or individuals in noisy settings at risk of hearing loss, such technology could be particularly beneficial.

Acknowledgments

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Author Declarations

Conflict of Interest

The authors disclose a potential conflict of interest. The study was part of E.L.'s master's project, supervised by J.M., in collaboration with headphone company Jabra. Two employees of Jabra, Kostas Gkanos and Sidsel Marie Nørholm, cosupervised the project and advised on the experiment design but did not participate in data analysis or results interpretation.

Ethics Approval

The experiment was approved by the Science-Ethics Committee for the Capital Region of Denmark (reference H-16036391).

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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