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Do headphones make the difference? Quality of audio devices change the hearing experience

A thesis presented by

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Dedication

To God, because He gave me the strength to continue during difficult times.

To my mother, because without her love, I would not have accomplished many things.

To my father, because without his help, I could not have finished my studies.

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Abstract

The perception of sound can differ significantly, regardless of its physical properties. The frequency content of a sound can provoke different psychoacoustic effects in humans and, at the same time, modulate differently the electrical waves of the brain. Audio devices such as headphones are variables that have not been taken into consideration in many studies concerning acoustic therapies, which strongly depend on the transmission means. Headphones become a fundamental key in acoustic treatments since they are responsible for transmitting the auditory stimulus. It is known that the frequency response of audio devices can change the frequency content of a signal. However, it is still unknown if their limited or even inappropriate functioning could affect acoustic therapy effectiveness. Therefore, the present work aims to explore the neurophysiological responses of the brain in healthy individuals listening to the same sound but in different headphones. For this purpose, three different frequency responses corresponding to three headphone brands (ATVIO, SHURE, and APPLE) were characterized in three different auditory stimuli. Participants who took part in the experiment were asked to differentiate among three stimuli in several sequences, while their electroencephalographic response was monitored. Headphones with a flatter frequency response (SHURE) provide more acoustic information to be interpreted by the brain. In turn, more information codification demands a larger number and a wider variety of mental resources. As a case in point, the transient neural response observed during an auditory discrimination task revealed that headphones with a flatter frequency response (SHURE) did not only activate lobes associated with decoding the physical properties of the sound and interpretation of auditory information (respectively, temporal and frontal lobes), but they also activated the region related to the spatial sense of human beings (parietal and occipital lobes).

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Chapter 1

Introduction

Audio systems as headphones, loudspeakers, computers, smartphones, and microphones can alter the frequency content of an audio signal. This alteration is caused by the quality and design of their components. In most cases, headphones or audio interfaces that do less modification to the sound are more expensive because they are built with more sophisticated pieces, for example, best-quality sound cards and headphones used for professional music (post) production like mixing and mastering. In particular, headphones are devices widely used in acoustic therapies. A common application of these therapies is to treat subjective tinnitus, a phantom sound caused by abnormal neural activity.

1.1 Motivation

This research project was proposed after exploring the results of a previous study concerning the reduction of tinnitus perception through acoustic therapies. The Neuroengineering & Neuroacoustics research group at Tecnológico de Monterrey conducted the study, testing four acoustic treatments and placebo therapy. The placebo therapy consisted of relaxation music combined with binaural sounds. Patients with this therapy reported a slight aggravation in the perception of tinnitus. Furthermore, one participant reported a reduction of tinnitus perception after using audio devices with an active noise-canceling feature. After reviewing related literature to explain this phenomenon, two key points were raised: 1) frequency of an auditory stimulus can suppress or accentuate the perception of tinnitus, and 2) standardization of audio devices for tinnitus treatment has not been undertaken. For these reasons, the present research aims to study the effect of frequency modification of sounds due to audio devices on the auditory nervous system.

1.2 Problem Statement and Context

Audio devices such as headphones, sound generators, and hearing aids are used in acoustic therapies to treat different auditory conditions such as chronic subjective tinnitus (CST). CST is defined as the condition of perceiving an unreal sound in the absence of an external auditory stimulus [1]. It affects 15-20% of the worldwide population [2]. This symptom is usually followed by stress, trouble to sleep, and incapacity to work, affecting the quality of life of the person with this condition. Tinnitus is considered subjective when the peripheral auditory system does not show an alteration, and it is objective when abnormal movement as the vibration of the tympanic membrane is observed. Subjective tinnitus is described as an abnormal neural activity due to a tonotopic change in the auditory cortex [3]. It can be perceived as a pure tone, known as tonal tinnitus, or as noise.

Different methods for reducing tinnitus perception have been developed, being most of them validated by subjective questionnaires and psychometric tests. However, new protocols for the evaluation of electrophysiological indicators have been proposed [4]. Researchers in the field have evaluated the effectiveness of therapies. Some of them had contradictory results, and acoustic treatments showed to take several months to reach effects [5–7]. Clinical devices as hearing aids or tailored earphones are necessary to apply the therapy [8,9].
Nevertheless, most studies lack informative specificities such as device model and technical specifications as frequency response. Many studies do not detail the therapy system, either

a pair of loudspeakers or headphones. The frequency response of not calibrated audio devices modifies the frequency content of a signal [10], and this could be a factor that increases or reduces the perception of tinnitus. For example, if a person with tonal tinnitus with a characteristic frequency of 8 kHz listens to an acoustic therapy with headphones that have a resonance at this frequency, the perception of the unreal sound could be increased. This overcompensation - suppression effect has been studied for its implementation in acoustic therapies but not in the devices used to play the auditory stimulus [11–13]. It is essential to consider this variable to guarantee that the sound reaches its original goal. Over time, methods have been found to reduce the perception of tinnitus. Still, its effectiveness is valued based on the experience of the patient, generally in the form of a questionnaire, and not with some physiological indicator or neural marker.

1.3 Research Questions

This study aims to answer the following research questions:

- Is it possible to detect differences in sound perception through the neural activity of the brain?
- Do headphone models change the electrical activity of the brain even if the same auditory stimulus is used?

The alternative hypothesis for this research is:

- There is a difference in the electrical activity of the brain caused by headphones with different frequency responses.

The main objective of this study is:

- To determine the effect of frequency responses of headphones in the electrical activity of the brain.

The specific objectives are:

- To identify changes in the electrical activity of the neural cortex by applying auditory stimuli with differences in the frequency domain, emulating the frequency response of three different headphone brands:
    - Atvio®
    - Shure®, and
    - Apple®.
- To evaluate neural plastic changes by habituating subjects to an auditory stimulus for one month, emulating the procedure followed for acoustic therapies.

1.4 Solution Overview

Headphones are audio tools used daily. There are different models with different properties in quality and usage. High-quality headphones may be costly because of the materials used for their creation. Commercial headphones are accessible for most of the population, but it does not justify their use in every aspect related to audio. In acoustic treatments, it may be challenging to acquire specialized audio devices. Fortunately, it is possible to find solutions that minimize the effect of quality in acoustic treatments. A solution is to implement calibration methods for in-ear headphones with integrated microphones [14] and thus, to reduce the resonances of the transfer function of the ear [15], a term that is discussed in later chapters. Another approach, which is discussed in chapter 3, is using a technique that reduces the effect of frequency responses in audio files. Subjective evaluation of individuals might be imprecise since it might be difficult to express the perception of a sense in words. Therefore, changes in neural activity caused by the frequency response of headphone models are assessed through electroencephalograms.

1.5 Main Contributions

This research contributes to the generation of new knowledge for the understanding of the human perception of sound. Results show evidence that audio devices as headphones might be a fundamental variable to improve acoustic therapies, particularly those applied for tinnitus.

1.6 Dissertation Organization

Chapter 2 describes the anatomy of the ear, the flux of auditory information into the brain, and the perception of sound in humans. It also explains the importance of the frequency response of audio devices and uses an inverse filtering technique for the calibration of headphones. Additionally, neural responses to auditory stimulation are discussed. Chapter 3 focuses on audio systems and methods that change the perception of sound, and audio devices used in acoustic therapies are carefully inspected. Chapter 4 describes the methodology used to analyze the electrical activity of the brain during auditory stimulation. Chapter 5 shows the results of the experimental paradigm, and their interpretation is discussed in chapter 6. Finally, conclusions on the performance of results are presented in chapter 7. Abbreviations and acronyms are defined in Appendix A. Variables are detailed in Appendix B. Complementary materials are presented in Appendices C-G.

Chapter 2

Background

2.1 Hearing

2.1.1 Ear Anatomy

The basic structure of the human ear can be divided into three sections: outer, middle, and inner ear. Fig 1. presents the anatomy of the ear. The outer ear consists of the pinna and the auditory canal. The pinna is a structure of the ear that redirects sound into the auditory canal and the rest of the hearing organ. It has been documented that the pinna increases sound level up to 20 dB in the range of 2 – 4 kHz [16,17], and therefore, resonances occurring in this part of the ear alter the frequency content of the sound. This alteration serves a greater purpose, such as directional cues and speech communication. Sound in the auditory canal travels as air pressure until it reaches the first part of the middle ear: the tympanic membrane. This oval-shaped membrane has a diameter of approximately 10 mm high and 8 mm wide. It transmits the incident sound to the three ossicles through vibration. The ossicles (malleus, incus, and stapes) transmit the mechanic vibration into the oval window of the cochlea. The middle ear matches the impedance of the air and the fluid inside the cochlea to transmit sound. It has been reported that the middle ear increases sound level between 20 – 35 dB to avoid the energy-transfer problem that would happen if air pressure reached the fluid in the oval window. Another part of the middle ear is the eustachian tube, and it keeps the air pressure inside the middle ear the same as in the outer ear. The inner ear consists mainly of the cochlea, the organ of Corti, and the auditory nerve.

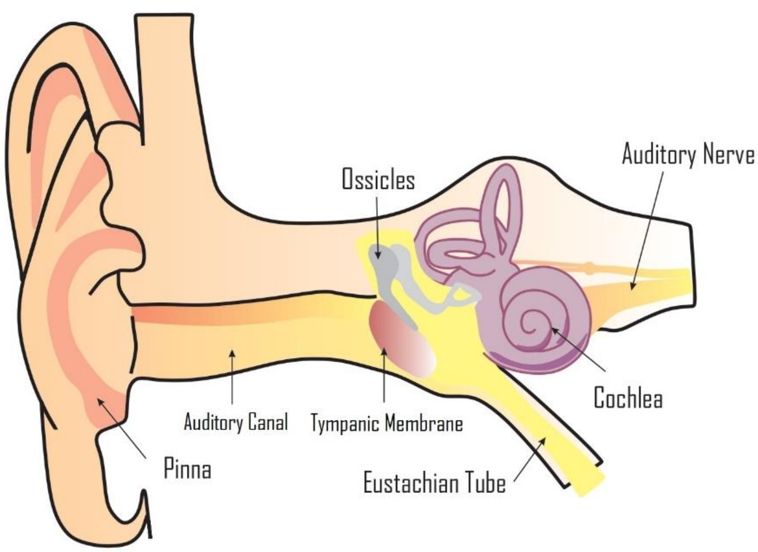


Fig. 1 Anatomy of the ear: the pathway from the external ear to the auditory nerve.

The outer part of the cochlea, called the bony chamber, is covered in bone filled with a sodium salt solution called perilymph. On the inside, in the membranous chamber, lies the basilar membrane covered in a potassium salt solution called endolymph. There is another space in the cochlea known as the round window that allows the fluid to move. As sound in the form of vibration enters the oval window, the basilar membrane starts to oscillate. The oscillation frequency can be determined according to the area where the basilar membrane vibrates and activates the hair cells in the organ of Corti. High-frequency oscillations travel only in the base of the cochlea represented in blue in Fig. 2, while low-frequency oscillations reach the apex represented in red. This is known as a tonotopic organization. The organ of Corti is placed in between the basilar membrane and the tectorial membrane, as shown in Fig. 3. It has two types of hair cells: inner and outer hair cells. Outer hair cells amplify sound according to the stimulated area of the tonotopic map of the basilar membrane. When the basilar membrane vibrates, it bends and moves the organ of Corti in direction to the tectorial membrane, causing a change in voltage at the tip of the outer hair cells called stereocilia. Activation of inner hair cells also occurs in the same way, releasing neurotransmitters through the auditory nerve with encoded information of sound in direction to the brain.

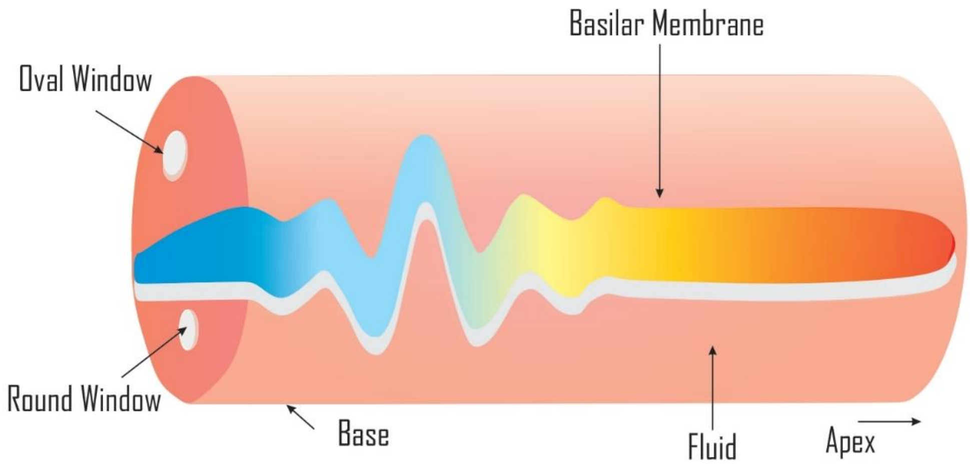


Fig. 2 Basilar membrane and inner part of the cochlea. It resonates in regions according to the frequency of sounds. The area in red resonates with low-frequency sounds, while the area in blue resonates with high frequencies.

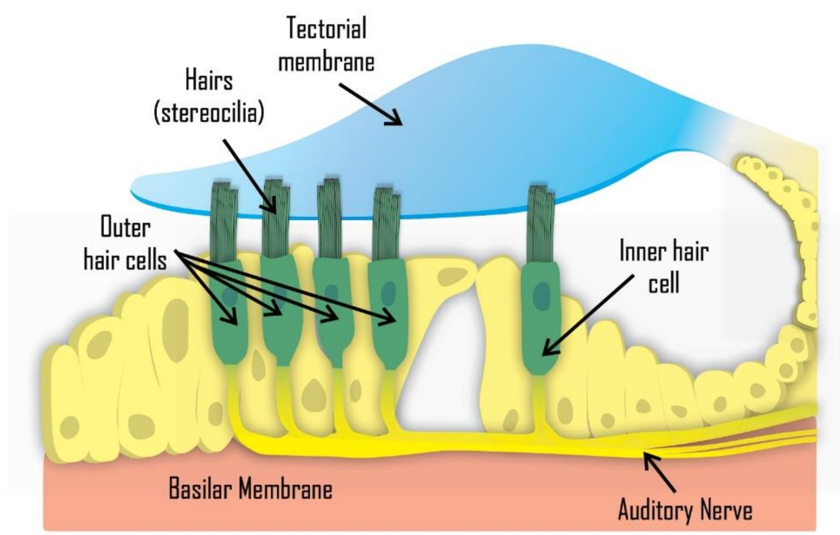


Fig. 3 Organ of Corti. This part of the auditory system sends the acoustic information to the brain as electrical impulses through the auditory nerve.

2.1.2 Central Auditory System

After the encoded information of the brain is transmitted through the auditory nerve, auditory processing includes several stages of the brainstem before reaching the auditory cortex. These stages are shown in Fig. 4. The sections of the auditory pathway involved in this process are the ventral (VCN) and dorsal (DCN) cochlear nuclei, the superior olive (SOC), the nucleus of lateral lemniscus (NLL), the inferior colliculus (IC), and the thalamus. These stages are known as the central auditory system. The auditory nerve branches to follow a parallel pathway covering many sections of the locations mentioned previously. In VCN and DCN, sound localization originates and is computed in the SOC [18]. Human beings hear in a binaural way since two ears are placed on the side of the head. Sound localization on the median plane is explained by two concepts: interaural time difference (ITD) and interaural level difference (ILD). ILD refers to the difference in level caused by a sound source being louder to one ear. This difference causes the listener to perceive the source in a position in space closer to the ear in which the sound was louder. This effect works best for frequencies of 3 kHz and higher. Below 3k Hz, ITD is best for sound localization and refers to the difference in timing on each ear caused by a sound source closer to one ear [19]. In SOC, neurons converge the auditory information of both ears, and dendrites compensate for the delay of each action potential to consolidate information simultaneously or inhibit the contralateral pathway where the sound was softer. The NLL is where the auditory information arrives after passing through the superior olive, but there is little evidence about this. Nevertheless, it is thought to be related to aspects of sound in the time domain, and only for one ear, either left or right. The auditory information continues through IC, where temporal, frequency, and spatial features are integrated before reaching the auditory thalamus, where these features start to be analyzed in frequency-time combination.

Finally, the information is sent to the auditory cortex, shown in Fig. 5, which lies in the temporal lobe. The cortex can be divided mainly into two sections: the primary auditory cortex (A1) and the secondary auditory cortex, made up of the belt and parabelt. A1 has a tonotopic organization. The belt and parabelt are less tonotopically arranged. The whole auditory cortex has neurons that process the frequency content, such as pitch, which is really important for music and speech understanding. However, the auditory cortex does not alone give humans the interpretation of hearing. It has also been reported that the auditory cortex can complete missing information with previous knowledge, such as the dominant frequency of auditory stimuli [18]. Nowadays, the understanding of the auditory cortex at an anatomical level is still being explored. Yet, neural oscillations in these regions have been studied, showing that brain waves could contain information related to rhythm, movement, attention, and location in space. This might imply that other cortical regions, such as motor and visual areas, are connected to the temporal region to understand sound fully.

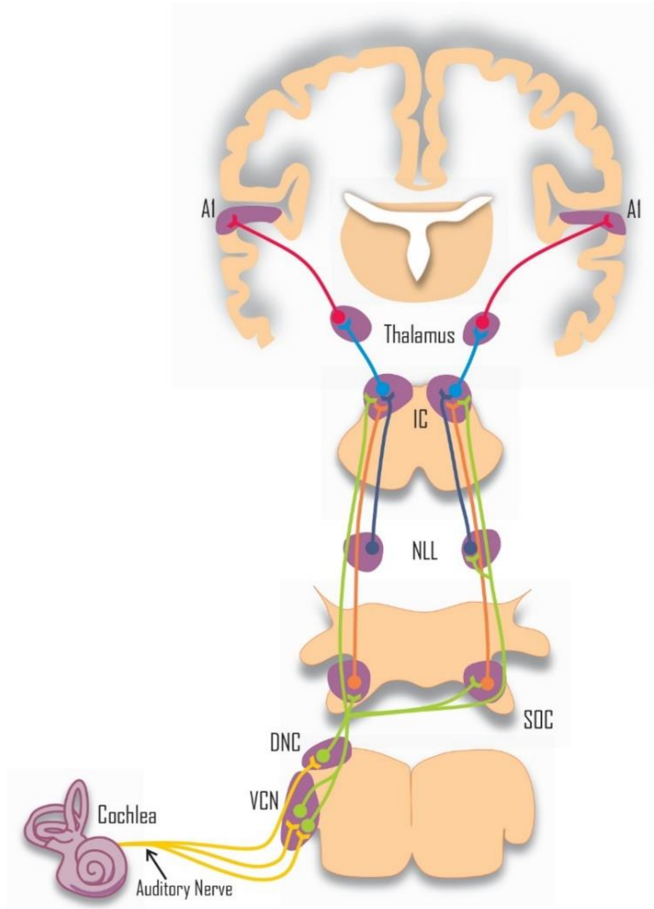


Fig. 4 Central auditory system: from auditory nerve to auditory cortex. The acronyms used for the figure are defined as follows: ventral and dorsal cochlear nuclei (VCN and DCN, respectively); superior olive (SOC); the nucleus of lateral lemniscus (NLL); inferior colliculus (IC), and the primary auditory cortex (A1).

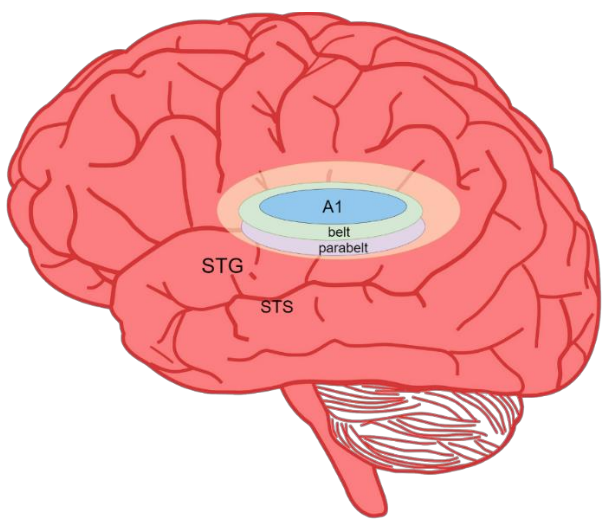


Fig. 5 Auditory cortex. This region is divided into: the primary auditory cortex (A1), the belt, and the parabelt. A1 is mainly arranged in a tonotopic way, implying that it processes most of the acoustic information in the frequency domain. A1, the belt and the parabelt are interconnected for better processing of auditory information.

2.1.3 Sound Perception

Sound can be broadly defined as a traveling wave in the form of vibration or the interpretation of acoustic waves and their characteristics. Here, the word “interpretation” is used because all sound knowledge is based on human perception. It can be studied in the physical and psychological realms. In physical acoustics, sound is studied in components of waves such as amplitude, frequency, and phase; and in parameters as sound pressure level, energy, and frequency content [20]. In psychoacoustics, a branch of psychophysics that studies the human auditory perception, sound is studied in components of loudness, pitch, and length; and in psychoacoustic features such as timbre, roughness, sharpness, and position in space [18,21,22]. It is essential to distinguish between psycho- and physical acoustics when the human perception of sound is being studied. For example, physical acoustic measurements can be performed in audio systems, such as microphones, loudspeakers, and rooms. Nowadays, it is possible to calibrate audio devices by measuring the transfer function of the system and the frequency response of devices.

Calibration is an important step in the use of an audio system because it ensures that audio devices reproduce sound correctly. The frequency response shows how an audio device changes the frequency content of a signal. The transfer function characterizes all the frequency responses of devices in a system. A calibrated system compensates or attenuates unintended alterations of devices. This might seem easy to perform for the audio system, but it does not mean that the final receiver, a human being, would perceive the sound correctly.

