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Vibro-Acoustical Beats: Inducing Auditory Perception Through Whole-Body Vibration

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ABSTRACT

People experience whole-body vibration (WBV) in many situations in daily life. Most of the time the vibrations occur simultaneously with acoustical signals, as both vibration and sound stem from the same source. This leads to multi-modal effects between WBV and sound that can be exploited for the design of multi-modal virtual environments and effect the overall perception of, for example, comfort in multi-modal situations such as riding in a car or attending a concert. It has been speculated that low level WBV lead to auditory cues which might influence the outcome of vibration experiments. This study uses an indirect approach to prove this hypothesis. The concept of binaural beats is broadened to vibro-acoustical beats. The simultaneous presentation of two sinusoidal signals with a few Hertz difference between headphones and whole-body vibration leads to the auditory perception of beats. This was tested with two different sound levels across five different frequencies from 31.5 to 125 Hz. By comparing the results of the vibro-acoustical beats with purely acoustically generated beats, it can be concluded that clearly perceivable vibrations approximately 10 to 15 dB above perception threshold lead to faint sound impressions approximately 17 to 20 dB less than the acoustical reference.

1. INTRODUCTION

In everyday life, people are exposed to vibrations in many situations, which cause the entire body to vibrate through contact with a source of vibration. These whole-body vibrations occur while a person is sitting or standing on a vibrating surface, for example in a vehicle or during a concert.
Most excitation sources generate vibrations, which in turn often lead to parallel noise radiation. They are thus directly causally related. Humans usually perceive such sources both in the auditory and tactile domain. For example, the engine in the vehicle is not only audible, but the occupants also perceive the vibrations. Visitors of a concert do not only hear the bass, but feel it all over their bodies if the sound level

exceeds a certain level. The perception of sound, however, is not exclusively restricted to airborne sound, but can also take place via bone conduction. Vibrations are transmitted via the skull bone directly to the inner ear, without first crossing the outer and middle ear like direct airborne sound. If the airborne sound is sufficiently strong or if vibrations are transmitted through the skeleton, the skull bone is stimulated to vibrate. This stimulates the hair cells in the cochlea and transmits corresponding acoustic impulses to the brain[1,2].

In the analysis of studies on the perception of whole-body vibrations, it is assumed at various points in literature that bone sound triggered by vibratory stimulation influences the study result[3–5]. Since bone conduction is very difficult to measure directly, indirect evidence of vibro-acoustical triggered beats effects will be provided here. Two tones with only slightly differing frequencies can be perceived as one tone with a fluctuating maximum at the mean frequency[6]. This effect is perceived strongest at a 4 Hz difference between the two frequencies[7,8]. It occurs both when the superposition of both signals reaches one or both ears simultaneously (beats) and when one of the two frequencies is reproduced dichotomically at each ear and the superposition only occurs in the brain (binaural beats). A pilot study[9] proved the possibility to create vibro-tactile triggered beat effects. In this study we will explore the methodology in more detail and with a broader set of parameters[10].

2. EXPERIMENTAL SETUP

Vibro-tactile beats thresholds were measured using two different sound levels of the acoustical references across five frequencies. The subjects got written instructions prior to the experiments and could discuss them with the experimenter. The experiments took part in multiple sessions, depending on the concentration and fatigue of the subjects. The vibration seat was calibrated individually for each subject and every session that involved WBV. During the first session the perception threshold for all five frequencies was measured in randomized order. The subjects were then presented with different examples of acoustically presented beats to familiarize themselves with the sensation of beats, before they measured the vibro-acoustic beats threshold. The majority of the subjects came back for a separate session and repeated the beats detection experiment in an acoustic-only condition in order to approximate an order of magnitude of the acoustic perception generated through vibration.

2.1. Apparatus

The two main components of the measuring setup are the vibration chair for generating the whole-body vibration and the test PC for controlling and storing the measurement data. The stereo output of the PC's internal sound card is used to play back all vibration and audio signals. One channel is used for the headphone signal and the other one for the shaker signal. An Alesis RA150 audio amplifier amplifies the vibration signal, the headphone signals remain unamplified. Figure 1 illustrates measurement setup.