As another example, white noise and pink noise will be compared. White noise sound contains all the frequencies in the hearing range: 20 – 20 kHz. The frequency content of this signal can be observed in Fig. 6. It is used for the analysis of audio devices. An audio system that does not alter the frequency content would show the same graph after being measured, meaning that the sound level is equal at every frequency. In the case of a human being, loudness, the psychoacoustical homologous of sound level, would be greater in the high-frequency range. This phenomenon is observed in the equal-loudness contours shown in Fig. 7, curves generated with a MATLAB function from Tackett [23]. Based on the work of Fletcher and Munson [24] and the international standard ISO 226 [25], these curves describe the perceived loudness level by humans. It shows the required level for a particular frequency to be perceived as equally loud as another. For example, 100 Hz at approximately 80 dB is equally loud to 1 kHz at 60 dB. Humans need less sound pressure level in the range of 1 – 6 kHz than frequencies outside this range. Therefore, if a sound that has the same level at every frequency is presented to a person, the high-frequency range could be perceived as very loud and might make the listener feel uncomfortable.

For this reason, and because human ear integrates logarithmically, another type of noise that balances the perceived loudness has been designed. It is known as pink noise, and the frequency content can be observed in Fig. 6. This color of noise reduces 3 dB each octave and gives the listener the impression of an equally loud, or flat, sound [26].

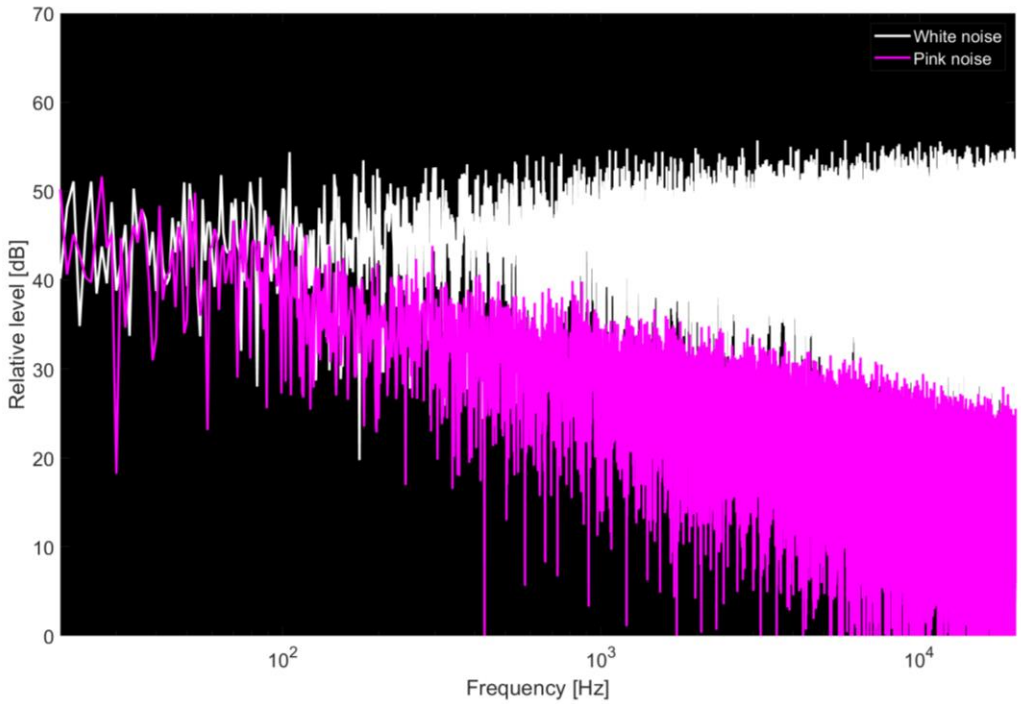


Fig. 6 Frequency content of white (white signal) and pink (pink signal) noises. As can be observed, pink noise follows a logarithmic behavior as human hearing.

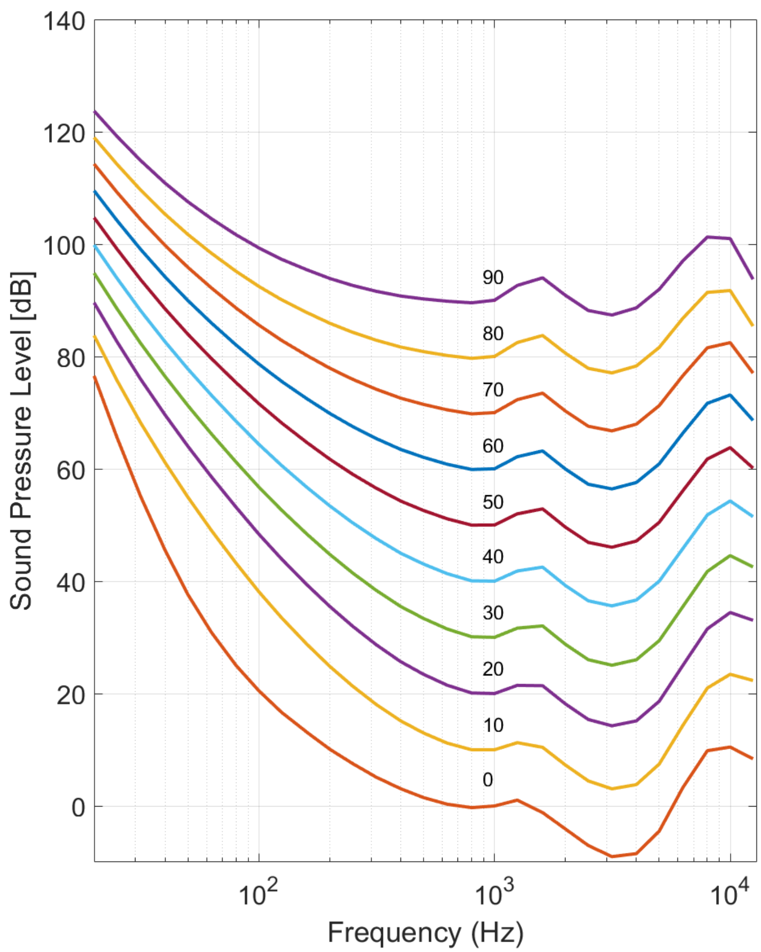


Fig. 7 Equal-loudness contours. This figure shows the level required for each frequency to be perceived as equally loud. Reference is set to 1 kHz.

It has been documented that the frequency content of a sound modifies another feature in perception: position in space. As mentioned earlier, the pinna and the auditory canal can alter sound frequency content due to resonances. Still, other parts of the body, such as the head and the torso, produce the same phenomenon, which has been referred to as either the transfer function of the auditory system or Head-Related Transfer Function (HRTF) [17]. Blauert explored the effect of specific ranges of sound in the perception of a source in space [27]. Subjects were asked to indicate the position of 1/3-octave noise pulses in space with modified frequency content. He identified that specific frequency ranges are important in spatial hearing. Frequency ranges of 300 - 600 Hz and 3,000 – 6,000 Hz are dominant in the perception of a source in front of the listener. Range of 8,000 – 9000 Hz gives the sensation of a sound coming over the head, and ranges 800 – 1,800 Hz, and 9,000 – 15,000 are important for rear localization. Fig. 8 shows the directional bands according to the responses of subjects. This effect indicates that the differences in level and time of sound reaching the closest ear (ILD and ITD)[19] are not the only ways for representing sound in space. This fact accentuates the importance of the frequency content of sound in every aspect of human auditory perception.

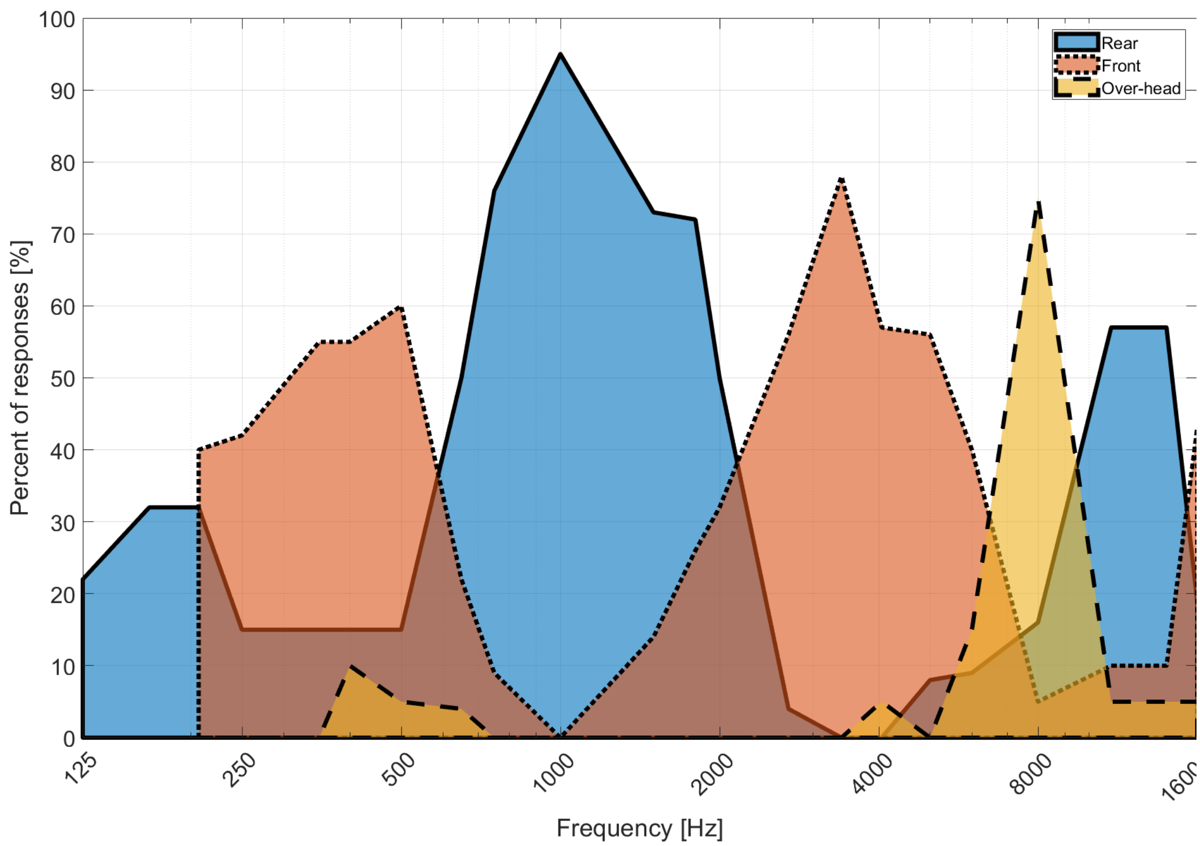


Fig. 8 Sound localization bands. The blue area represents frequencies that provide a sense of sound in the rear direction. The red area represents frequencies that give an auditory sense of the front, and the yellow area offers a sense of sound over the head.

2.1.4 Psychoacoustic Effects

Sound can produce psychoacoustic effects in the listener. These are the outcomes of auditory processing in specific regions of the auditory system. In this section, a few phenomena will be discussed.

A typical acoustic phenomenon is masking, which is present in daily life. It occurs when a sound reduces the perception of another sound until it is no longer perceived [21]. A broad example would be when two people talk on the street, and traffic noise attenuates speech intensity. Therefore, the speakers must raise their voices to be heard. Frequency and intensity features are responsible for this effect, but it also has a more physiological approach. The tonotopic organization of the basilar membrane processes sounds in different areas, usually referred to as bands. When sounds have close frequencies, they are processed in the same band in the cochlea. The ear does not have a specific frequency area for each audible frequency, but instead, it encompasses them in bands. These are called the critical bands, and each one of them has a bandwidth, referred to as the critical bandwidth, and it increases with frequency, as shown in Fig. 9. The main idea of this concept is that a sound with a level higher than another, and both falling in the same critical band, could reduce or "mask" the perception of the lesser sound. This effect, known as the masking effect, is present in simple sounds as pure tones and complex as noise.

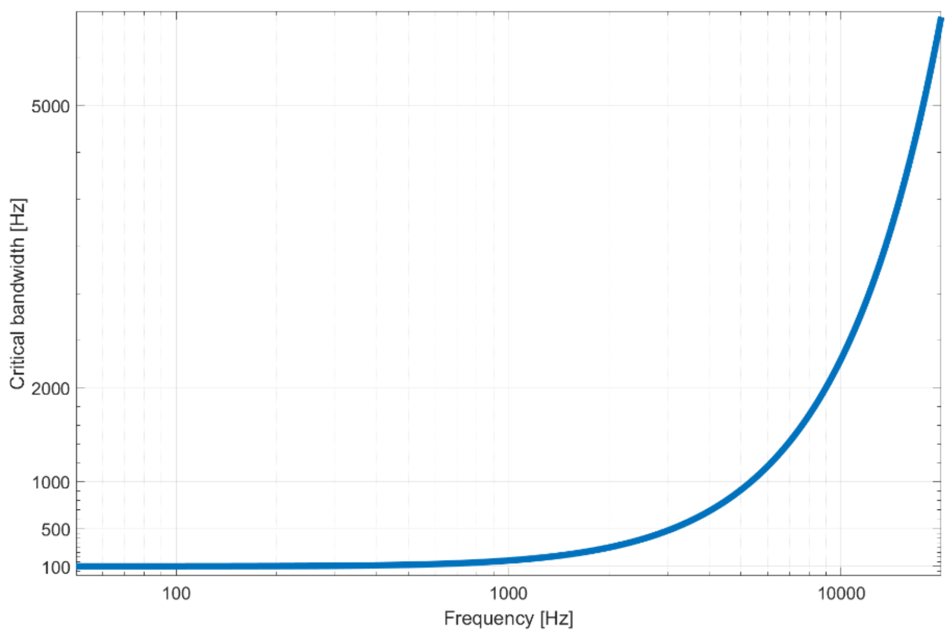


Fig. 9 Critical bandwidth as a function of frequency. The x-axis shows the center frequency, and the y-axis shows the width of the critical bandwidth. As the center frequency increases, the bandwidth becomes wider.

Another interesting psychoacoustic effect is the Zwicker tone [28], discovered by Zwicker. This effect is caused after a long period of noise exposure. It can be referred to as "short-term" tinnitus since it causes the listener to perceive a pure tone for a couple of seconds equivalent to a gap in the frequency content of the noise. It is assumed that this perception of sound is caused in the central auditory system. A neural model mentions the possibility of existing neurons responsible for detecting noise and inhibiting the firing rate of output neurons. This inhibition lasts long after the stimulus is terminated and unbalances inhibition across the tonotopic map, allowing neurons outside the inhibition range to fire information, causing the perception of a sound.

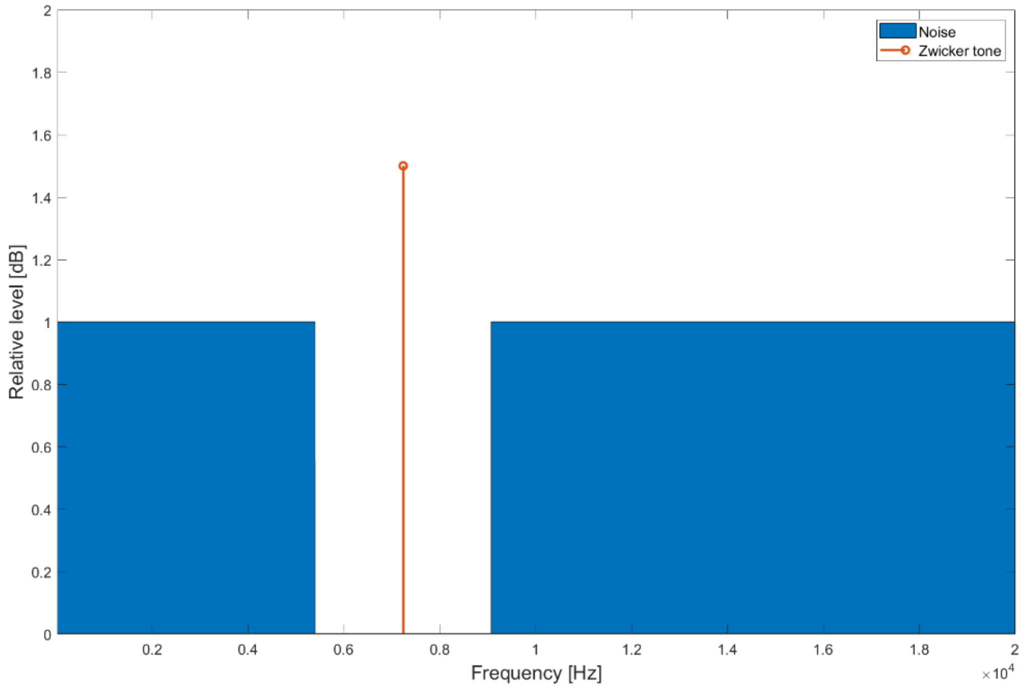


Fig. 10 Zwicker tone equivalent to gap in noise. The blue area represents the frequency content of a noise signal. The red vertical line shows the perceived unreal sound with a frequency equivalent to the noise gap center.

The McGurk effect is another psychoacoustic phenomenon that occurs when a visual stimulus changes the interpretation of a sound. For example, if a person hears the word “far” but an image is projected with the word “bar”, the visual image may change the perceived sound to “bar” [29]. Certain individuals might or might not perceive this effect, and it has been attributed to activation in the superior temporal sulcus.

A final psychoacoustic effect is binaural beats. These are the outcome of listening to pure tones with a small difference in frequency on each ear. The listener would perceive a sound with a modulation frequency equivalent to the difference between the two tones. For example, if a wave of 495 Hz is presented on the right ear, and another one of 505 Hz is presented in the left ear, the listener would hear a tone with a modulation frequency of 10 Hz. First signs of binaural beat detection have been observed in the brainstem, where it has been previously mentioned that the early stages of auditory processing and integration occur [30]. Binaural beats have been used with several aims, such as reduction of migraine [31], tinnitus [32], and pain [33].

In summary, abnormal perception of sounds is caused by their physical characteristics. Hearing is an omnidirectional sense rich in information, and the brain tries its best to decode and interpret the data, even if it cannot do it flawlessly. This adds up to the importance of sound in the study of human perception from the previous section.

2.2 Frequency Response of Audio Devices

2.2.1 Frequency Response and Transfer Function

The frequency response of an audio device is modeled by a curve representing the output signal of a device compared to the original input [34]. The transfer function of an audio system is defined as a function modeling the trajectory of a passing signal through different audio devices (e.g. signal being emitted by a speaker, traveling through a room, being captured by a microphone, and being digitized by a soundcard) [10]. It can be said that the transfer function contains the frequency response of all devices in the system. Fig. 11 denotes the frequency response of each device in an audio chain: a computer creates a signal ($\boldsymbol{H}_{\mathbf{L}}$), followed by an audio interface ($\boldsymbol{H}_{\mathbf{I}}$) emitting the signal in electrical current to headphones, changing the signal into air pressure ($\boldsymbol{H}_{\mathbf{S}}$) and including the resonances of the room ($\boldsymbol{H}_{\mathbf{R}}$). Then, the captured signal is sent back to the audio interface via a microphone ($\boldsymbol{H}_{\mathbf{M}}$) and, finally, to the computer. $\boldsymbol{H}_{\mathbf{TF}}$ is the transfer function of the audio system. Ideally, the curve of the frequency response should be a flat line, meaning that there are no resonances or attenuations in frequencies. Arrows show the signal flow in the system. Fig. 12 shows a typical representation of the frequency response of left (L) and right (R) headphones. Frequency responses of low-quality audio devices can significantly alter the harmonic content of sound files depending on the quality of their components. Therefore, every audio device should be taken into consideration in studies using auditory stimuli. Other types of transfer functions caused by parts of the body can be measured. Sound waves entering the ear canal cause resonances that increase the level in ranges of frequency. This change has been termed as the transfer function of the ear canal [17]. HRTFs are measured in the ear. They contain frequency information of sound being reproduced in external sources such as loudspeakers and how body parts such as the head and torso modify the auditory stimulus [10].

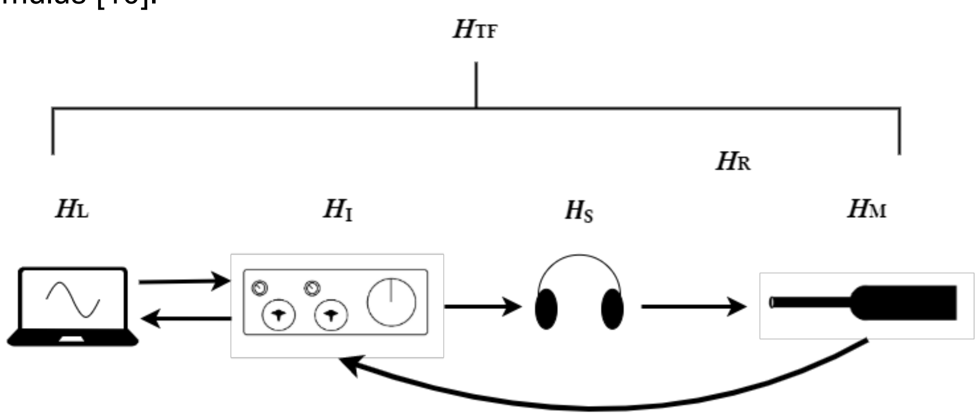


Fig. 11 Signal flow of sound for measurement of frequency response. The frequency responses in the transfer function of the audio system ($\boldsymbol{H}_{\boldsymbol{TF}}$) are those from: computer ($\boldsymbol{H}_{\boldsymbol{L}}$), audio interface ($\boldsymbol{H}_{\boldsymbol{I}}$), headphones ($\boldsymbol{H}_{\boldsymbol{S}}$), resonances of the room ($\boldsymbol{H}_{\boldsymbol{R}}$), and microphone ($\boldsymbol{H}_{\boldsymbol{M}}$).

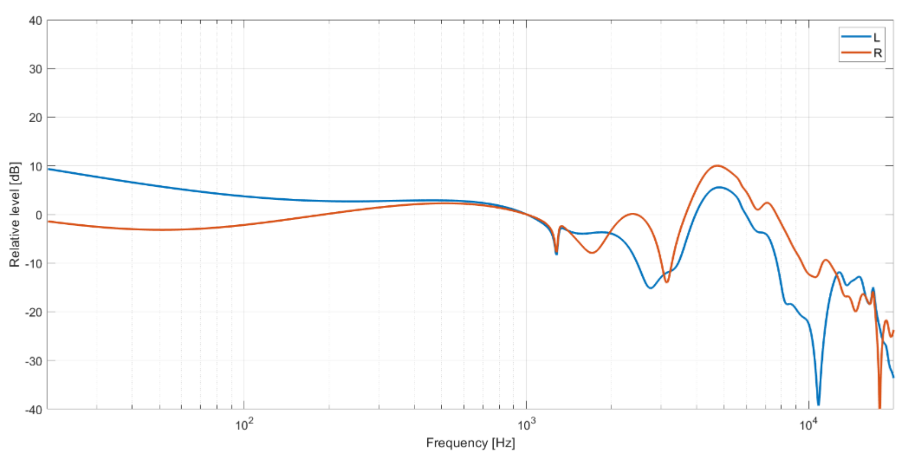


Fig. 12 Example of a frequency response graph. The blue line refers to left headphone (L) and the red line to right headphone (R).

2.2.2 Headphone models

For this study, three types of headphones were used: supra-aural, circum-aural, and intra-aural headphones [35]. Frequency responses are shown in Fig. 13. The first type of headphones is an Atvio® supra-aural model (ATVIO), which is placed on top of the ears without completely covering them. These are commercial headphones, and the curve is not close to a flat line. The second type is Shure® SRH1840 circum-aural headphones (SHURE). This model completely covers the ears, attenuating the external sound significantly. Most of these headphones are used in the music industry due to their high quality. In Fig. 13, it can be observed that the frequency response is close to being flat. The third type are Apple® EarPods® (APPLE) intra-aural headphones. This model is inserted in the ear, transmitting sound directly into the ear canal. Because of their small size, earbuds cannot reproduce frequency in the very-low range. However, new technology has permitted to adapt components for boosting these frequencies and add noise-canceling features [36]. In all graphs, the transfer function of the ear canal is observed in the high-frequency range. Frequency responses were measured with a 3D printed dummy head shown in Fig. 14. This acoustic tool is necessary to measure the models accurately. Specifications of headphone models are shown in Appendix C.

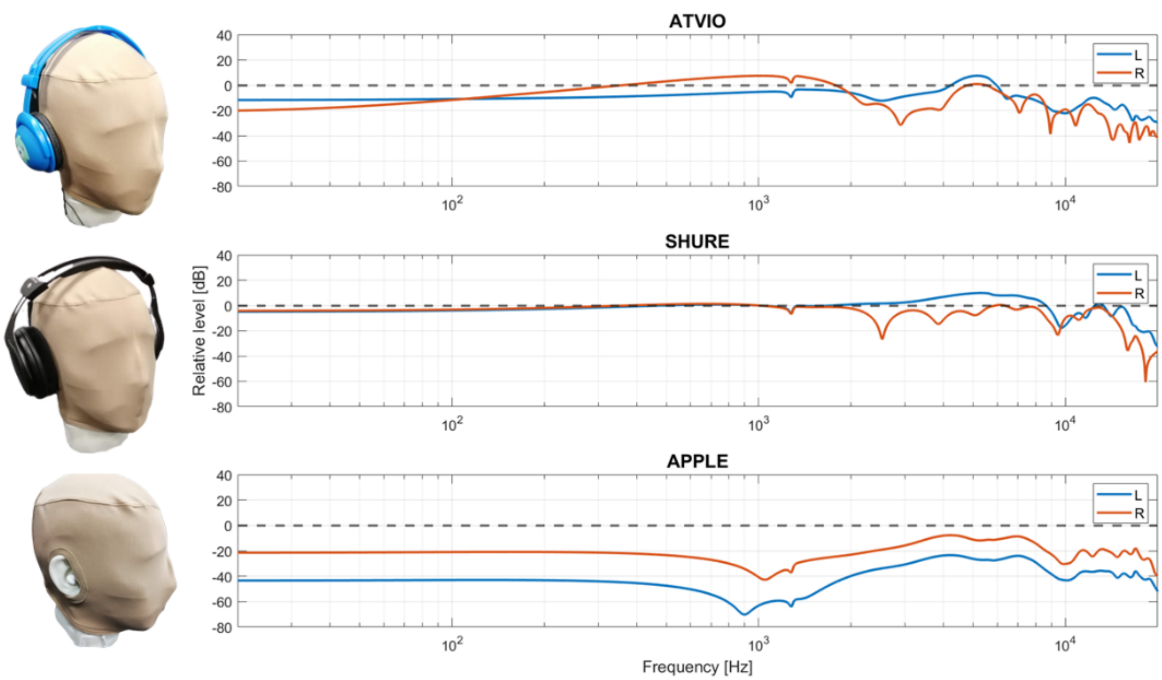


Fig. 13 Frequency response of headphones. Left (L) and right (R). Dashed line shows the target (ideal) curve.

Fig. 14 3D-printed dummy head and point-source (cone-shaped object on the left). The head is used to measure frequency responses because it approximately includes the resonances of the head and ears.

2.2.3 Inverse Filtering

This section explains a filtering technique introduced in [37] and implemented in [38] during the calibration of a point source (PS). Here, the calibration process for flattening the frequency response of ATVIO is detailed. The same methodology is retaken in Chapter 3 to calibrate the frequency response of a headphone model to other responses. Calibration was not performed using the dummy head because it is an anatomical model of a person, and the transfer function of the ear varies across individuals.

2.2.3.1 Materials and Method

Measurements were performed with MATLAB [39] using Maximum Length Sequence (MLS) method playing white noise through PS, and each headphone of ATVIO. MLS method was used due to its robustness to noise in areas different than anechoic rooms. Emitted sounds were recorded with a calibrated Shure® mx150 (SM) microphone connected to a Focusrite® Scarlett 2i4 audio interface (SC). The sample rate was set to 96 kHz. A dbx® RTA-M (DBX) microphone was established as a reference and to correct both transfer functions: SM and PS. SM was chosen to be the measurement microphone because the additional measurements were performed on a 3D printed dummy head with small holes in the ears to observe the transfer function, including the resonances of the ear, and only SM could fit. In the end, only the direct measurements between the microphone and headphones were used. PS was powered by an Alesis® RA-100 reference amplifier (AMP).

The method consists of three inverse filters for calibrating the measurement system and one inverse filter to calibrate the headphones. The fast Fourier transform (FFT) of the captured signals will be referred to as the frequency response or to the transfer function before decibel conversion unless stated otherwise. These functions are usually expressed in their decibel conversion form, but for simplicity, they will not be converted until the last step. FFT and the inverse fast Fourier transform (IFFT) are defined by:

$$FFT[\,S(t)\,] = \sum_{t=1}^{n} S(t) W_n^{(t-1)(f-1)} \tag{1}$$

$$IFFT[\,S(f)\,] = \frac{1}{n}\sum_{f=1}^{n} S(f) W_n^{-(t-1)(f-1)}, \tag{2}$$

where $S(t)$ is a sample in voltage units of a signal in time t (or the IFFT of $S(f)$), $S(f)$ is the FFT of $S(t)$, f is the frequency up to half of the sample rate, and $w_n = e^{(-2\pi i)/n}$ one of the n roots of unity. An impulse emitted PS and captured DBX is generated to record the impulse response of the audio system, $H_{sys}(t)$. It can be modeled as a linear function that expresses the process in time as a summation of the impulse responses of devices in the audio system:

$$H_{sys1}(t) = H_{PS}(t) + H_{DBX}(t) + H_{AMP}(t) + H_{SC}(t)\,, \tag{3}$$

For simplicity, and because AMP is powering PS and the signal is played through SC, these three devices can be defined as one integrated system (PSAMP).

$$H_{sys1}(t) = H_{PSAMP}(t) + H_{DBX}(t), \tag{4}$$

where $H_{PSAMP}(t)$ is the impulse response of PS, SC and AMP, and $H_{DBX}(t)$ the impulse response of DBX. Now, using (1) to transform each term in (4) in the frequency domain, it is obtained:

$$H_{sys1}(f) = H_{PSAMP}(f) + H_{DBX}(f), \tag{5}$$

where $H_{PSAMP}(f)$ is the frequency response of PS, SC and AMP, and $H_{DBX}(f)$ the frequency response of DBX. Now, let $X_{n1}(t)$ be a noise signal function before being emitted by PSAMP, and $Y_{N1}(f)$ the output of PSAMP captured with DBX. Then the harmonic content of $Y_{N1}(t)$ computed by the definition of (1) is expressed as a convolution:

$$Y_{N1}(f) = H_{sys1}(f) X_{N1}(f). \tag{6}$$

Since the transfer function of the audio system is not flat, the harmonic content of the signal is altered. DBX is set as the reference because the frequency response provided by the manufacturer shows a close-to-flat curve, implying that PSAMP is the system needing calibration. To calibrate, noise $X_{\mathrm{N2}}(f)$ can be reshaped before being emitted by PSAMP, creating an inverse filter:

$$X_{\mathrm{N2}}(f) = \frac{Y_{N1}(f)}{H_{sys1}(f)}\;, \tag{7}$$

where $X_N(f)$ is the harmonic content of the reshaped or predicted signal created for flattening the response of PSAMP. Finally, the signal with the inverse filter is returned to the time domain with the IFFT in (2):

$$X_{\mathrm{N2}}(t) = IFFT[\,X_{\mathrm{N2}}(f)\,]. \tag{8}$$

According to (8), it can be stated that the curve of PSAMP is approximately flat and is ready to perform measurements. Here, it is important to clarify that the harmonic content of the sound with which the measurements are going to be performed is the one being modified to calibrate PSAMP. As mentioned earlier, SM was the microphone used for measurements, and because its frequency response is not flat, the procedure from (5)-(8) was repeated to calibrate SM to DBX. This is equivalent to calculating a second inverse filter. The new system can be defined as in (5) with the new variables:

$$\boldsymbol{H_{sys2}(t) = Hcal_{PSAMP}(t) + H_{SM}(t)}, \qquad (\mathbf{9})$$

where $\boldsymbol{Hcal_{PSAMP}(t)}$ is the impulse response of the calibrated PSAMP and $\boldsymbol{H_{SM}(t)}$ the impulse response of SM. Eq. (6)-(8) are computed again to obtain the new signal for the calibrated system, $\boldsymbol{X_{N3}(t)}$. Finally, the whole system is calibrated, and the signal captured with SM is similar to being captured with DBX. The last step of this method consists of replacing PSAMP with ATVIO since this method aims to calculate the raw frequency response of the headphones and flatten its curve. The last system is defined as:

$$\boldsymbol{H_{sys3}(f) = H_{SM}(f) + H_{C}(f)}. \qquad (\mathbf{10})$$

To get the predicted signal for the calibrated headphones, (6)-(8) are used again. Note that the convolution, $\boldsymbol{H_{sys3}(f)X_{N3}(f)}$, is the same as $\boldsymbol{H_{C}(f)}$, which contains information about the frequency response of ATVIO. The convolution will also be referred to as $\boldsymbol{Y_{N3}(f)}$. Once the equations are computed, the inverse filter, $\boldsymbol{X_{N4}(t)}$, is measured after being emitted by the headphones, denoting this measurement as $\boldsymbol{Y_{N4}(t)}$. The raw and the inverse filtered frequency response in decibels are defined as follows:

$$\boldsymbol{R_{C}(f) = 20log|Y_{N3}(f)|} \qquad (\mathbf{11})$$

$$\boldsymbol{Rcal_{c}(f) = 20log|Y_{N4}(f)|}, \qquad (\mathbf{12})$$

where $\boldsymbol{Y_{N4}(f)}$ is $\boldsymbol{X_{N4}(f)}$ emitted by the calibrated headphone. The raw ($\boldsymbol{R_{c}(f)}$, first graph) and the inverse filtered frequency response ($\boldsymbol{Rcal_{c}(f)}$, second graph) are shown in Fig 15. This whole procedure was implemented to calculate the frequency response of a pair of headphones shown in Fig 16. Since the signal passing through each headphone is prepared to filter all resonances except those from the headphone model, it allows the measurement microphone to capture the natural frequency response of ATVIO. It can be observed that the curves after the inverse filtering technique are flatter than the raw curves. It is essential to mention that even if the method reduces most of the resonances, it is limited to the quality of the components in the headphones. As shown in the graphs, there is still some difference between the target line and the high/low-frequency range. If audio systems did not affect the harmonic content of sound files, the expected output would be a curve without resonances, but the output is not flat as it is observed. Nevertheless, this procedure seems to improve the performance of the model.

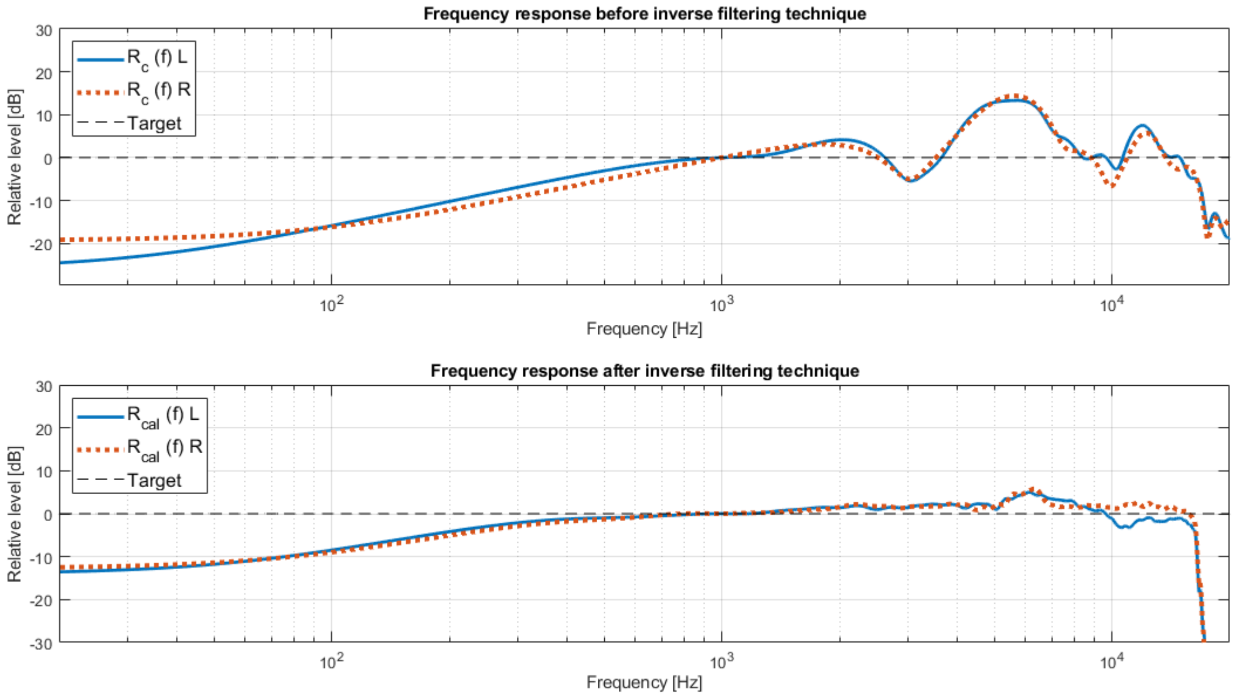


Fig. 15 ATVIO before and after filtering technique. Solid lines represent the left headphone curves, dotted lines the right headphone, and dashed line the target (ideal) response. Top graph corresponds to the curves before inverse filtering technique and bottom graph to the curves after the calibration.

Fig. 16 ATVIO measured using MLS and inverse filtering technique. Headphones were measured inside an isolation booth to minimize sound reflection. Maximum Length Sequence method (MLS) reduces artifacts and noise signals recorded during the measurement.

2.3 Neural Activity in Audition

2.3.1 What is the Role of Lobes to Process Auditory Information?

Research through the years has shown the role of brain regions in auditory processing. It has been observed that the frontal lobe receives information from the temporal lobe, reflecting early and late auditory processing in A1. In human beings, studies have reported an intricate connection between A1, the secondary auditory cortex, and the frontal lobe for the processing of information related to language, spatial localization, and object recognition [40]. The flow of information in the brain is shown in Fig. 17. First, auditory information travels in the auditory nerve through the brainstem in the direction of the auditory cortex. Following, A1 passes most of the information to the belt region, where early acoustic features start to being processed. Then, the belt region continues to deliver information to the parabelt, where late acoustic characteristics are being analyzed before sending them to other lobes (temporal-parietal-occipital region (TPO)) via the rostral superior temporal gyrus (STG) and the superior temporal sulcus (STS). Part of this information is also sent directly to the prefrontal cortex (PFC). In PFC, auditory information is processed mainly in two regions: the ventral lateral (VL) and dorsal lateral (DL) regions. DL processes information related to sound localization and the use of auditory working memory for complex tasks. Auditory working memory can be broadly defined as the memory needed to retain auditory stimulus for some time [41]. Noticeable activity in DL has been observed in tasks of high cognitive demands. VL processes information related to language, such as semantic, word discrimination, and attention directed to sound. Noticeable neural activity in VL has also been reported in processing features like pitch, rhythm, and auditory discrimination [40]. Activation of the brain in the parietal region has been observed during spatial localization-attention [42], and auditory-motor transformation tasks while listening to music [43]. Activation in the occipital region has been documented for salient sounds [44], indicating the involvement of the visual cortex in spatial localization and stimulus attention. Activation was contralateral to the physical location of the sound in space. Visual imagery might be an explanation of activation in this area [45].

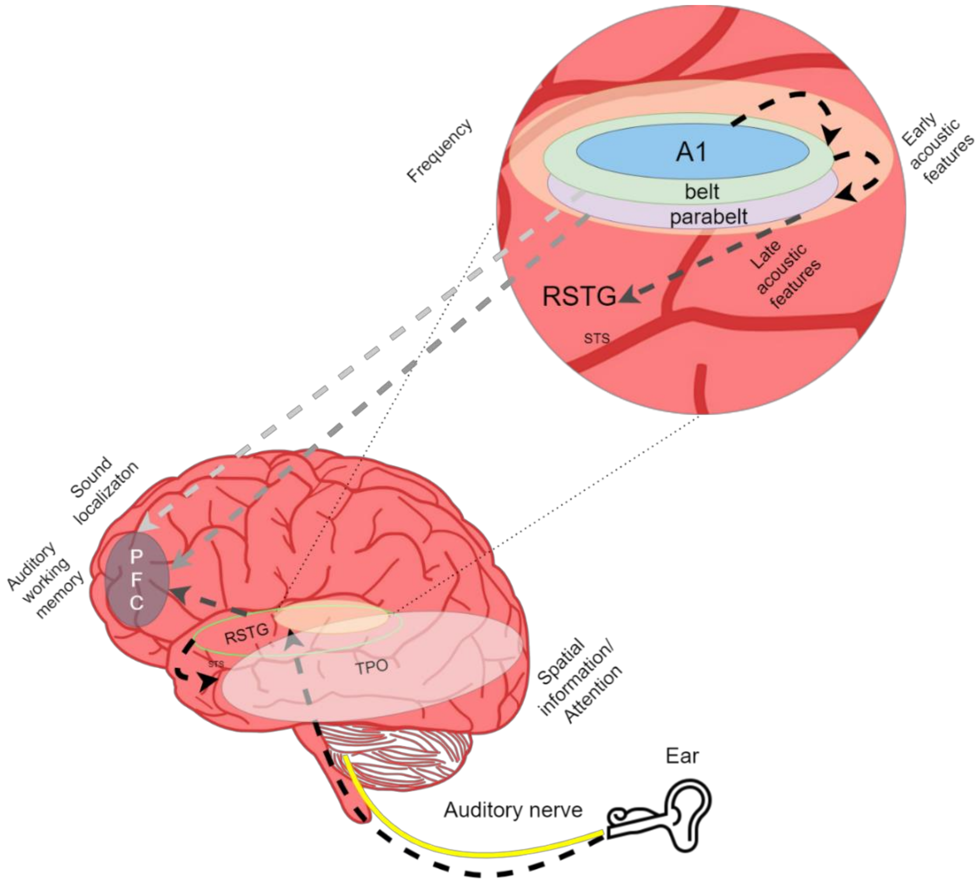


Fig. 17 Auditory processing: from ear to auditory cortex. Sound is received by the ear and sent to the auditory cortex through the brainstem. After its arrival, information is sent to the prefrontal cortex (PFC) and the temporal-parietal-occipital region (TPO). Some information is sent in parallel to PFC. The color of the lines denotes the amount of information sent from one area to another. Light gray arrows represent a small amount of data, and black arrows represent a large amount.

2.3.2 How are Neural Oscillations Modulated when Humans Hear?

Neuroimaging techniques allow studying the electrical activity of the brain. Electroencephalography (EEG) is a neuroimaging technique that records the electrical activity of the cortex by placing electrodes on the scalp of the head. Neurons communicate through chemical or electrical synapses [18]. Electrical synapses cause ionic current to transmit information, and it also synchronizes the electrical activity by grouping neurons. These are considered synchronized when EEG values are above those of a resting state, and desynchronized when values are below. EEG records these events by discretizing the signal in values of micro voltage. Neural activity oscillates at different frequencies depending on human emotions and sensory processes [46]. The main frequency ranges of brain waves and their association with emotions are described in Table 1 based on the work of Abhang et al. [46]. Prominence is defined as abnormal values of neural synchronization. Suppression describes abnormal values of desynchronization. The optimal condition is when values are just above the resting state. Neural ranges may vary across individuals. To solve this issue, it is possible to calculate the bandwidths by measuring the individual alpha frequency (IAF) of each person. This concept comes from the theory that oscillations in the brain and body are coupled in frequency [47].