The vibration seat without backrest is constructed on the basis of an electrodynamic shaker. It consists of a cuboid wooden foot on which a shaker is placed. A seat plate of 46x46 cm is mounted on the shaker piston. The plate is supported by strong springs supported on the shaker housing. Thus the piston is approximately at the working point when a subject sits on top. The test persons sit upright on the vibration seat and their feet are in contact with the ground. In order to ensure that the thighs are aligned parallel to the seat surface and the lower legs are angled at 90 degrees, any distance between the feet and the floor is eliminated with compensation plates. The test persons wear normal everyday clothes and footwear during the test. A Kistler 8636C10 accelerometer, which is fixed to the lower end of the piston, records the

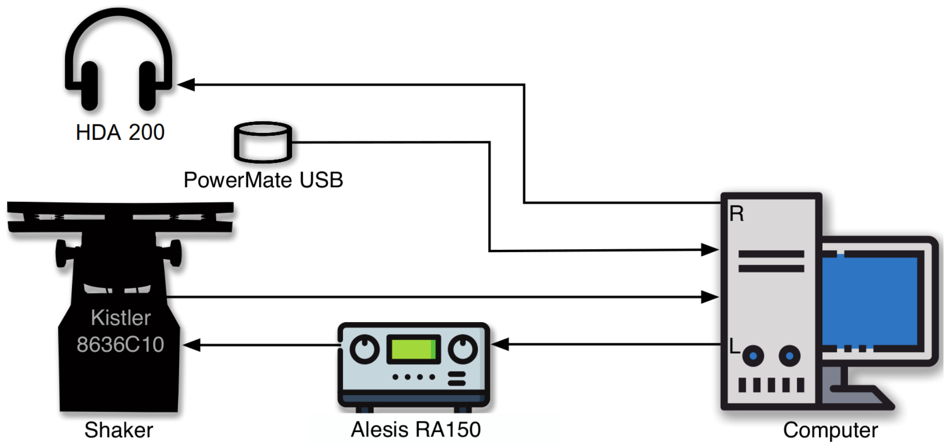

Figure 1: Schematical presentation of the experimental setup

vibrations in z-direction. In order to enable the test subjects to control the test parameters, a PowerMate endless controller is used. Sennheiser HDA200 headphones are available for acoustic reproduction of the stimuli. Thanks to their closed design, they attenuate any ambient or radiated noise of the vibration chair. The frequency response of the entire transmission system is not smooth, but has pronounced maxima and minima, which are particularly dependent on the person sitting on the vibration seat. This transfer function is known as the Body Related Transfer Function (BRTF)[11]. To compensate for this effect, the BRTF is measured for each subject directly before the experiment and all stimuli are equalized and calibrated during the experiment using inverse filters based on the BRTF.

2.2. Methods

In a first session the perception thresholds for each of the five frequencies tested was measured, using an adaptive 3AFC 1up-2-down method. During the main experiment the subjects used a method of adjustment to evaluate the perception of the vibro-acoustical beats. The acoustical reference signal was played back continuously at a fixed sound pressure level for each stimulus. The tactile feedback was reproduced simultaneously starting at an arbitrary vibration level. The task of the subject was to adjust the level of the vibration with the infinite controller until they just perceived a beating sensation. They were instructed to push the controller, once that level was reached, thus logging the value and starting the next stimulus. The frequencies and sound pressure level combinations were presented in random order. Each stimulus was presented five times. This beats detection experiment was then repeated in an acoustic-only condition, meaning the second frequency was not presented as a vibration, but was played back via headphones, too.

2.3. Subjects

All subjects participated voluntarily and were not paid. They indicated that they do not know of any spinal conditions. Out of the 28 subjects for the vibro-acoustic experiment 7 were female. Their average age was 28 years old (22 - 41 years old). The average body weight was 71.3 kg (51 - 85 kg) and the body height 177 cm (160 - 194 cm), the respective BMIs ranged between 19.9 and 27.7 kg/m^2.
20 subjects out of these participated in the acoustic-only beats experiment; 5 of these were female. Their average age was 27.2 years old (23 - 35 years old). Their average body weight was 70.8 kg (51 - 85 kg) and their body height 181 cm (160 - 194 cm), the respective BMIs ranged between 19.9 and 25.9 kg/m^2.