Table 1 Neural activity in emotions. ADHD: Attention-deficit/hyperactivity disorder.

Band	Frequency range (Hz)	Prominence	Suppression	Optimal condition
Delta	0.1 - 4	Brain injuries, learning problems, inability to think, and severe ADHD	Inability to rejuvenate body and revitalize the brain, and poor sleep	Feel rejuvenated and promotes the immune system natural healing and restorative, deep sleep
Theta	4 - 8	ADHD, depression, hyperactivity, impulsivity, inattentiveness	Anxiety, poor emotional awareness, stress	Creativity, emotional connection, intuition and relaxation
Alpha	8 - 13	Daydreaming, inability to focus, being very relaxed	Anxiety, high stress, insomnia	Relaxed state
Beta	13 - 30	Anxiety, high arousal, inability to relax and stress	ADHD, daydreaming, depression and poor cognition	Conscious focus, memory, and problem solving
Gamma	> 30	Anxiety, high arousal, and stress	ADHD, depression and learning disabilities	Attention, focus, binding of senses, consciousness, mental processing, and perception

Brain oscillations have been observed during auditory processing. Table 1 condenses information of revised literature concerning auditory stimulation [48–56]. The center and far-right columns indicate the neural condition of brain waves during auditory processes in the far-left column.

Table 2 Neural activity in audition.

<table>
<tr><th>Auditory process</th><th>Synchronization</th><th>Desynchronization</th></tr>
<tr><td>Sound localization</td><td>Delta</td><td rowspan="3">Alpha</td></tr>
<tr><td>Cognitive and memory performance, task demands, episodic memory</td><td>Theta
Gamma</td></tr>
<tr><td>Motor tasks</td><td>Beta</td></tr>
<tr><td>Presentation of external sound (Auditory Cortex), Recognition of acoustic material</td><td>Gamma</td><td>Alpha/Beta</td></tr>
<tr><td>Encoding of acoustic material and new information</td><td>Alpha</td><td>-</td></tr>
</table>

2.3.3 Processing of Electroencephalographic Signals in Spontaneous and Evoked Modality

Further analysis of EEG can be divided into two modalities: spontaneous and evoked activity. Spontaneous activity is observed when subjects do not perform a specific task, while exposed to a constant stimulus, or during resting state [57]. Neural activity is recorded for long periods (e.g. 10 minutes) to reduce artifacts during signal acquisition. These signals are later analyzed in the time-frequency domain. It is common to record a resting state, usually referred to as baseline, to later reference activity during constant stimulation and observe neural synchronization and desynchronization. A typical representation of spontaneous activity is a topographic map shown in Fig. 18. Zero value corresponds to the resting state, positive values to neural synchronization, and negative neural desynchronization.

Evoked activity is observed during specific tasks. Sensory, emotional, and cognitive processes are analyzed in waves observed in the neural activity of the brain after the onset of a stimulus, usually referred to as Event-Related Potentials (ERPs). Components in waves are studied in terms of latency and amplitudes because these features vary depending on the aim of study. In the case of sound, auditory ERPs (AERPs) show information of perceived loudness [58], attention deviation [59], and central auditory system performance [60]. The morphology of an AERP is presented in Fig. 19, and the most common components are:

- Waves I – VI. Show responses of the brainstem.
- N1. Sensible to attention. Response generated by auditory stimulus.
- N2. It is observed when a non-repetitive stimulus suddenly appears in a train of repetitive sounds. Commonly referred to as the mismatch negativity.
- P3. Present in sudden shifts in tone pitch or intensity. Amplitude is increased when participants put a lot of effort into a task and decreased when participants are not sure if they heard a target stimulus during an auditory discrimination task.

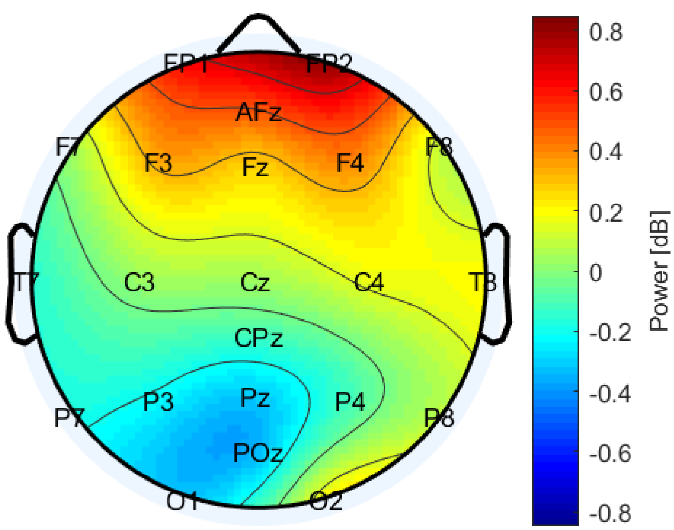


Fig. 18 Topographic map with power values of synchronization and desynchronization in decibels. The letter on top of the map specifies the location of electrodes on the scalp in line with the 10/20 system.

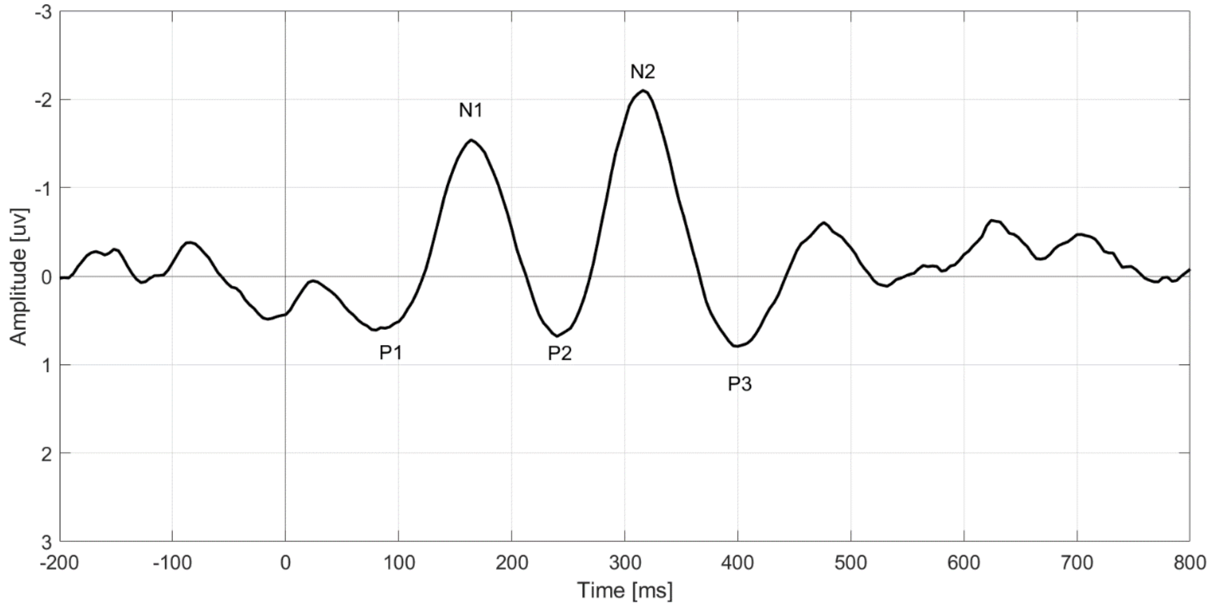


Fig. 19 AERP morphology. The letter denotes if the component is positive (P) or negative (N). The number corresponds to latency after stimulus onset. For example, N1 corresponds to a negative component present approximately 100 ms after onset. Latencies vary in time and, for this reason, the number is reduced to an integer.

Chapter 3

State of the Art

3.1 Audio Devices used in Acoustic Treatments for Tinnitus

This section reviews acoustic therapies for tinnitus treatment and carefully inspects the audio devices used to deliver the auditory stimulus. This neurological disorder was chosen because the motivation for this research was born while studying the phenomenon. There is enough evidence in the literature reporting that the frequency content of a stimulus could set off its perception.

A literature review for this work was conducted following these criteria:
1. Acoustic therapies only used for tinnitus treatment.
2. Databases consulted were AES e-Library, EBSCO Academic Search Ultimate, EBSCO Education Source, MEDLINE, PubMed, ScienceDirect, Scopus, and Springer Nature Journals.
3. Sound played through audio devices.

Table 3 presents the selected literature according to the criteria mentioned above. Only 25 out of 48 selected studies shown in Table 3 provided information about the audio devices used in the experimental protocols, but none presents a performed calibration. The most common devices were hearing aids, sound generators, and headphones. The main acoustic procedures were categorized and are described below. At the end of each therapy section, the impact of the frequency response of audio devices is detailed.

3.1.1 Frequency Content

Alteration of the spectral density (harmonic content) of a sound file is one of the most studied therapies. One of these types of alterations is tailor-notched sounds therapies. It is thought that overcompensation of sound level around tinnitus frequency could trigger the unreal sound, and suppression could prevent awareness [5,6,9,11–13,61,62]. Sounds with the removed tinnitus frequency showed better results in patients after 12 months of exposure than in a control group [11]. Improvement in patients that used a smartphone application with tailor-made notched music has been also reported [13]. Adjustment of the therapeutic noise spectrum reported a decrease in perceived tinnitus loudness in participants with tinnitus pitch less than 6 kHz. Still, for those with higher tinnitus pitch, loudness was unchanged or slightly higher [8]. Patients using notch-based hearing aids had better results in the Tinnitus Questionnaire-based evaluation [9]. The use of filtered noise around the tinnitus frequency and its harmonics mixed with music has shown positive results in tinnitus reduction, and side effects with an overcompensation of sound level in the frequency band around the characteristic tinnitus frequency [12]. Contrary to the results shown above, some authors have not reported significant tinnitus perception changes with this therapy [5]. Furthermore, some patients reported feeling an unpleasantness in amplified and notched different frequencies than only attenuated sounds [62].

Contrary to the tailor-notched approach, another type of alteration is to filter noise in a bandwidth around the tinnitus frequency [8,63–67]. This modification aims to mask the perception of the unreal sound. This method is different from Tinnitus Retraining Therapy (TRT) because this last one sets noise level just below the tinnitus loudness level, without completely masking it. Bandpass noise adjusted to tinnitus frequency has been used, and improvements in the short-term have been observed [63,64]. A comparison between white noise and narrow-band noise peaks centered at the tinnitus frequency combined with music has been studied as well [65]. Participants in the music group performed better in the Tinnitus Handicap Inventory (THI) scores than those in the only-noise group. An interesting finding was reported in a study comparing 1-octave range notched noise centered around the tinnitus pitch frequency, 1-octave wideband noise, and low-frequency noise. The three sounds showed improvements in participants, but there were no significant differences across groups [66]. Recently, a neuromodulatory effect of bandpass noise correlated to positive improvements has been demonstrated [67]. From studies in Table 3, none of them reported the same type of audio devices for the implementation of therapies.

The frequency response of audio devices could modify the effect of these types of therapies. If the frequency response of the headphones either overcompensates the tinnitus characteristic frequency or attenuates frequencies outside this range, it could trigger the perception of the unreal sound.

3.1.2 Tinnitus Retraining Therapy (TRT)

TRT, a therapy proposed by Jastreboff [68] that intends to reduce tinnitus perception by habituation to the reactions of the limbic system, has been evaluated in different studies [7,69–77]. It consists of playing a noise filtered around the characteristic tinnitus frequency, and which level is just below the tinnitus level, without completely masking it. The noise level is gradually reduced, causing the psychoacoustic effect of reduction in tinnitus level as well. The simplified version of TRT protocol has been studied [69], and significant differences compared to the extended version were not reported. Effectiveness of TRT in patients with tinnitus and single-sided deafness has been demonstrated, and positive results of TRT combined with music have been reported [71,77]. Personalized colors, such as pink, white, and red noise, showed improvements in reducing discomfort caused by tinnitus [72]. It was observed that the use of a hearing aid in TRT was more effective in adults [78]. In another study, a multimodal TRT that comprised several stages as counseling, sound therapy, and cognitive behavioral therapy reported improvements in distress and stress after a five-year follow-up [7,79]. Improvement in tinnitus within the first three months, six months [75], and after 18 months has been observed [73]. Sound generators with TRT has shown significant improvements in patients with hyperacusis [74]. Contrary to the results shown above, significant differences were not found when TRT was compared to the center counseling protocol [76]. From studies in Table 3 that correspond to this section, none reported the same audio device implemented in therapy.

Since TRT aims to reduce the tinnitus level by gradually reducing the noise file level, the frequency response of headphones could minimize the effect. Headphones could increase the tinnitus frequency level, changing the level distance between the unreal sound and the filtered noise, and therefore, cancel the psychoacoustic approach.

3.1.3 Personalized Tones

Two commercial systems currently aim to relax and reduce tinnitus perception with personalized sounds: (1) Widex® Zen and (2) Desyncra™ for tinnitus. Fractal tones delivered by the Widex Zen device have been evaluated in [80–82]. This device has different fractal tones settings and its own hearing device. It also has a noise setting. These tones are created based on a pitch-intensity relationship to the tinnitus characteristic frequency and hearing loss. A group using the system had less tinnitus annoyance than a control group in a study, and no significant differences in tinnitus annoyance were reported among the four fractal settings [80]. Better responses in patients with whistle-type have been reported [81], and therapy benefits were maintained six months after counseling strategies [82].
Acoustic coordinated reset neuromodulation (CRN) is another therapy that aims to modulate neural activity [83–85]. CRN consists of tones around the tinnitus frequency distributed in calculated patterns to induce neural desynchronization. CRN system has been evaluated in several studies, and significant positive differences were observed compared to other therapies [83]. Desyncra for Tinnitus, a system that implements CRN, has been validated and reported reliable matches in the tinnitus pitch [84]. Positive responses after four months of implementing the hearing threshold CRN, a variation of CRN, have been reported [85].
It should be noted that Widex Zen [86] and Desyncra for Tinnitus [87] are two different systems.

Since both personalized tones systems rely on playing sounds having a frequency-intensity relation with the tinnitus frequency and adjusting to the hearing loss curve, the frequency response of the devices could significantly reduce or increase the level of the tones, modifying the distance between stimuli levels and reducing the effectiveness of the therapy.

3.1.4 Heidelberg Neuro-Music Therapy

Heidelberg Neuro-Music Therapy (HNMT) is a method that combines sound and counseling [88,89]. Both studies included in Table 3 reported a reduction in tinnitus perception after one [89] or ten [88] weeks after therapy, but none mentioned the audio devices used.

In this therapy, the audio devices used could not be found. In the case that there is no standard device for the stage of the treatment that reproduces sound through a speaker or headphones, the effect of the therapy would rely entirely on the correct functioning of the audio devices. If the system is not calibrated, the harmonic content might be different from the expected one, and treatment for a general population might not be achieved.

3.1.5 Binaural Beats

The binaural beats therapy consists of presenting two sounds that differ in frequency on each ear [32,90]. In a study, an entrainment effect by a frequency-modulated sound with a 10 Hz carrier has been reported [90]. The results were attributed to the daily stimulation of a pleasant sound that produces a relaxation effect. Contrary to the results shown above, sounds as ocean waves with 8 Hz binaural beats have reported negligible improvements [32], showing no significant difference between the sound of the waves with the binaural beats and the binaural beats alone. None of them reported the same type of audio device for the implementation of the therapy.

Since this therapy uses stereophonic sound files, the proper functioning of both headphones is mandatory. For example, suppose a headphone attenuates the frequency level or completely fails to play the frequency on one of the ears. In that case, the binaural beat effect might not be perceived by the listener, and the treatment would fail to induce a relaxation state in the subject.

3.1.6 Other Therapies

Pure tones and narrow-band noises with amplitude and frequency modulated sounds have been used [91]. It was observed that modulated high-frequency stimuli suppressed tinnitus more than the other types of sounds. Contrary to other findings, noise did not have a significant impact on this study. Hearing aids plus sound generators in tinnitus treatment did not present substantial differences from those with only the hearing aid [2,92]. The multiple-frequency masking therapy, white noise mixed with frequencies matching the tinnitus sound, had better results than white noise combined with a single frequency matching the tinnitus frequency [93]. Ultrasound in the form of passband white noise in the range above 20 kHz must be carefully used since it has reported eradication, aggravation, or masking of tinnitus in particular types of patients [94]. Natural sounds and broadband noise for tinnitus therapy have been evaluated, and results showed a significant improvement after three and six months of its implementation [95]. The use of narrow-band noise has reported reductions in the THI and Visual Analogue Scale (VAS) scores [64].

Contrary to other results, broadband noise and nature sounds at a sound level interfering with tinnitus reported no significant difference from noise without nature sounds [96]. Effectiveness of amplitude-modulated sounds and pure tones matched to the tinnitus characteristic frequency has been reported [97,98]. Sounds mimicking tinnitus at different sleep stages have shown reductions in tinnitus intensity [99]. A mobile application called RTR for tinnitus treatment that contains an extensive library of sounds such as crickets, birdsongs, traffic, highway, relaxation music, and color noises reported improvements six months after its implementation [100]. Recently, a therapy that combines TRT and CRN has been proposed. The cochleural alternating acoustic beam therapy (CAABT) consists of a sound with a stimulus and carrier tones. Sounds appear simultaneously, and a carrier sound (white noise) is always present. After three months, all patients in that therapy reported a reduction in tinnitus annoyance [101]. Effectiveness of noise and tinnitus-matched stimulus during sleep delivered by either an in-ear device that played noise (white noise, band noise, or combined) or a bedside sound generator was evaluated [102]. It was reported that a reduction in tinnitus perception was improved with the in-ear device compared to the bedside sound generator. Only two studies from the same author reported the same audio device [97,98].

In therapies mentioned in this section, a common approach was not found. However, audio devices are the tools used for the implementation of the treatment. Therefore, the aim of the therapy for the betterment of the listener depends entirely on the proper functioning of the devices.

Table 3 Studies concerning acoustic therapies for tinnitus treatment that pointed out the audio device in use.

Ref.	Therapy section	Study aim	Audio devices	Results
[8]	Frequency content	Investigate improvement of tinnitus perception with behind-the-ear devices	Siemens 'Tinnitus Control Instruments' (TCI) noise device. Hearing aid not specified.	For those with higher tinnitus pitch, loudness was unchanged or slightly higher.
[80]	Personalized sounds	Determine if different types of sounds improve tinnitus by delivering them in hearing aids.	Widex Mind 440 15-channel, wide dynamic range compression hearing aid with a compression threshold as low as 0 dB HL.	The group using the system had less tinnitus annoyance than a control group, and no significant differences in tinnitus annoyance were reported among the four fractal settings.
[91]	Other therapies	Search for auditory stimulation to suppress tinnitus with frequency- and amplitude- modulated sounds.	Sennheiser HDA-200 headphones.	Modulated high-frequency stimuli suppressed tinnitus more than the other types of sounds. Noise did not have a significant impact.
[6]	Frequency content	Evaluate neural plastic changes in two modalities of frequency content modification.	Apple iPad-II. Modified headphones Sennheiser PX360.	Participants in active listening modality showed reduction in neural activity related to tinnitus.
[63]	Frequency content	Evaluate a music-technology-based therapy for tinnitus.	Sennheiser HDA 200.	Reduction of tinnitus in the short term.
[95]	Other therapies	Evaluate the effect of nature sounds delivered through hearing aids.	Bilateral prototype ReSound combination hearing aids connected wirelessly (using a Bluetooth streamer, Resound Phone clip 2) to the user's smartphone containing nature sounds. Standard combination aids (Resound Live TS or Alera TS, Verso TS) with broadband noise generator. The devices had the same frequency range.	Significant improvement after three and six months of therapy implementation
[81].	Personalized sounds	Demonstrate the effectiveness of sound therapy with sound generators.	Twenty retroauricular behind the ear (BTE) hearing aids with an open fitting Mind 9440 model with fractal sounds (WidexTM) and Reach 62 Model (BeltoneTM) with white noise systems.	Better responses in patients with whistle-type tinnitus.
[84]	Personalized sounds	Evaluate a tinnitus system operated by participants	Consumer mobile device (Apple iPod touch 5th generation) running a custom application (Mobile Tinnitus App) in an IOS environment. Earphones adapted from open-fit receiver-in-the-ear canal hearing aids that allow a high degree of acoustic environmental transparency during therapy.	Reliable matches in the tinnitus pitch.
[71]	TRT	Verify effect of sound generators in TRT	Wearable sound generators (silent Star, Viennatonne, Audifon-Resound).	Effectiveness of TRT in patients with tinnitus and hyperacusis was demonstrated after six months of the therapy.

[61]	Frequency content	Evaluate the effect of personalized music after 12 months of implementation	Sennheiser HD 202 II Professional around-the-ear headphones or Sony MDR-EX15 in-ear earbuds MP3 players (SanDisk Clip Sport MP3 Player).	Significant and clinical improvements in treated group after three months of exposure.
[5]	Frequency content	Test treatment of tailor-notched music	Mobile device, an iOS application (App) has been developed for modifying the music in real-time. Headphones Sennheiser HD 201.	No significant tinnitus perception changes were found with this therapy
[72]	TRT	Evaluate the effect of colored sounds for the reduction of tinnitus perception	Oticon Alta 2 Pro Ti.	Personalized colors, such as pink, white, and red noise, showed improvements in reducing discomfort caused by tinnitus.
[96]	Other therapies	Demonstrate that nature sounds are a better therapy than broadband noise	Headphones Philips ViBE SA4VBE08KF/97 4GB MP3 players with Panasonic RP-HJE290GUK Premium Black Earphones with a Budloks Earphone Sports Grip earpiece attached for secure retention within the ear.	Broadband noise and nature sounds at a sound level interfering with tinnitus reported no significant difference from noise without sound.
[65]	Frequency content	Compare the effects of music to that of broadband noise	AirDrives Interactive Stereo earphones, Sansa Clip+ MP3 Player.	Participants in music group performed better in the Tinnitus Handicap Inventory (THI) scores than those in the only-noise group.
[97]	Other therapies	Compare frequency- and amplitude-modulated, and unmodulated sounds for the suppression of tinnitus.	Sennheiser HDA 2000 headphones.	Amplitude-modulated sounds and pure tones matched to the tinnitus characteristic frequency significantly reduced tinnitus perception.
[103]	Other therapies	Evaluate the effectiveness of sound generators and hearing aids combined with counseling	Siemens Hearing Aid and siemens Sound Generator.	Significant improvement was found in both participants with normal hearing and hearing loss
[102]	Other therapies	Determine if Otoharmonic Levo System reduces tinnitus perception	Levo System, a custom in-ear device designed to be used with a tinnitus-matched stimulus, compared to (a) the same Levo System but with a noise stimulus chosen by the participant from a limited range of options and (b) Marsona 1288 bedside sound generator (bedside sound generator device; BSG group) custom-fit earbuds.	Reduction in tinnitus perception was improved with the in-ear device compared to the bedside sound generator.
[82]	Personalized sounds	Evaluate Zen therapy for tinnitus treatment	Open fit ear molds with Hearing Aid (Widex Clear 440 Fusion RIC).	Therapy benefits were maintained six months after counseling strategies.
[73]	TRT	Compare the effect of TRT in participants with hearing loss to those with normal hearing	Sound Generator (Siemens and Makichie), iPod or Radio. Hearing Aid (No information about hearing aid).	Tinnitus improvement was observed after 18 months of the therapy.
[99]	Other therapies	Evaluate if neuronal reorganization caused by sounds during stages of sleep are better for suppressing tinnitus	iPod Touch and delivered through personalized headphones created for each patient.	Sounds mimicking tinnitus at different sleep stages showed a reduction in tinnitus intensity
[66]	Frequency content	Evaluate the effect of notched noise and matched noise to tinnitus frequency for suppression or reduction of tinnitus.	iPod Nano with Ety-Kids 5 (Etymotic Research, Inc. Elk Grove Village, Illinois) earphones.	No significant differences across groups
[85]	Personalized sounds	Verify a clinical improvement in tinnitus perception using Desyncra for tinnitus.	Desyncra for Tinnitus, customized iPod with our software and app, plus a set of our custom designed earphones.	Positive responses after four months of implementing the hearing threshold CRN were reported

[62]	Frequency content	Compare and explore the unpleasantness of environmental sounds with modified frequency content.	Sony MDR-1RNCMK2 headphones.	Some patients reported feeling an unpleasantness in amplified and notched different frequencies than only attenuated sounds.
[32]	Binaural beats	Assess the effect of binaural beats combined with sounds to reduce tinnitus perception	MP3 player through an audiometer (GSI-61). Sennheiser HAD 200 headphones.	Sounds as ocean waves with 8 Hz binaural beats reported negligible improvements
[98]	Other therapies	Evaluate the effect of modulated sounds and pure tones matched to tinnitus frequency.	Sennheiser HDA 2000 headphones.	Only amplitude-modulated sounds reduced tinnitus perception in the short term.

3.2 How do the New Audio Technology Change Audition?

Thanks to technological advances, audio formats and recording techniques have improved many aspects of auditory perception. Immersive spatial sound has been possible thanks to HRTF measurements to create spatial hearing in binaural systems. Recordings in the ear contain the acoustic features that have been modified due to diffraction caused by body parts and resonances of the room [104]. This information is later applied to sound as filters to virtually position a source in space.

The measurement of HRTF in people might be difficult because of the size of microphones and correct placement in the ears. Therefore, artificial structures as dummy heads have been developed to simulate the head and torso of people [105]. This microphone structure has average dimensions of a human being, creating binaural recordings artificially. Microphones are placed inside the ear to record audio signals coming from different locations.

New systems as Dolby Atmos [106] surround the listener in an environment of speakers. The recent development of Dolby Atmos has been implemented in computers, using metadata to emulate spatial audio in headphones [107].

Another format is Ambisonics, and it comprehends the coding and decoding of sound. First-order Ambisonics record sounds in a tetrahedral configuration of microphones to add definition in the space domain [108]. This information is later decoded to enable the artificial positioning of a sound in a 360° fashion. Higher-order Ambisonics reach a higher representation of space, but it also requires sophisticated systems to decode and reproduce the information.

Recently, headphones that measure the audition of participants for audio enhancement have been developed [109]. Nuraphones measure hearing levels with otoacoustic emissions. The headphones have a built-in speaker and microphone. The speaker produces an imperceptible sound signal that travels through the auditory organ. Then, the ear reflects part of the sound in the direction of the microphone. This reflection encodes auditory information, such as hearing levels [110]. The acoustic input is sent to the software of the headphones to adjust levels in frequency according to the audition curve. This effect is similar to the tailored-music therapy explained in section 3.1.1.

Chapter 4

Methods

4.1 Sample

A total of 31 volunteers (mean age = 21.226 years old, standard deviation = 1.857,14 males, 17 females) participated in this study. Participants were recruited through a Google Forms survey on the internet. Applicants were excluded if they did not fulfill the following criteria: ages 19 – 24, currently studying at university level or one-year graduate from university level, no hearing or neurological disorders, no musical lectures, ear training, or playing an instrument for more than five years.

4.2 Equipment

For the characterization of headphones, the same procedure and equipment described in chapter 2 were applied. Instead of calibrating the headphones to a flat curve, they were calibrated to the frequency response of other models. Three headphone models were measured for this study: ATVIO, SHURE, and APPLE. The level was set to 95 dB SPL and measured with a sound level meter at the beginning of the measurements. The gain level of microphones was adjusted in order to avoid clipping and weak signals. All measurements were performed in an isolation booth at the music production studios of Tecnológico de Monterrey (Monterrey, N.L.). Each headphone was measured with SM with plane incident wave, approximate length of the ear canal [111,112].

An Interacoustics AD226 audiometer was used for the pure-tone audiometry test in ranges 125 – 8k Hz. Heart rate for the calculation of the IAF was measured with a pulse oximeter Hergom® MD300. Quiztones application for frequency discrimination was used to discard participants with trained ears [113]. For EEG data acquisition, a 24-channel electrode cap following the 10/20 international system and a Smarting EEG Bluetooth amplifier were used. Data was recorded using OpenViBE software during the experimental procedure and analyzed in MATLAB using the EEGLab toolbox and FastICA algorithm.

Filtered pink noise files for the experimental paradigm and implementation period were generated in MATLAB [114]. Audio files for the implementation period were created in REAPER digital audio workstation to add words in specific points of time to monitor each participant. Further information will be explained in the Procedure section.

4.3 Characterization of Headphones

The method follows the same idea as the previously mentioned technique. Additional to modifying the signal with the inverse filter of the loudspeaker-microphone impulse response before the output, the difference of the frequency response between headphones is computed. This would be the equivalent of calibrating a pair of headphones to the response of another. Using this method, ATVIO is calibrated to

SHURE and APPLE. The frequency response of SHURE and APPLE, $\boldsymbol{R_s(f)}$ and $\boldsymbol{R_A(f)}$, before decibel conversion is defined as follows:

$$\boldsymbol{H_s(f) = Y_{N5}(f) = H_{sys4}(f)X_{N3}(f)} \quad (13)$$

$$\boldsymbol{H_A(f) = Y_{N6}(f) = H_{sys4}(f)X_{N3}(f)}, \quad (14)$$

where $\boldsymbol{X_{N3}(f)}$ is the calibrated harmonic content of the signal mentioned before (10). Equation (7) is used to compute the difference between ATVIO and the other two models

$$\boldsymbol{DR_{CS}(f) = \frac{H_C(f)}{H_s(f)}} \quad (15)$$

$$\boldsymbol{DR_{CA}(f) = \frac{H_C(f)}{H_A(f)}}. \quad (16)$$

Now the frequency response of the target headphone is in the denominator and not the one of the system as in (7). Once the differences are computed, the inverse filter between headphones is calculated. As an example, if it is desired that ATVIO sounded like the professional headphones, $\boldsymbol{H_s(f)}$ can be isolated from (15):

$$\boldsymbol{H_s(f) = Y_{N5}(f) = \frac{H_C(f)}{DR_{Cs}(f)}}. \quad (17)$$

Finally, $\boldsymbol{H_s(f)}$ and $\boldsymbol{H_A(f)}$ are converted as in (11) to get the frequency responses in decibels, $\boldsymbol{R_s(f)}$ and $\boldsymbol{R_A(f)}$. In Fig. 20, the frequency response curves of the headphones and their difference are shown. SHURE are specialized headphones used for music production. In the graph, it can be observed that the curve is flatter in SHURE than in ATVIO and APPLE. There are a few resonances after 3 kHz and below 300 Hz. This one is the most expensive of the two models. ATVIO is not as flat as the previous one, and there are many resonances after 20 kHz and below 500 Hz. This model is the cheapest of the headphones. APPLE has a reduced frequency range, and sensitivity at very high frequencies is observed. Lines with arrows correspond to (15) and (16) in decibels. This implies that the output of ATVIO will approximate SHURE or APPLE. The graphs look smooth because the signals were windowed to the first transient captured by the microphone as in the first technique.

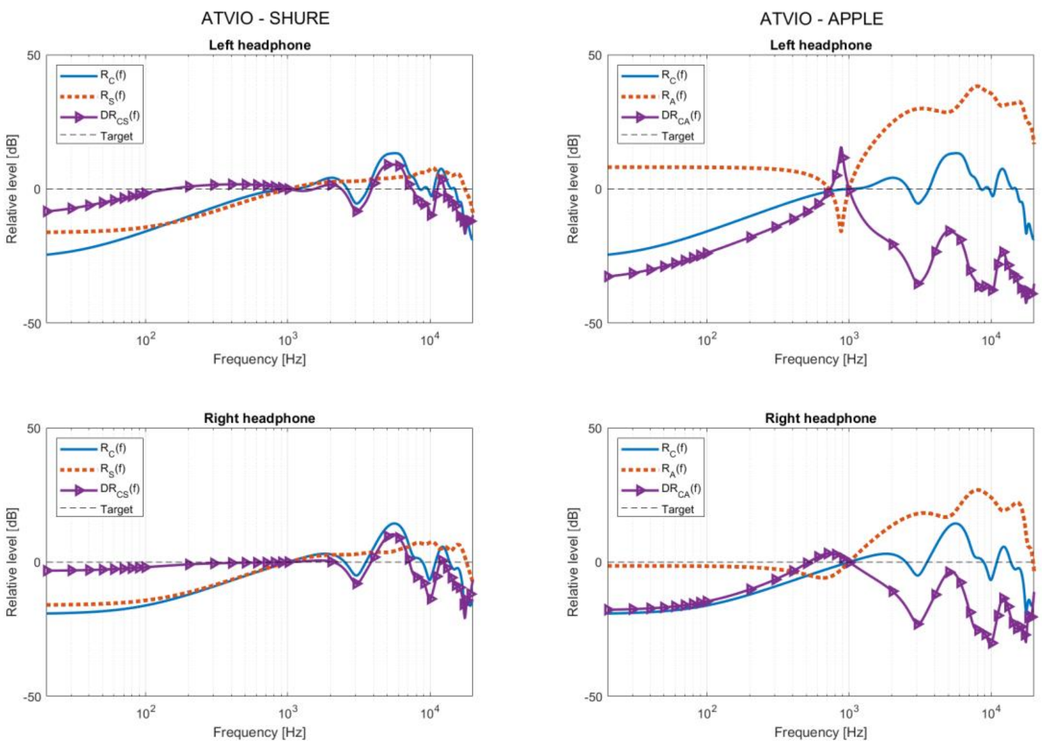


Fig. 20 Frequency responses of headphones and their differences. The solid line represents ATVIO. The dotted line represents either SHURE or APPLE. The line with arrows is the difference in curves. Left column analyses ATVIO and SHURE and right column ATVIO and APPLE. Dashed line representes the target (ideal) curve.

4.4 Experiment Design

Figure 21 presents the study design. Each participant was interviewed prior to the EEG recording session. During the interview, participants filled in a neurological assessment questionnaire from the Institute of Neuroscience of the University of Guadalajara (Appendix D). This questionnaire helped to exclude participants that might present neurological disorders. Afterward, each participant filled in a questionnaire related to their hearing. Questions were proposed by Dr. Arturo Aguilar, an otolaryngologist. After the hearing questions, each participant underwent a pure-tone (PTA) audiometry in the range of 125 – 8kHz inside an isolation booth. Answers to the hearing questionnaire and PTA were reviewed by the same otolaryngologist, who determined if they were eligible for the study. After the audiometry, each participant took a frequency discrimination exam using the Quiztones application on a computer. This step ensured that participants did not have a trained ear, which may bias the research. Participants listened to pure tones and tried to identify the frequency in Hz. Four options appeared on the screen. The application has two levels: easy and expert. The maximum score was 100, meaning that all frequencies were correctly identified. The exclusion score was set to 70. If participants had a score equal or higher than 70 in the easy level, they continued onto the hard level. Only one participant scored 70 in the hard level. After interviewing the individual and revising its application form, it was decided to include its participation since it was reported that the participant did not study anything related to music or audio, never had music lessons, and never played a musical instrument. The participant just had a good ear. Once participants were accepted in the study, they were scheduled for EEG sessions and divided into three groups corresponding to the headphone models to which they were exposed for a month: ATVIO, SHURE, and APPLE.

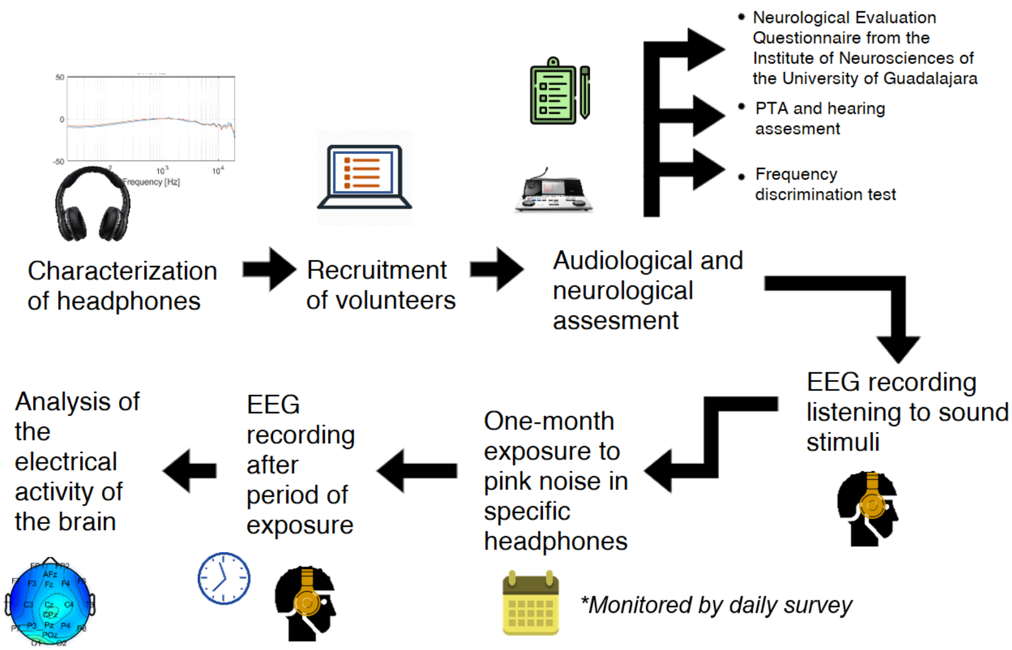


Fig. 21 Study design. The design proceeded in seven steps: from the characterization of headphones to analysis of the electrical activity of the brain.

4.5 Procedure

4.5.1 First Session

The EEG recording session consisted of four sections: (1) a 5-minute baseline spontaneous activity recording, (2) a section explaining components of sound, (3) evoked activity recording in the form of a 5-forced-choice psychoacoustic test (5-FC), designed according to the psychoacoustic methods described in [115], and (4) three 5-minute spontaneous activity recording while listening to sound stimuli.

First, each participant read and filled in an informed consent of the study. Following the informed consent, the heart rate of each participant was measured with a pulse oximeter to calculate the IAF for data processing. The researcher then asked the participant to remove all metallic items such as jewelry, coins, keys, and belts to minimize electrical interference with the EEG equipment. Following, the researcher cleaned the forehead, back of the ears, and vertex of the participant. After cleaning the areas, the researcher placed the electrode cap on the head of the participant, adjusted it, connected the Bluetooth device to the cap, and injected hydrogel to reduce the impedance on the scalp. Impedances were monitored through the Smarting Streamer application. After verifying that all signals were being correctly displayed in the streamer, the signals were routed to the acquisition server of the OpenViBE application. Section one began by recording the electrical neural activity of participants for five minutes with closed eyes, as shown in the first block of Fig. 22.

Having recorded the baseline activity, the researcher started section two by first explaining the volunteer four components of sound in musical terms that could help the participant differentiate the sounds for the 5-FC: pitch, duration, loudness, and timbre. This was performed to allow the participant to associate the terms with the physical characteristics of sound: sound level, time, frequency, and frequency response. The sound of a piano was used to explain the concepts of pitch, duration, and loudness. For timbre, the sounds of a piano, flute, and accordion playing the same musical notes with the same pitch were compared. This protocol was retrieved from the Handbook of Neurologic Music Therapy and is shown inf Fig. 23 [116]. Finally, the researcher played the audio files of the three instruments separately, and the participant had to guess which instrument was playing. Once the participant successfully recognized the instruments, the researcher made the association between timbre and frequency response, explaining that frequency response could be observed as the “timbre” of audio devices and how humans can differentiate the sound quality of one pair from another. After the participant successfully understood the concepts, section three began by placing ATVIO on the head of the participant for answering the 5-FC shown in Fig. 24, where the volunteer had to differentiate three audio files of pink noise, one of them was the pink noise without inverse filtering since the frequency response of ATVIO would be the noise alone. The other two sounds were previously inverse filtered into two headphone models (SHURE and APPLE) to simulate that the participant was listening to the file in three different headphones. Audio files consisted of 2.73 seconds of a pink-noise. The three different frequency responses of headphones were presented in 36 different combinations shown in Appendix E. The participant had to listen to three sounds of pink noise and answer the following question:

¿How do the audio files sound?

Five options were given:

A) All audio files sound the same,
E) All audio files sound different,
I) Audio files 1 and 2 sound the same,
O) Audio files 2 and 3 sound the same, and
U) Audio files 1 and 3 sound the same.

These questions were recommended with the advice of a psychologist to reduce the bias of negative formulation of phrases, being the word different from the negative case.
In section four, the electrical neural activity of the participants was recorded for five minutes while listening to three stimuli, as shown in blocks two, three, and four in Fig. 22. Fig. 25 shows a participant during an EEG session.

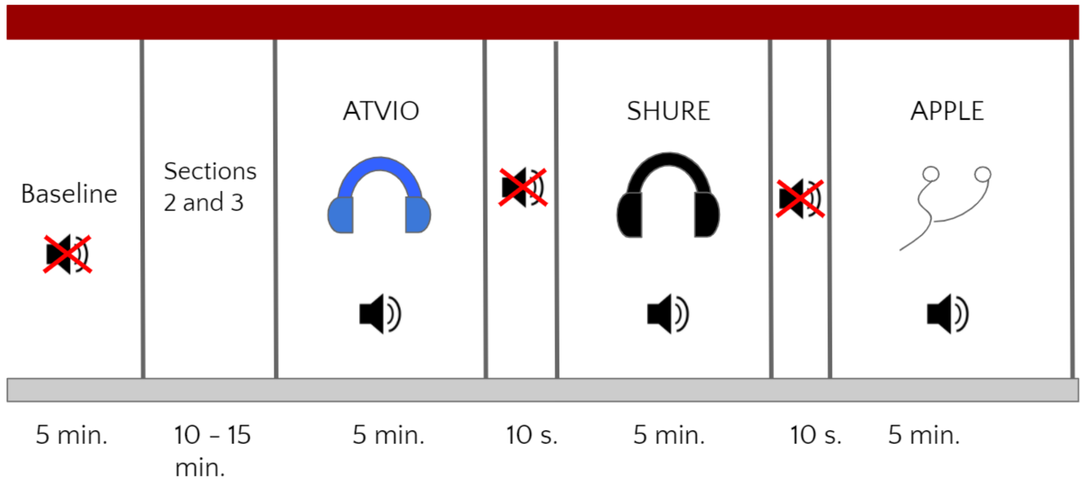


Fig. 22 Spontaneous activity acquisition. The first block on the left corresponds to baseline recording. The second, third, and fourth block represent the 5-minute recordings listening to ATVIO, SHURE, and APPLE.

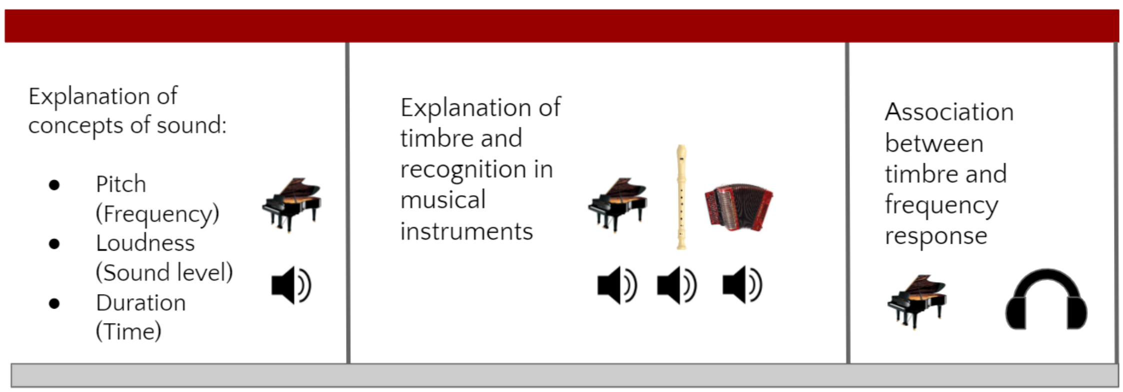


Fig. 23 Explanation of components of sound related to the frequency response. The aim was to explain the concept of timbre and associate it with frequency response.