2.4. Stimuli

The two sinusoidals presented simultaneously to create the beating sensation had a four Hertz difference. The sinusoidals covered the frequency range from 31.5 to 125 Hz covered in half-octave steps. The acoustical reference was presented at two different levels, leading to ten different combinations as shown in Table 1. All combinations were measured five times, each, for the vibro-acoustical condition as well as the acoustic-only condition.

Table 1: Overview of the chosen parameters

Frequency	Presentation	Level
31.5 / 45 / 63 / 90 / 125 Hz	vib-ac: WBV / ac. only: both ears	variable
35.5 / 49 / 67 / 94 / 129 Hz	both ears	40 / 60 phon

Calibrating the headphone signal using an KEMAR artificial head led to inconsistent results across multiple measurements for frequencies below 125 H as the ears could not be covered entirely and different positions of the headphones led to different results. Measurements without the ears provided consistent results but deviated from the with-ear-measurements. Additionally the resulting signals were not perceived as equally loud across the frequency range. Thus the 125 Hz calibrated sound pressure level was taken as reference and the lower frequencies were calibrated manually using the mean of five subjects who adjusted the other sounds using a method of adjustment.

3. RESULTS AND DISCUSSION

All subjects experienced the beating sensation for every parameter combination. Asking the subject to just slightly get up from the vibration seat to eliminate the WBV after they perceived vibro-tactile beats, made the beating sensation disappear. This eliminates the faint airborne sound from the shaker as the source for the beating sensation.
The results of the beat-detection experiments are evaluated using a three-factorial variance analysis (ANOVA). Table 2 displays the results for each main factor frequency (F), measurement repetition (No) and headphone level (SPL) as well as their interactions.

3.1. Vibro-acoustical beats

For vibro-acoustical beats each of the main effects is highly significant, with $p < 0.001$. For the main effect frequency, as well as for the third-order interaction, a Mauchly test is positive, which is why the Greenhouse Geisser correction is applied. In addition, there are two significant interactions of the first order, namely between frequency and repetition as well as between frequency and headphone level.

3.1.1. Main effects

The left panel of Figure 2 shows vibration level above threshold (dB SL) needed to create the impression of beats for each frequency across all repetitions. Mean and standard deviation are shown, as well as a beeswarm plot to indicate individual results. While at 31.5 Hz on average only about 10 dB SL are

Table 2: Results of the three-factorial ANOVA for both beating experiments. Significant results are marked by an asterisk.

	Vibro-Acoustical Beats		**Acoustical beats**	
Factor	**Correction**	**p-value**	**Correction**	**p-value**
F	Greenhouse-Geisser	0.000 *	Greenhouse-Geisser	0.076
No		0.000 *		0.617
SPL		0.000 *		0.000 *
F*No		0.009 *		0.328
F*SPL		0.000 *		0.327
No*SPL		0.766		0.111
F*No*SPL	Greenhouse-Geisser	0.474	Greenhouse-Geisser	0.648

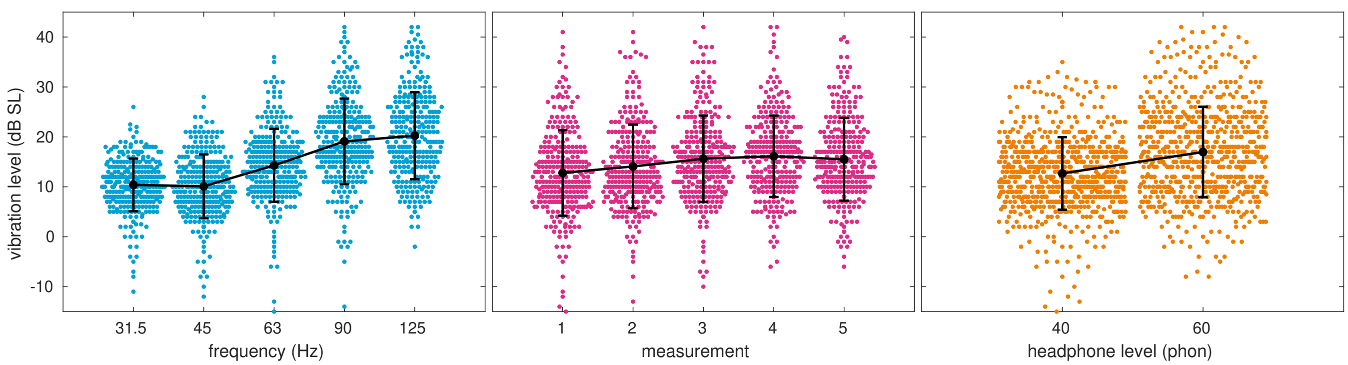

Figure 2: Main effects for the vibro-acoustical beats experiment. Mean values, standard deviations and distributions of the set acceleration levels (dB SL) as a function of each of the main effects; colored beeswarm plots illustrate individual data points.