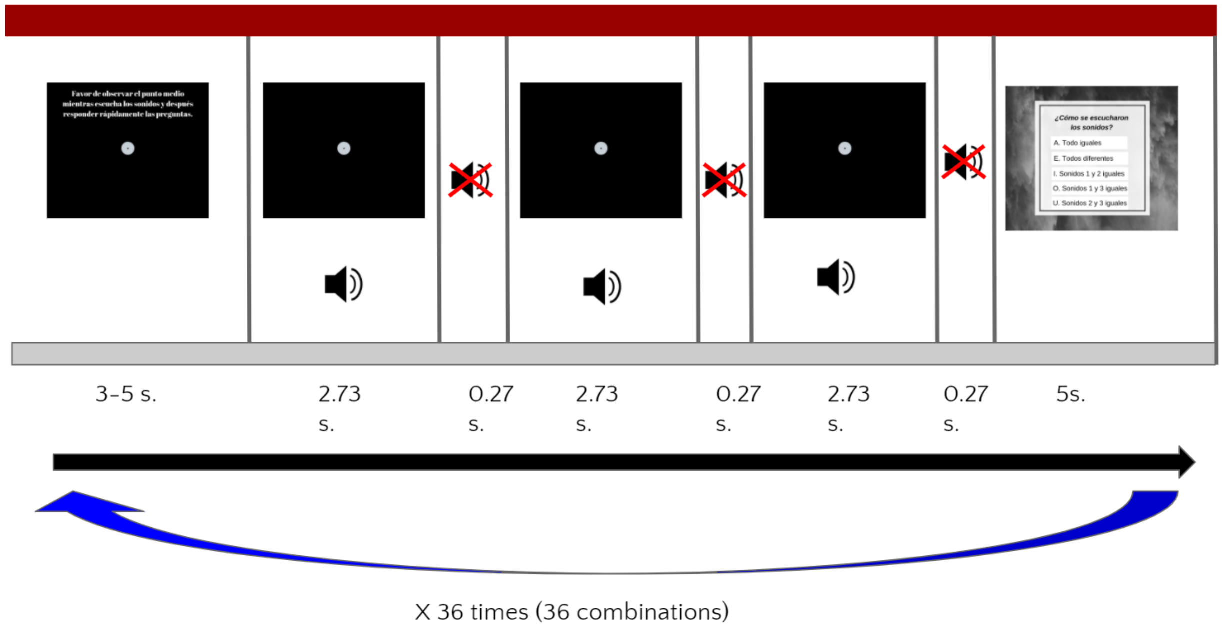


Fig. 24 5-FC psychoacoustic test. The participant first was asked to view a point on the screen. Then, three sounds were played through the headphones. Finally, the participant answered a question regarding the perception of the sounds.

At the end of the first session, each participant was given the pair of headphones used for the test, and 30 audio files were given to the participant to listen in their mobile devices and computers. Audio files contained the same 2.73 seconds file looped for 20 minutes according to the assigned headphone. Audio devices were inspected to turn off audio enhancers and equalizers, and were calibrated with the sound level meter to play the audio files at 60 ± 2 dB. This level was selected according to the recommendation of the World Health Organization for mobile devices [117]. Only one participant heard the file at 55 dB because it felt that 60 dB was quite loud. Each audio file had pink noise filtered to the headphone of the assigned group, and words were distributed in time through the sound file.

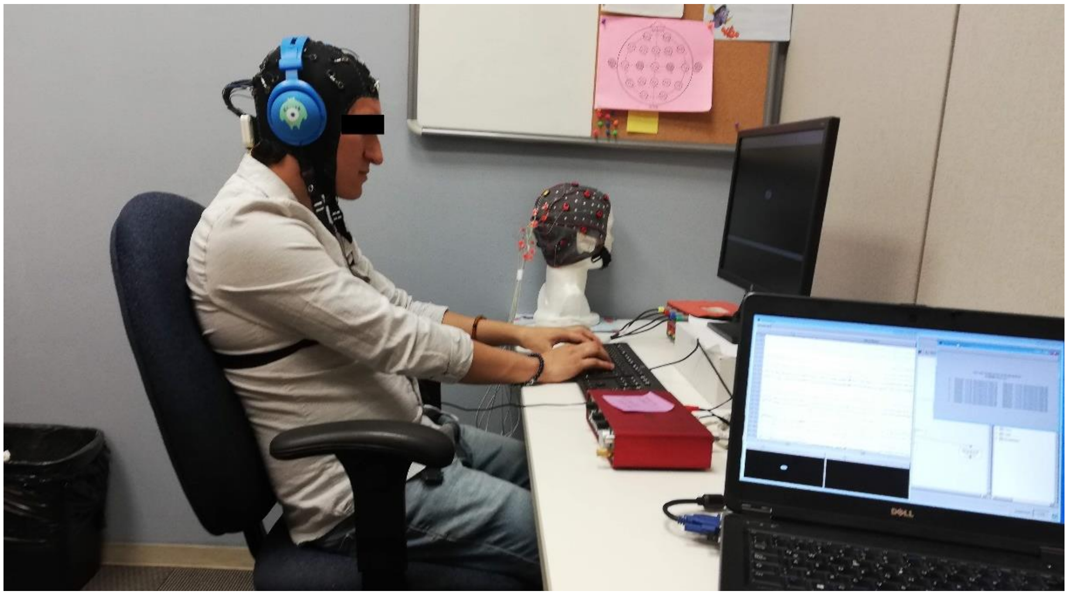


Fig. 25 Participant answering 5-FC.

4.5.2 One-month Pink Noise Exposure

The participant had to listen to one audio file per day for 20 minutes every day for 30 days and fill in an online questionnaire. Each audio file had a greeting at the beginning:

“Thank you. Your participation is essential for the study. Please, make sure that you put on your headphones correctly, and the volume level is adjusted at the assigned level”,

and a reminder for the questionnaire at the end:

“Thank you very much. We appreciate the time you dedicate to our study. We remind you to fill in the follow-up questionnaire after this recording.

In the questionnaire, the participant had to write his or her ID, the assigned group, the number of the audio file heard on that day, the number of words heard in the file, the words in the text presented in Appendix F, and had to state if the whole audio file was heard. In the end, the participant could write comments or describe any discomfort while listening to the audio file if applicable.

4.5.3 Last Session

This session followed the same procedure as the first one except for the heart rate measurement.

4.6 Signal Analysis

4.6.1 Data Acquisition and Preprocessing

EEG data of each subject was recorded using a 24-channel electrode cap with a sample rate of 250 Hz. Data were preprocessed in MATLAB with EEGLab functions as follows: First, the baseline was removed. Second, data were band-pass filtered in range 0.1-100Hz with a notch in 60 Hz. Third, monopolar referencing against the average between left and right mastoids was performed. Fourth, EEG signals were visually inspected to remove three types of artifacts: (1) cardiac and (2) ocular electrical activity, and/or (3) electrode pop-ups. Fifth, a copy of the data without the artifacts was high-pass filtered with a cut-off frequency of 1 Hz, and Individual Component Analysis (ICA) was applied to the signal through the FastICA algorithm to detect independent electrical sources. Finally, ICA weights were imported to the 0.1 – 100 Hz bandpass signals, and components were removed. In the end, only data of 29 individuals from the first session and 25 of the last session were used because data were free of artifacts.

4.6.2 Data Processing

4.6.2.1 Spontaneous Activity

For spontaneous activity analysis, the EEG signals were processed as follows: For the first session, the activity of 29 subjects was averaged since they have not been exposed to a specific stimulus yet. For the last session, data of 25 participants were averaged according to groups: seven EEG datasets were averaged for ATVIO, ten for SHURE, and eight for APPLE. A time-frequency analysis of the electrical activity of the brain was performed for both sessions. All neural bands followed the same procedure for data processing. First, a 5-minute baseline recording of each participant was filtered with a bandpass filtered in the range of neural band of interest. Then, data were squared to calculate the power of the signal and averaged in windows of one second. Following, each of the three 5-minute EEG recordings listening to pink noise was filtered to the neural band of interest, and the absolute power of the signal was calculated. Afterward, data were referenced to the baseline to obtain values of neural synchronization and desynchronization. Finally, the absolute power of each participant was averaged:

$$\boldsymbol{AP} = \frac{\sum_{i=1}^{t} \frac{\boldsymbol{v}_i^2}{\overline{\boldsymbol{v}}_{baseline}^2}}{\boldsymbol{t}}, \qquad (\mathbf{18})$$

where $\boldsymbol{v}_i^2$ is the power of the 5-minute signal listening to pink noise in sample corresponding to time $\boldsymbol{t}$, $\overline{\boldsymbol{v}}_{baseline}^2$ is the average power of the baseline, and $\boldsymbol{AP}$ the average absolute power of each subject.

Since time signals were filtered in frequency, power seems to decrease with higher frequencies. This is called the $\boldsymbol{1/f}$ phenomenon, where $\boldsymbol{f}$ is the frequency [118].

Therefore, a decibel conversion of the referenced power to reduce the effect of power-law was calculated with the following formula:

$$\boldsymbol{GAP = 10log_{10}(\sum_{i=1}^{n} AP_i)} \qquad (19)$$

where $\boldsymbol{GAP}$ is the grand average band power in decibels of the neural activity per headphone, and $\boldsymbol{n}$ is the number of subjects. Therefore, there are three $\boldsymbol{GAPs}$ per neural band, corresponding to ATVIO, SHURE, and APPLE.

4.6.2.2 Evoked Activity

For evoked activity analysis, the neural activity of participants was divided from the beginning for the comparison of the absolute area under the curve ($\boldsymbol{AUC}$) of the ERPs: trials of seven participants in ATVIO were averaged, ten for SHURE, and seven for APPLE. Five participants from a total of 29 were discarded because they did not continue in the study or their data had too many artifacts. EEG data of only correct answers were extracted for each subject in a time window of 2.2 seconds. Data were extracted 200 ms before the question window was displayed to the participant and two seconds after the question image was displayed. A window of 2.2 seconds was selected because the total average reaction time of participants was 1.98 seconds on the first session and 2.01 seconds in the last session. After the extraction of trials, data were analyzed with intertrial coherence analysis (ITC) to identify real components in the trials of ERPs for each group. After ITC analysis, data were averaged per group to calculate a grand average ERP (GERP) for the first and the last session. Finally, the intersection of the GAERP ($\boldsymbol{INT}$) of the first and last session validated with ICA was computed to identify the magnitude of $\boldsymbol{AUC}$:

$$\boldsymbol{AUC = \sum_{i=1}^{t} |INT_t|}, \qquad (20)$$

where $\boldsymbol{t}$ correspond to each sample of $\boldsymbol{INT}$ in time.

4.7 Statistical Evaluation

4.7.1 Spontaneous Activity

In the spontaneous activity section, data from participants in the first session were divided into neural oscillation bands but not in groups since none of the participants was previously exposed to a specific headphone model. For the last session, data were analyzed per oscillatory band and per groups according to the headphone model to which they were assigned after the first session. Shapiro-Wilk normality test (SW) showed no significant evidence of normality in the residuals of data ($p < 0.05$) in any of the five oscillatory bands. Levene's test (LT) for homogeneity of variances showed significant evidence in bands alpha, beta, and gamma ($p > 0.05$) but not for delta and theta ($p < 0.05$). Assumptions of analysis of variance (ANOVA) were not accomplished in any session. Therefore, the non-parametric Friedman test (FT) was selected to investigate if the mean of the GAP in decibels registered by 22 electrodes differ. Then, a post-hoc two-sided Eisinga test (ET) for pairwise comparison was performed.

To analyze the spontaneous activity of the last session, SW failed to reject the hypothesis that data comes from a normal distribution ($p > 0.05$) only in alpha but not in the other four oscillatory bands ($p < 0.05$). Bartlett's test (BT) for homogeneity of variances showed significant evidence in alpha ($p > 0.05$) LT did not show significant evidente in the four remaining bands ($p < 0.05$). Data were separated into groups: ATVIO, SHURE, APPLE; therefore, independence can be considered. Assumptions of ANOVA were accomplished only for alpha. Therefore, One-Way ANOVA was selected to investigate if the mean of the GAP in alpha registered by 22 electrodes differ. Then, a post-hoc two-sided Tukey test (TK) for pairwise comparison was performed. For the rest of the bands, non-parametric Kruskal-Wallis test (KW) and a post-hoc two-sided Wilcoxon rank-sum test (WRS) were selected.

For comparison between the first and the last session, SW failed to reject the hypothesis that data comes from a normal distribution ($p > 0.05$) for most of the bands except Beta. Therefore, a two-sided t-test for the difference between the means of the first session and the last session per band and per group was selected for delta, theta, alpha, and gamma. For Beta, a two-sided Sign-test was selected. Statistical analyses were performed per band and not across bands.

4.7.2 Evoked Activity

In the evoked activity section, AUC was divided into groups to analyze statistical differences between the first and last sessions. SW rejected the hypothesis that data comes from a normal distribution ($p < 0.05$). LT for homogeneity of variances did not show significant evidence in data ($p > 0.05$). Assumptions of ANOVA were not accomplished. Therefore, KW was selected to investigate if the AUC across the three groups differed significantly. Then, WRS was computed.

4.7.3 5-FC

For the answers of the 5-FC, statistical analysis in the difference of answers of 36 scenarios between first and last session was computed for each group. SW test did not show significant evidence of normality in the residuals of data ($p < 0.05$). LT for homogeneity of variances showed significant evidence in data ($p > 0.05$). ANOVA assumptions were not accomplished. Therefore, FT was selected to investigate if differences in answers across groups were significant. The post-hoc test was not selected because the data was not significantly different ($p > 0.05$).

Statistical analysis in the difference of average reaction time (RT) of 36 scenarios between the first and last session was computed for each group. SW test showed significant evidence of normality in the residuals of data ($p > 0.05$). LT did not show significant evidence in data ($p > 0.05$). Therefore, ANOVA was selected to investigate if differences in reaction time were significantly different. Following, TK was used for multiple comparisons.

Chapter 5

Results

The present chapter presents electroencephalographic and statistical results of both spontaneous and evoked activity of the brain of participants in two scenarios: before and after thirty days of exposure to pink noise in three different models. Only the figure for alpha is herein reported. The rest of them (delta, theta, beta, and gamma) are reported in Appendix G. In figures of GAP, colors in the negative values refer to neural desynchronization and colors in positive values to synchronization. Color in 0 dB represents baseline, neural activity when participants do not perform a task and have eyes closed. Typical decibel values are in the range ± 1 - 4 dB [74]. Only significant differences are reported in the text. The complete p-values are reported in tables 4-6.

5.1 Spontaneous Activity

5.1.1 First Session

With a level of significance of 0.05, there is enough evidence to reject the null hypothesis that there are no differences in the mean of the GAP for every band ($p < 0.05$).

In pairwise comparisons, there was enough statistical evidence to conclude a significant difference between SHURE and APPLE ($p < 0.025$) in delta. ATVIO and SHURE present higher power values than SHURE, ATVIO in the right hemisphere in the temporal region, and ATVIO in the frontal region.

APPLE showed significant differences compared to ATVIO ($p < 0.025$) and SHURE ($p < 0.025$) in theta. APPLE showed higher power values in the frontal and right occipital region.

SHURE showed significant differences compared to ATVIO ($p < 0.025$) and APPLE ($p < 0.025$) in alpha. Fig. 26 compares the electrical activity of headphone models. SHURE showed lower power values compared to APPLE and ATVIO.

APPLE showed significant differences compared to ATVIO ($p < 0.025$) and SHURE ($p < 0.025$) in beta. Neural activity was higher in most of the brain cortex in APPLE.

ATVIO showed significant differences when compared to SHURE ($p < 0.025$) and APPLE ($p < 0.025$) in gamma. SHURE showed higher power values in temporal, parietal, and occipital regions. APPLE showed higher power in frontal, occipital, and temporal-parietal areas.

Table 4 P-values of FT and ET for the first session.

		Neural Band				
		Delta	Theta	Alpha	Beta	Gamma
	FT	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**
ET	ATVIO - SHURE	0.306	0.260	**< 0.025**	0.820	**< 0.025**
	SHURE - APPLE	**< 0.025**	**< 0.025**	**< 0.025**	**< 0.025**	0.083
	ATVIO - APPLE	0.306	**< 0.025**	0.710	**< 0.025**	**< 0.025**

5.1.2 Last Session

With a level of significance of 0.05, there is enough evidence to reject the hypothesis that there are no differences in the GAP for every band ($p < 0.05$).

All pairwise comparisons between ATVIO, SHURE, and APPLE differed significantly in bands alpha, beta, gamma, and delta ($p < 0.025$). The results of neural activity sustain statistical analysis. SHURE registered lower power values compared to ATVIO and APPLE in bands delta, theta, alpha, and beta. High values of power were registered mostly in the occipital and frontal areas in delta, theta, and gamma. The right temporal region reported high power in gamma. APPLE shows higher neural activity in all bands. ATVIO reported low alpha levels in the frontal, central and occipital region; and in the frontal, central and left temporal region in delta. In theta, beta, and gamma, high values of power above baseline were observed mostly in the temporal, parietal, and occipital areas.

Table 5 P-values of KW/ANOVA and WRS/TK for the last session.

	Neural Band				
	Delta	Theta	Alpha	Beta	Gamma
Statistical Test	KW	KW	ANOVA	KW	KW
	< 0.05	**< 0.05**	**< 0.05**	**< 0.05**	**< 0.05**
Pairwise comparison	WRS	WRS	TK	WRS	WRS
ATVIO - SHURE	**< 0.025**	**< 0.025**	**< 0.025**	**< 0.025**	**< 0.025**

SHURE - APPLE	**< 0.025**	**< 0.025**	**< 0.025**	**< 0.025**	**< 0.025**
ATVIO - APPLE	**< 0.025**	0.039	**< 0.025**	**< 0.025**	**< 0.025**

5.1.3 First Session vs. Last Session

With a level of significance of 0.05, there is enough evidence to conclude that there is a difference in the GAP between the first and last sessions in all groups in delta, alpha, and gamma ($p < 0.025$).

In theta, there is enough evidence to conclude that there is a difference in GAP between the first and last session in ATVIO and APPLE ($p < 0.025$). In beta, there is a significant difference in GAP between the first and last sessions only in SHURE ($p < 0.025$).

Table 6 P-values of T-test/Sign-test between sessions.

	Neural Band				
	Delta	Theta	Alpha	Beta	Gamma
Statistical test	T-test	T-test	T-test	Sign-test	T-test
ATVIO	**< 0.025**	**< 0.025**	**< 0.025**	0.286	**< 0.025**
SHURE	**< 0.025**	0.319	**< 0.025**	**< 0.025**	**< 0.025**
APPLE	**< 0.025**	**< 0.025**	**< 0.025**	0.623	**< 0.025**

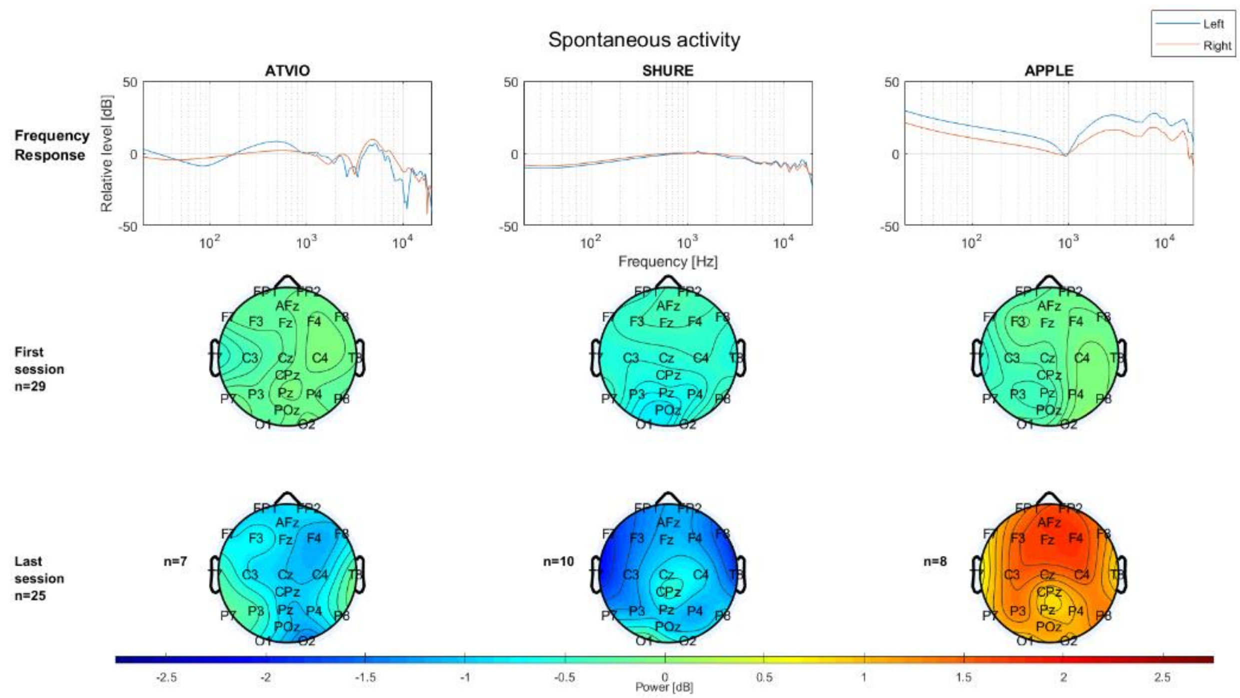


Fig. 26 GAP in alpha band. First row shows the frequency response of every headphone. Second row presents GAP in first session. Third row presents GAP in last session.