recorded, the vibration level to create a beating sensation rises up to 20 dB for 125 Hz. The results thus follow those of the pilot study. However, the mean results are lower, which might be attributed to the different methodology. The inter-individual difference increases slightly with frequency. A post hoc test shows a significant difference for all frequencies except between 31.5 Hz and 45 Hz as well as between 90 Hz and 125 Hz. The middle panel shows the influence of the repetition. With each of the first four repetitions, the test subjects need a slightly higher acceleration level to perceive the beating sensation. The mean of the last measurement slightly declines compared to the fourth measurement. The standard deviation does not change across repetitions. Pairwise post-hoc testing indicates significant differences between the first two and the fourth presentation, but no significant differences to the last presentation. So, while there are small differences between the measurements, there does not seem to be a general trend to increasing vibrations levels needed over time. Just as with frequency and repetition, the headphone level has a significant effect on the vibro-acoustic beats experiment. With increasing head phone level an increase in vibration level is needed to still perceive the vibration. The increase of the headphone level of 20 dB leads to on average to an increase of 5 dB vibration level in order to produce the beating effect.

3.1.2. Interaction effects

Figure 3 visualizes the interaction effects between headphone level and frequency, plotting the vibration level needed to perceive vibro-tactile beats across frequency for each of the headphone levels tested separately. The third panel on the right visualizes the mean values of both headphone level conditions for easier comparison. For both headphone levels tested, the vibration level increases with increasing frequency. There is little difference in vibration level needed for 31.5 and 45 Hz, but the slope of the increase of vibration level differs for higher frequencies leading to a 10 dB difference for 125 Hz. This can be explained by the compressed dynamic range of WBV towards higher frequencies, as intensity perception decreases with increasing frequency[12].

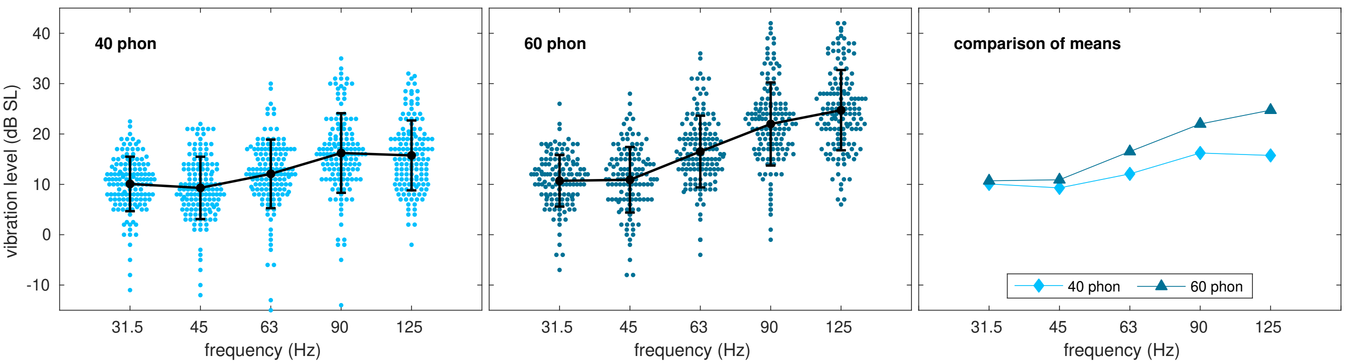

Figure 3: Interaction effect between frequency and headphone level for the vibro-acoustical beats experiment. Mean values, standard deviations across subjects and repetition; colored beeswarm plots illustrate individual data points.