5.2 Evoked Activity

With a level of significance of 0.05, there is enough evidence to reject the hypothesis that there are no differences in AUC across headphone groups ($p < 0.05$). The most significant difference was observed between groups ATVIO and SHURE ($p < 0.025$). The blue line corresponds to the GAERP in the first session, and red line to the last session. The purple area shows INT of the two GAERPs. The area under the curve is presented in the graph on the second row of the Fig 27. Area in red shows the time where the signal passed the significance test of ITC at 0.05 level of significance in the first session, and yellow is for the last session. The area in orange corresponds to ITC analysis intersection, meaning that same components were present in both the first and last session. Figure 28 shows the AUC for each electrode per group. The figure presents four cases of ERP components: (1) components present in both sessions, (2) components present in first but not final session, (3) components present in last but not first session, (4) and components not present in any session. Electrodes with large labels are case 1, the rest are cases 2-4. For ATVIO, components in both sessions were present in FP1, FP2, AFZ, F3, F4, F7, F8, Cz, C3, C4, P4, P8, POz, O1, and O2. For SHURE, components were present in FP1, FP2, AFZ, Fz, F3, F4, F7, F8, Cz, C3, C4, T7, T8, CPz, Pz, P4, and P8. For APPLE, components were present in FP1, FP2, AFZ, Fz, F3, F4, F7, Cz, C3, C4, CPz, P7, P8, O1, and O2.

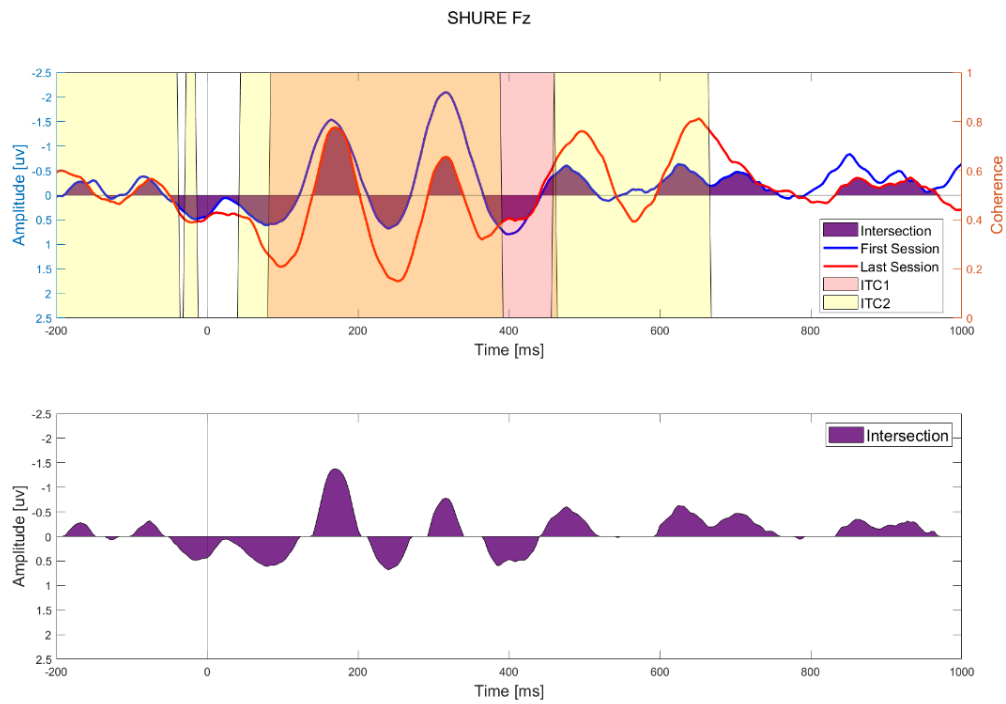


Fig. 27 GAERP and INT in case 1 filtered at 25 Hz. The blue line is the GAERP in the first session, the red line is in the last session, and the area in purple is INT. Areas in light red and yellow are possible components of GAERP for the first and last session, respectively.

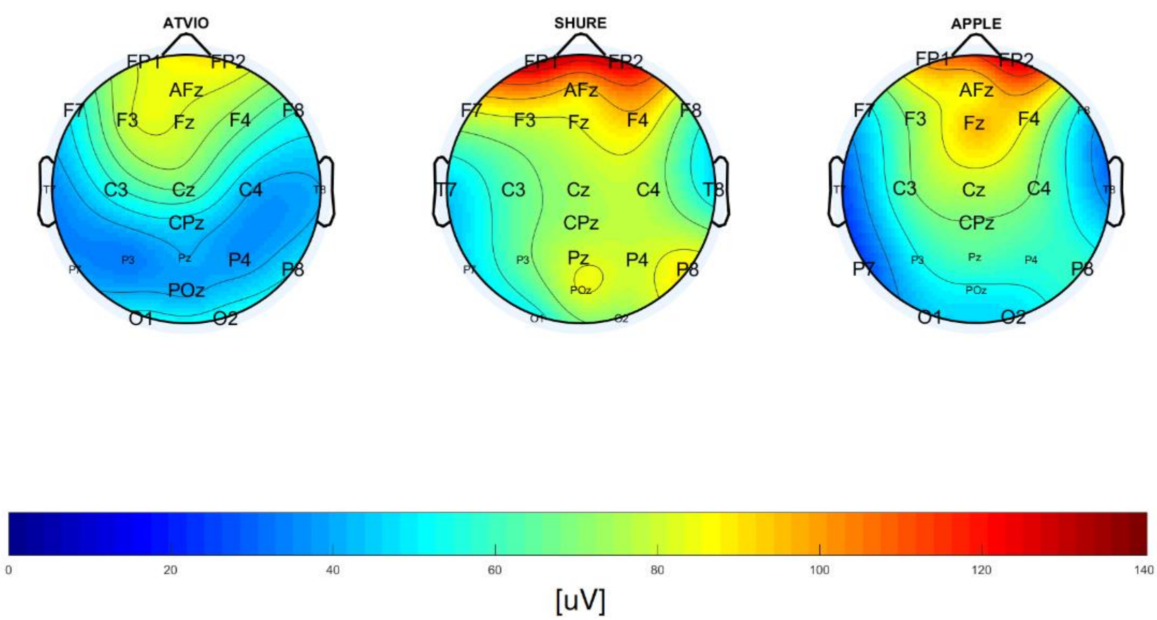


Fig. 28 AUC of INT for each electrode per group. Electrodes with large labels correspond to case 1.

5.4 Answers and Reaction Time

With a significance level of 0.05, there is enough evidence to fail to reject the hypothesis that the differences in answers are significant ($p = 0.6326$).

Differences in average RT showed evidence of significant difference ($p < 0.05$), being the most notable difference between SHURE and APPLE ($p < 0.05$). Fig. 34 presents differences in RT and answer for 36 scenarios in SHURE. Labels in x axis show the 36 combinations of sounds. C corresponds to ATVIO, S for SHURE, and A for APPLE. For example, CSA means that first ATVIO was presented, then SHURE, and at the end APPLE. Top graph shows the reaction times and their deviation for each question in SHURE. Bottom graphs shows the differences in percentage of the first session and last session. Figures for APPLE and ATVIO are presented in Appendix E.

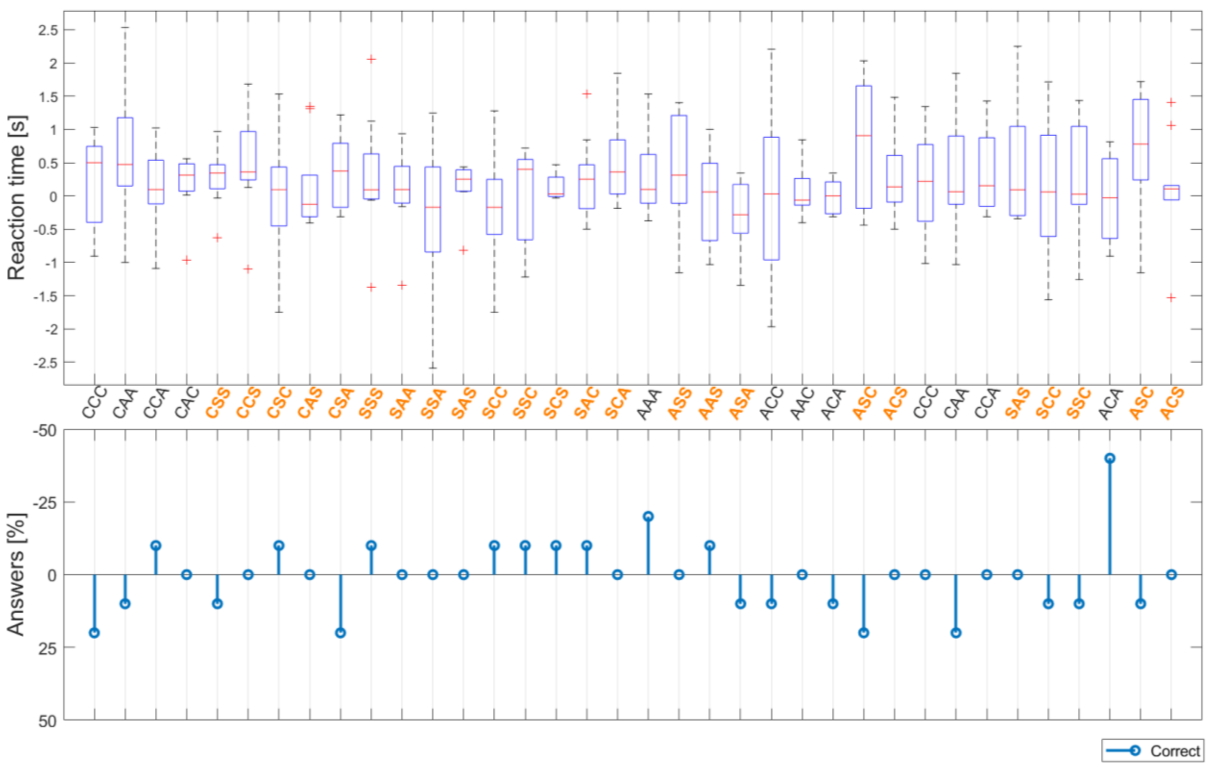


Fig. 29 Difference in answers and RT of first and last session for SHURE.

Chapter 6

Discussion

6.1 Review

Forty-eight studies concerning acoustic therapies for tinnitus treatment from 2010-2019 were reviewed. They were divided into six categories, and within categories, none of the authors used the same audio devices. The standardization of audio devices for experimental designs in tinnitus treatment has not yet been considered, even though it has been previously mentioned [119]. The most used devices were hearing aids. Across studies, the most used pair of headphones was Sennheiser HDA 200. These headphones were designed for extended high-frequency testing [120]. Some studies did not find significant differences using a specific type of therapy or when compared to other therapeutic sounds [5,32,66,76,91], and others found worsening of tinnitus [12,94]. Another finding was that two methods might seem to contradict each other, but positive results have been reported for both. One approach is to filter sounds and remove the frequency bandwidth around the tinnitus frequency, as mentioned in the Harmonic Content section. The other method consists of the opposite of this, leaving the frequencies around the tinnitus frequency and masking it or setting the filtered noise level just below the unreal sound. It appears that these methods, when controlled, have a positive impact on tinnitus reduction. Nevertheless, if these are not intended, the frequency response of the device used must be considered to prevent alterations in the harmonic content of the therapy. Another finding was that the patient was free to choose the type of device (headphones or earphones) to use in some studies. This could cause differences in results since it is impossible to determine specifications such as the frequency range, frequency response, sound level, and stereo compatibility unless the devices are measured in advance. For example, suppose the binaural beats therapy must be implemented. In that case, scenarios as headphones playing the sound in mono, a fabric defect that sends only the left channel to both sides, or the frequency range outside the range of the device could be present. Some studies implemented their therapies through mobile devices [13,84,95,100]. It is crucial to calibrate mobile devices and turn off integrated audio enhancers and make sure that listeners do not set sound levels above recommendation [117].

From the 48 revised articles, only 10 reported the use of neuroimaging techniques (NI) to evaluate the effectiveness of acoustic therapies [6,11,12,67,75,83,89,94,99,100]. The rest of the articles and some of the mentioned above used subjective data to evaluate the effectiveness of the therapies, being the most common tests THI, Tinnitus Functional Index, Hospital Anxiety and Depression Scale, and VAS. NI allows observing objective responses of the brain to evaluate the effectiveness of treatments, not just based on subjective perception. This research field has been previously referred to as Neuroacoustics [3,4].

6.2 Limitations of Other Methods Compared to the Inverse Filtering Technique

Although the calibration methods mentioned in chapter 1 seem to perform well, signal processing happens in real-time. This requires adding a microphone to the device and modifying the actual model. A calibrating system by Sonarworks allows adjustment to mobile devices according to the hearing preferences of the listener [121]. In a clinical approach, hearing choices may be discarded if the therapy has another aim. The methods implemented in this study modify the harmonic content to the inverse frequency response in a computer. It only requires measuring the frequency response of the headphones in advance. All sound files are not filtered in real-time but in the sound file itself, minimizing other functionality errors of computers and mobile devices. After calibrating the signal, researchers could have evidence that artifacts and resonances caused by the system are minimized. These nuisance factors would not have much impact on the experiment results. High-quality sound devices are usually quite expensive, and patients and researchers might not have enough resources to acquire them. It is always best to have adequate tools for experiments, but other solutions like the technique proposed in this work could be an alternative implementation.

6.3 Neural Activity while Listening to Sounds

In this study, neural responses differed from psychoacoustic answers, giving enough evidence to sustain the central hypothesis. The analysis of neural activity recorded with EEG of participants listening to pink noise in emulated headphone models was undertaken for this study. The total sound pressure level on each headphone was 60 ±2 dB. Pink noise was selected to elicit auditory response over the neural cortex because of its flat-power density spectrum [68]. It has reduced loudness at high frequencies, range in the hearing area where other signals as white noise could cause discomfort [26,28].

Due to the high cost of SHURE and APPLE, and because the type of headphones was a factor that caused differences in the perception of sound, models of ATVIO were purchased for each participant. The second inverse filtering technique was applied to emulate as if the participants were listening to noise in three different headphones. Note that the curves of frequency response were corrected as if they were measured with pink noise. This was also applied in the inverse filtering technique of the sounds.

6.3.1 Spontaneous Activity

Figures in the spontaneous activity section and Appendix G show the GAP of the electrical activity in each band. Large positive values indicate neural synchronization, and negative values indicate desynchronization. Values in 0 dB indicate baseline. These terms will be used interchangeably.

The first analysis aimed to determine differences in the electrical activity of the brain while people listened to the same sound in different headphones before and after a month of daily exposure. Alpha band of EEG was analyzed since it is related to most of the cognitive states of human beings [46]. Widespread neural synchronization in the brain cortex in this band can be related to the encoding of acoustic material [48]. It has also been documented that a more widespread neural desynchronization on alpha is related to an increase in the complexity of a task, an efficient task performance, and more effort and attention needed [49]. In ATVIO and APPLE, widespread neural synchronization in alpha was observed. This could be related to the encoding of information effect in neural activity. Pink noise is composed of all audible frequencies, but as headphones do not allow the brain to encode all the frequencies, the brain must complete the missing information. In contrast, there was more neural desynchronization in SHURE. This could be related to the frequency response of the headphones. Due to the flatter response in SHURE compared to ATVIO and APPLE, it can be said that the participants listened to a complete sound since most of the audible frequencies were delivered through the headphones with the minimum alteration of the three models. As all the auditory information has already been encoded, the brain now interprets such information showing desynchronization [49]. These values are small since the task is a simple one. In APPLE, synchronization can be observed in a larger area compared to ATVIO. This could be associated with a reduction in the frequencies and levels of the sound. It seems that APPLE modifies more audio information and makes the brain complete much more missing data. The last analysis aimed to determine differences in the electrical activity of the brain after a month of daily exposure. In Fig. 26 third row, there was a significant change in neural synchronization/desynchronization in the whole cortex in the last session compared to the first session for all headphone models. Both ATVIO and SHURE show lower GAP values, but SHURE showed the lowest values. This could mean that, after a month of exposure, the stage of encoding acoustic material is skipped, and the brain goes directly to the retrieval and recognition of sound [48], related to cognitive performance [50]. The opposite is observed in APPLE. An explanation could be that, as this model has a reduction in the mid-range of frequencies, the brain is continually trying to recreate or complete sound characteristics, and therefore, the brain is not wholly focused on the treatment. On the contrary, SHURE are studio-quality headphones, so less completion of information is needed, and the brain uses all of its resources to focus on the treatment.

The beta-band was analyzed since it is related to cognitive states of conscious focus, memory, and thinking [46]. As observed in the second row of GAP in beta, only APPLE reported neural activity values closer to the baseline. SHURE and ATVIO did not differ significantly. Recent research related to auditory stimuli and their influence in the beta-band has shown modulation of neural activity in the auditory cortex. It has been linked to rhythmic patterns, such as clicks of a metronome [53]. During the first session, while being exposed to the five-minutes noise, ten participants reported that they heard a rhythmic pattern. Eight participants reported it while listening to ATVIO, five while listening to SHURE, and only two while listening to APPLE. This might be the reason that neural activity in ATVIO and SHURE was not significantly different and why neural activity in APPLE is closer to the baseline. In both APPLE and SHURE, there was desynchronization in neural activity because the rhythmic pattern was evident. During the month of exposure, only one participant in SHURE reported hearing the rhythmic pattern for three days while listening to the assigned audio file. This is possible since all audio files were the same pink noise file of 2.73 s looped over five minutes. This band seems to be related to the motor area and body movement [49], but it has also been linked to memory processing [48]. Desynchronization has been observed while presenting memorized sounds during the Auditory Steinberg Memory task [48]. In figure of beta-band in Appendix G, it is observed that the lower values of GAP are in SHURE. This might indicate that most participants were focused on the sound in SHURE because it was easier to recognize than in the other two stimuli. The human brain goes directly towards auditory interpretation, agreeing with the results in the alpha-band. Contrary to these results, desynchronization was found in both alpha- and beta-bands, and not only in beta, agreeing with the findings in [49,53].

Gamma-band was analyzed since it is related to cognitive states of attention, memory, information, and learning processing. The second row of gamma figure in Appendix G showed greater synchronization in the occipital and left temporal region in SHURE, and left temporal and the right frontal/occipital areas of APPLE. From the results mentioned in the beta section, most participants perceived the rhythmic pattern in ATVIO compared to SHURE and APPLE. Gamma has shown to encode rhythmic and beat information [53]. This might explain why neural activity had less synchronization in ATVIO. The brain uses more resources to complete information. The rhythmic pattern might be less evident in this model, especially if the dominant frequencies are in a range with a reduced level. APPLE, the model with a reduced and irregular frequency response, needs to complete the missing information. Therefore, it needs more resources to encode the information, as shown in the alpha section. In the last session, neural activity is similar to beta-band, having the greatest GAP in the central-occipital region. There is evidence stating that gamma can be coupled to other bands [51]. It appears that after the month of exposure, participants in APPLE still needed more resources to process the acoustic stimuli in ATVIO.

Delta-band has been related to states of unconsciousness [46]. Synchronization in this band, while being awake, has been associated with brain injuries and neural disorders [4,46]. On the other hand, neural oscillations in delta band have been observed in several cases: activation of the temporal cortex during sound localization tasks [55], cortical entrainment to stimuli, and years of musical training [53], and alignment in the phase of neural oscillations during rhythmic stimulation, increasing stimulus processing and decreasing reaction times [51]. APPLE group had the longest reaction time for both the first and the last session. As mentioned in the alpha band section, this might be due to the acoustic encoding process instead of directly processing the information, reflecting in widespread alpha synchronization [48]. SHURE group had a longer reaction time than ATVIO, but neural activity did not differ significantly. This might indicate that participants using supra-aural and circum-aural headphones processed information better than when using intra-aural headphones.

Theta-band activity is found mostly in states of sleep [46]. As in theta, prominence in this band has been found in auditory disorders [4]. However, there is evidence reporting that desynchronization and synchronization change levels with experience and learning [48], and that synchronization increases in task demands [50]. Neural desynchronization also increases with memorized stimuli such as words. As observed in the figure of GAP in Appendix G, SHURE has the most desynchronization values, possibly indicating that after a period of exposure, this group recognized the sounds better, agreeing with results in alpha.

6.3.2 Evoked Activity

AUC in 5-FC showed greater activation in PFC in all groups. This evidence is not surprising because most of the auditory information integrates into PFC [40]. Interestingly, there was a greater widespread AUC in SHURE in the cortex. Larger values of AUC are observed in the parietal-occipital region, an area associated with spatial representation of sound sources and localization of a human being in space [42,45]. Those values might indicate that SHURE stimulates the sense of space more than ATVIO and APPLE. As mentioned earlier, the frequency content of sound can alter spatial representation and the processing of acoustic features. It is possible that SHURE, compared to ATVIO and APPLE, creates a more enriched acoustic environment that allows the brain to significantly improve the use of auditory working memory to discriminate sounds, sustaining the evidence in the alpha band analyzed in spontaneous activity. In channel Fz, ERP showed all aural stimulus components and late components of cognitive processing. In Fig. 27, component N1 has a large amplitude in both sessions, and N2 only in the first session. This result might indicate that the brain needed fewer resources to discriminate sounds in the last session, which can be attributed to the constant stimulation during the implementation period.

Participants did not seem to have problems to differentiate the three auditory stimuli psychoacoustically. Answers to the first and last sessions did not differ significantly. The lowest score was reported in SHURE, with 89.44% of correct answers. However, the reaction time between SHURE and APPLE was significantly different, having SHURE the shortest reaction time in the last session. The fastest time overall was in the last session of ATVIO with 1.34 s, and the longest was in the first session of APPLE with 1.8753. This information is provided in Appendix G.

6.4 Limitations and Future Work

The filtering technique is limited to the performance of the headphones. Reducing resonances in the frequency response turns in a compromise of the frequency range of the audio device. A better implementation could be observed if high-quality headphones were used for auditory stimulation, but this might not be accessible for researchers in some cases. Therefore, specialized affordable headphones should be considered for future development.

This study only included healthy participants with normal hearing to validate the Proof of Concept before evaluating the effect in people with other conditions. Nevertheless, these findings could be related to the overcompensation - suppression effect mentioned in the acoustic treatments section. Therefore, they prove that audio devices play a crucial role in the effectiveness of therapies. A future study should include participants with neurological conditions as chronic subjective tinnitus to validate audio device standardization for treatments.