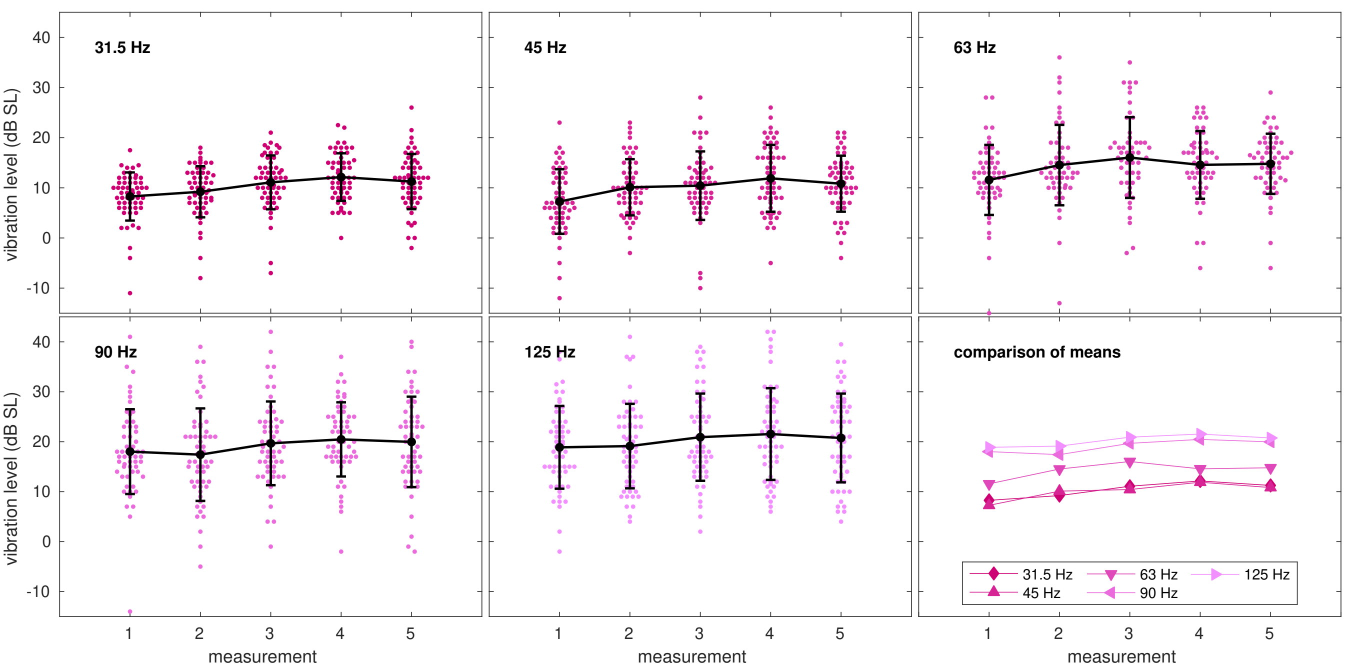

Figure 4: Interaction effect between frequency and repetition for the vibro-acoustical beats experiment. Mean values, standard deviations across subjects and headphone levels; colored beeswarm plots illustrate individual data points.

The effect of repeated measurements is plotted separately for each frequency in Figure 4. Again, the last

panel in the lower right corner compares the mean values across the different frequencies. For the lower frequencies the vibration level steadily increases up to the fourth repetition, while the initial increase is steeper for 63 Hz and does not increase after the third presentation. For the upper two frequencies the overall increase in vibration level needed is not as big and the mean remains stable from the third measurement on.
The interaction between repetition and headphone level is not significant, indicating that the effect across repetition is the same independent of the headphone level used.

3.2. Acoustical beats

As shown in Table 2 for acoustical beats only the effect of headphone level is significant ($p < 0.001$). None of the interaction effects is significant ($p > 0.05$).

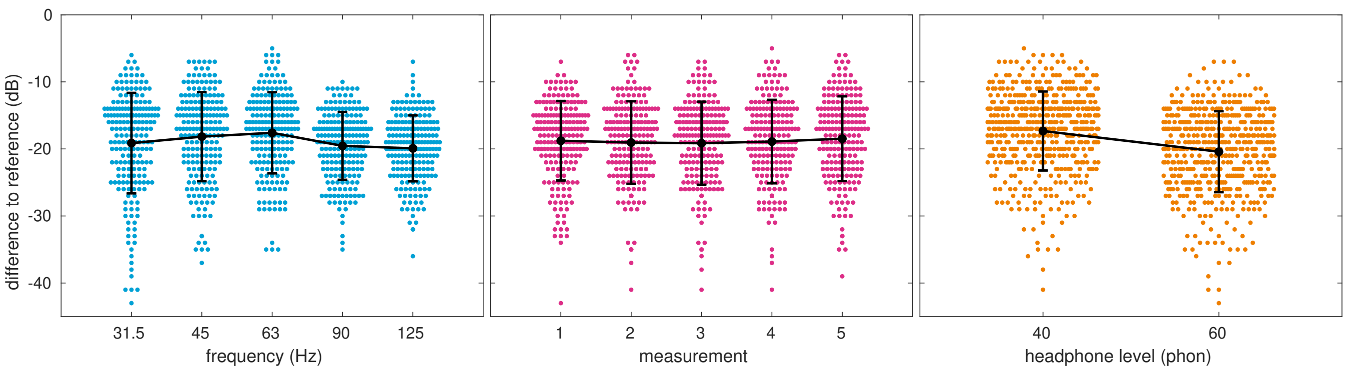

Figure 5: Main effects for the acoustical beats experiment. Mean values, standard deviations and distributions of the set difference to the reference tone level (dB) as a function of each of the main effects; colored beeswarm plots illustrate individual data points.

Again, the three main effects are plotted side-by-side in Figure 5. The figures show the difference in sound pressure between the adjustable second sinusoidal needed to create the beating sensation and the fixed reference in decibels. Contrary to the vibro-acoustical beats experiment there is no significant influence of frequency or repetition. The standard deviation for lower frequencies is slightly higher than for higher frequencies which can be explained by smaller dynamic range and higher hearing threshold towards lower frequencies. The headphone level has a significant influence on the perception of beats. With increasing headphone level the level difference between the two sinusoidals can be decreased.

3.3. Estimation of the evoked sound level

By comparing the mean values of the results for each frequency and headphone level the amount of sound that was generated by the whole-body vibration an estimate can be attempted. Looking into the results of the experiments in detail this does not prove to be an easy linear relation. Independent of frequency the level of the second sinusiodal to produce the beats sensation was about 17.3 dB below the 40 phon reference and 20.4 dB below the 60 phon reference. As the dynamic range for low frequencies is smaller for lower frequencies this would approximate to a loudness from 10 phon for 31.5 Hz to 20 phon for 125 Hz for the 40 phon reference and 20 to almost 40 phon for the 60 phon reference. The mean vibrational level needed to create vibro-acoustical beats was strongly dependent on frequency and reference tone level as shown in Figure 3. Even though very few individuals perceived vibro-acoustical beats for vibration levels very close to the perception threshold for WBV, the majority of subjects needs clearly perceivable vibration 10 to 20 dB above threshold depending on the frequency. But although the acoustic beats experiment lead to different sound pressure levels producing the beating sensation for 31.5 and 45 Hz, the same level of vibration is needed to create vibro-acoustical beats for these two frequencies. This implies that, depending on context, the same vibration level leads to differing acoustical impressions. Only at higher frequencies do the vibration levels needed to provoke beats diverge. Thus, based on the data of these experiments there is no general conversion from vibration level to evoked sound level possible.

4. CONCLUSION

Vibro-tactile beats prove that WBV can evoke a sound perception. An ANOVA reveals significant influence of frequency, repetition and headphone volume on the vibro-tactile beats effect. Depending on the frequency, the beating effect started on average at an acceleration level of 15 dB above the individual perception threshold. However using the results a second experiment with the same methodology and acoustic-only stimuli does not lead to direct link between vibration level exposition and sound level evoked. Clearly perceivable vibration of 10 to 15 dB above individual thresholds generated the same beats effect as acoustically presented sinusoidals of the same frequency of 17 to 20 dB below the 40 and 60 phon acoustical reference.

Future examinations should include the influence of the upper body posture as well as the head posture. Subjects were reminded to sit upright during the experiment, but were not fixated in that position. Some test persons stated that a slight change in the head posture would lead to a shift in perception.

The initial hypothesis was that the evoked sound is bone conduction which is supported by the influence of body posture. However it has to be kept in mind that this experiment is not a direct proof of bone conduction. Even though sound perception was evoked it cannot be concluded whether the sound was produced by stimulating the cochlear through bone conduction similar to regular beats, or whether this is achieved by stimulating sound-related areas in the brain similar to binaural beats or a combination thereof.

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