This work does not intend to promote a specific brand of audio devices, nor state that one of the headphones used during the experiment is, in general, better than the other two models. It instead wants to prove that the frequency response affects brain oscillation responses, and therefore, might modify the effect of auditory stimuli. For these reasons, audio devices must be chosen with caution when implemented in acoustic treatments.

Chapter 7

Conclusion

Standardization of audio devices for the implementation of acoustic treatments should be considered by researchers to ensure that therapies reach original intent. It is feasible to flatten the frequency response of headphones for better performance in therapies. Acoustic features can be analyzed in the electrical activity through neural bands, demonstrating that frequency responses change the perception of a sound. As shown herein, if headphones do not appropriately send the whole auditory information, the human brain will first complete missing information (auditory encoding reflected as neural synchronization of the alpha and theta waves). It will then interpret the sound that is receiving (interpretation reflects as neural desynchronization of the alpha and theta waves). Only SHURE headphones sent more information, and the human brain went directly towards auditory interpretation. The transient neural response observed during an auditory discrimination task of three stimuli revealed that ATVIO and APPLE activated the temporal and frontal lobes. These regions are associated with decoding the physical properties of the sound and interpretation of auditory information. However, and surprisingly, SHURE headphones did not only activate those lobes, but they also activated the parietal-occipital region. This area is related to the spatial sense of human beings. As SHURE headphones were the only audio devices that allowed the participants to hear a broad frequency band in this study, they enabled the listener to achieve a clearer sense of space.

Appendix A

Abbreviations and acronyms

Table 1A Abbreviations and acronyms.

	Description
ATVIO	Atvio® headphone model
SHURE	Shure® headphone model
APPLE	Apple® headphone model
A1	Primary auditory cortex
VL	Ventral lateral region
DL	Dorsal lateral region
EEG	Electroencephalography
CRN	Acoustic coordinated reset neuromodulation
SM	Shure® mx150 microphone
DBX	dbx® RTA-M (DBX) microphone
5-FC	5 asked forced- choiced test
AP	Average absolute power
GAP	Grand average band power
INT	Interesction of GAERP of first an last session
FT	Friedman test
ET	Eisinga test
SW	Shapiro-Wilk test

LT	Levene's test
ANOVA	Analysis of variance
WRS	Wilcoxon rank sum test
TK	Tukey’s test
BT	Bartlett's test
ST	Sign test
KW	Kruskal-Wallis test
RT	Average reaction time
CST	Chronic subjective tinnitus
VCN	ventral cochlear nucleus
DCN	dorsal cochlear nucleus
SOC	Superior olive
NLL	Nucleus of lateral lemniscusa
IC	Inferior Colliculus
HRTF	Head-related transfer function
ILD	Interaural level difference
ITD	Interaural time difference
ADHD	Attention-deficit/hyperactivity disorder
FFT	Fast Fourier transform
IFFT	Inverse fast Fourier transform
STS	Superior temporal sulcus
TPO	Temporal-parietal-occipital region
PFC	Pre-frontal cortex

IAF	Individual alpha frequency
ERP	Event-related potential
AERP	Auditory event-related potential
TRT	Tinnitus retraining therapy
THI	Tinnitus handicap inventory
HNMT	Heidelberg Neuro-Music Therapy
CAABT	Cochleural alternating acoustic beam therapy
MLS	Maximum length sequence
PS	Point-source
AMP	Alesis® RA-100 reference amplifier
SC	Focusrite® Scarlett 2i4 audio interface
PSAMP	PS, SC and AMP as one system
GAERP	Grand average event-related potential
ITC	Intertrial coherence
AUC	Area under the curve
VAS	Visual analogue scale
PTA	Pure-tone audiometry
ICA	Individual component analysis

Appendix B

Variables and Symbols

Table 1B Variables and symbols.

	Descritpion
$\boldsymbol{S(t)}$	Sample in voltage units in time t
$\boldsymbol{S(t)}$	Sample in voltage units in frequency f
$\boldsymbol{t}$	Time
$\boldsymbol{f}$	Frequency
$\boldsymbol{Hz}$	Hertz
°	Degrees
$\boldsymbol{kHz}$	Kilohertz
$\boldsymbol{W_n}$	Roots of unity
$\boldsymbol{H_{sys}(t)}$	Impulse response of system “sys”
$\boldsymbol{H_{sys}(f)}$	Transfer function of system “sys”
$\boldsymbol{H_{var}(t)}$	Impulse response of device “var”
$\boldsymbol{H_{var}(f)}$	Frequency response of device “var”
$\boldsymbol{X_n(t)}$	Input signal “n” in time domain
$\boldsymbol{Y_n(t)}$	Output signal “n” in time domain
$\boldsymbol{X_n(f)}$	Frequency content of input signal “n”
$\boldsymbol{Y_n(f)}$	Frequency content of output signal “n”
$\boldsymbol{R_{var}(f)}$	Frequency response of device “var” in decibels
$\boldsymbol{DR_{AB}(f)}$	Difference in frequency response between devic “A” and “B”

s	Seconds
min	Minutes
ms	Miliseconds
mm	Milimeters
dB	Decibels
SPL	Sound Pressure Level
v^2	Absolute power
$\overline{v}^2_{baseline}$	Average absolute power in baseline

Appendix C

Technical specifications of audio devices

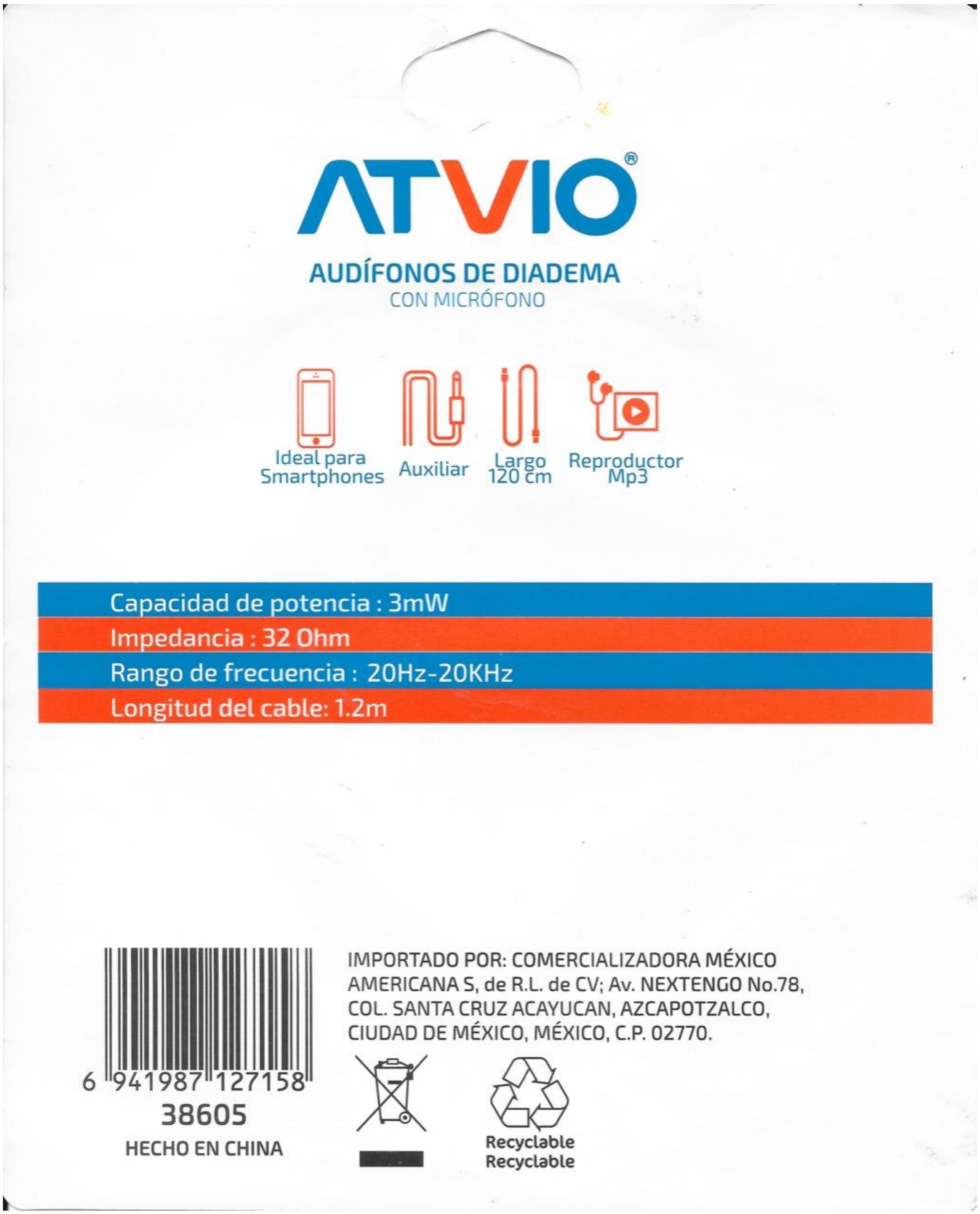


Fig. C1 Specifications of ATVIO.

SHURE

SRH1840

PROFESSIONAL OPEN-BACK HEADPHONES

SRH1840 Professional Open-Back Headphones

OVERVIEW

The SRH1840 Professional Open-Back Headphones feature individually matched drivers for an unparalleled acoustic performance, including smooth, extended highs and accurate bass. Developed with premium materials and precision engineering, the custom-crafted design is extremely lightweight and durable. Ideal for mastering or critical listening applications. The included storage case, replacement set of velour ear pads, replacement cable, and threaded adapter ensure years of uninterrupted listening enjoyment.

FEATURES

- Individually matched 40 mm neodymium drivers for unparalleled acoustic performance with smooth, extended highs and accurate bass
- Open-back, circumaural design for exceptionally natural sound, wide stereo image, and increased depth of field
- Lightweight construction featuring aircraft-grade aluminum alloy yoke and stainless-steel grilles for enhanced durability
- Steel driver frame with vented center pole piece improves linearity and eliminates internal resonance for consistent performance at all listening levels
- Ergonomic dual-frame, padded headband is lightweight and fully adjustable for hours of listening comfort
- Optimized for connection to external headphone amplification systems
- Dual-exit cables with gold-plated MMCX connectors provide secure connection and detachability for easy storage or replacement
- Replaceable velour ear pads with high-density, slow-recovery foam for exceptional comfort
- Individually tested and serialized
- Legendary Shure durability withstands the rigors of everyday use
- Includes additional pair of velour ear pads, two detachable cables, threaded ¼" (6.3 mm) gold-plated adapter, zippered hard storage case and two-year limited warranty

SPECIFICATIONS (SUBJECT TO CHANGE)

Type	Open-back, circumaural
Driver Type	Dynamic, Neodymium magnet
Driver Size	40 mm
Frequency Range	10 - 30,000 Hz
Sensitivity (@ 1 kHz)	96 dB/mW
Impedance (@ 1 kHz)	65 Ohms
Maximum Input Power	1000 mW
Plug	Gold-plated 1/8" (3.5 mm) stereo plug with threaded 1/4" (6.3 mm) gold-plated adapter
Cable Length/Type	2.1 meters (6.9 ft) / Dual-exit, detachable oxygen-free copper
Removable Ear Pads	Yes
Collapsible	No
Weight (without cable)	268g (9.4 oz)

ACCESSORIES AND REPLACEMENT PARTS

Replacement Velour Ear Pads	HPAEC1840
Threaded ¼" (6.3 mm) Adapter	HPAQA1
Zippered, Hard Storage Case	HPACC2
Replacement Dual-Exit Detachable Cable	HPASCA2

AVAILABLE MODELS

SRH1840-BK	SRH1840 Premium Closed-Back Headphones, Black. Includes additional pair of velour ear pads, two detachable cables, zippered hard storage case, threaded 1/4" (6.3 mm) gold-plated adapter.

Data subject to change without notice in interest of product improvements.

www.shure.com

Fig. C2 Specifications of SHURE.

EarPods with 3.5 mm Headphone Plug

$19.00

Add to Bag

Pickup:
Check availability

Ships:
1–3 business days
Free Shipping
Get delivery dates

Need some help? Contact us.

Product Information

Overview

Unlike traditional, circular earbuds, the design of the EarPods is defined by the geometry of the ear. Which makes them more comfortable for more people than any other earbud-style headphones.

The speakers inside the EarPods have been engineered to maximize sound output and minimize sound loss, which means you get high-quality audio.

The EarPods also include a built-in remote that lets you adjust the volume, control the playback of music and video, and answer or end calls with a pinch of the cord.

Highlights

Designed by Apple

Deeper, richer bass tones

Greater protection from sweat and water

Control music and video playback

Answer and end calls

What's in the Box

EarPods with 3.5 mm Headphone Plug

Tech Specs

General

With Remote and Mic

System Requirements

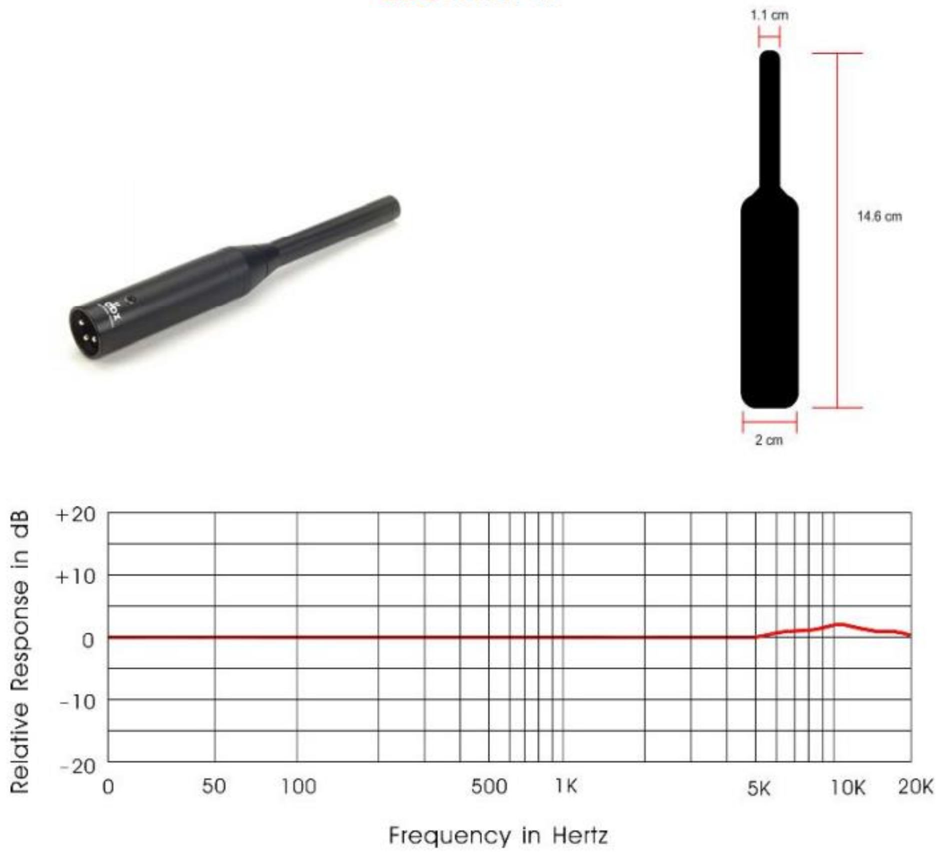
Compatibility Information

The remote and mic are supported by all models of iPod, iPhone, and iPad (not all models support volume up/down functions). Audio is supported by all iPod models.

Requires software version 1.0.3 for iPod nano (4th generation), 2.0.1 for iPod classic (120GB), and 2.2 or later for iPod touch (2nd generation).

Fig. C3 Specifications of APPLE.

dbx RTA-M



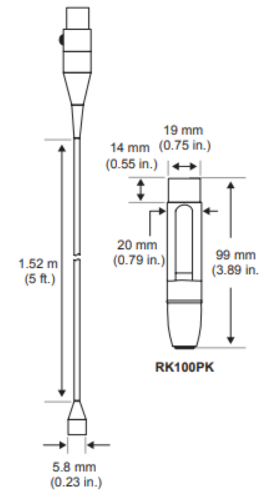
The RTA-M is an omni-directional, flat frequency measurement microphone specially designed for the Driverack series to pick up all frequencies from 20 Hz to 20 kHz , ensuring accurate "pinking"/real-time analysis of your audio. It runs on phantom power (supplied by the Driverack units) and comes with a clip and case.

Features:

Polar Pattern : omni-directional
Element : back electret-Condenser
Frequency Response : 20 Hz - 20 kHz
Impedance : 250 +/-30% (at 1,000Hz)
Sensitivity : -63 dB +-3 dB (0 dB=1V/ microbar 1,000 Hz indicated by open circuit)
Operating Voltage : phantom power 9V-52VDC

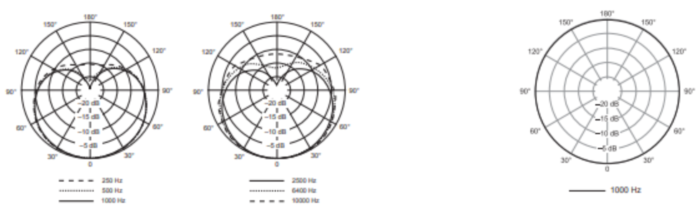
Fig. C4 Specifications of DBX.

Specifications		MX150/C			MX150/O	
Polar Pattern	Cardioid			Omnidirectional		
Transducer Type	Electret Condenser			Electret Condenser		
Frequency Response	20 to 20,000 Hz			20 to 20,000 Hz		
Output Impedance	**TQG:** **XLR:**	N/A 165.5 Ω		**TQG:** **XLR:**	N/A 165.0 Ω	
Sensitivity open circuit voltage, @ 1 kHz, typical	**TQG:** **XLR:**	-51.0 dBV/Pa[1] (3.0 mV) -39.0 dBV/Pa[1] (11.0 mV)		**TQG:** **XLR:**	-46.5 dBV/Pa[1] (4.5 mV) -34.5 dBV/Pa[1] (19.0 mV)	
Maximum SPL 1 kHz at 1% THD[2]		**2500 Ω load:**	**1000 Ω load:**		**2500 Ω load:**	**1000 Ω load:**
	TQG: **XLR:**	147.5 dB SPL 134.5 dB SPL	147.5 dB SPL 129.5 dB SPL	**TQG:** **XLR:**	143.0 dB SPL 130.0 dB SPL	143.0 dB SPL 125.0 dB SPL
Signal-to-Noise Ratio[3]	**TQG:** **XLR:**	57.5 dB 57.0 dB		**TQG:** **XLR:**	60.0 dB 59.5 dB	
Dynamic Range @ 1 kHz		**2500 Ω load:**	**1000 Ω load:**		**2500 Ω load:**	**1000 Ω load:**
	TQG: **XLR:**	111.0 dB SPL 97.5 dB SPL	111.0 dB SPL 92.5 dB SPL	**TQG:** **XLR:**	109.0 dB SPL 95.5 dB SPL	109.0 dB SPL 90.5 dB SPL
Self Noise equivalent SPL, A-weighted, typical	**TQG:** **XLR:**	36.5 dB 37.0 dB		**TQG:** **XLR:**	34.0 dB 34.5 dB	
Clipping Level @ 1 kHz, 1% THD		**2500 Ω load:**	**1000 Ω load:**		**2500 Ω load:**	**1000 Ω load:**
	TQG: **XLR:**	2.0 dBV 1.0 dBV	1.5 dBV -4.5 dBV	**TQG:** **XLR:**	2.0 dBV 1.0 dBV	1.5 dBV -4.5 dBV
Common Mode Rejection 20 to 20,000 Hz	**TQG:** **XLR:**	N/A ≥60 dB		**TQG:** **XLR:**	N/A ≥60 dB	
Polarity	**TQG:** **XLR:**	Positive pressure on diaphragm produces positive voltage on pin 3 with respect to pin 1 Positive pressure on diaphragm produces positive voltage on pin 2 with respect to pin 3				
Power Requirements	**TQG:** **XLR:**	5 V DC (0.04–0.18 mA) 11–52 V DC[4] phantom power (IEC-61938), <2.2 mA				
Weight	**TQG:** **XLR:**	21 g (0.7 oz.) 121 g (4.3 oz.)				
Operating Temperature Range	-18°C (0°F) to 57°C (135°F)					
Storage Temperature Range	-29°C (-20°F) to 74°C (165°F)					

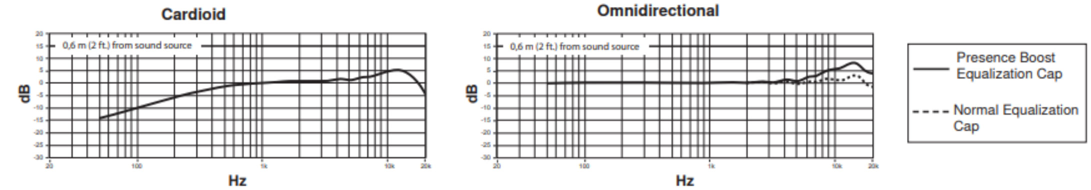


[1] 1 Pa=94 dB SPL
[2]THD of microphone preamplifier when applied input signal level is equivalent to cartridge output at specified SPL
[3]S/N ratio is the difference between 94 dB SPL and equivalent SPL of self noise, A-weighted
[4]All specifications measured with a 48 Vdc phantom power supply. The microphone operates at lower voltages, but with slightly decreased headroom and sensitivity.

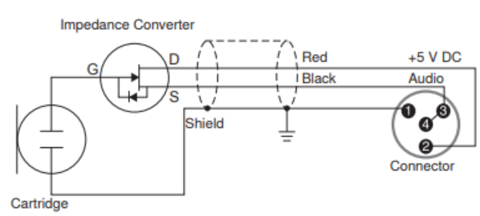
Typical Polar Patterns



Frequency Response



Wiring Diagram



Test Circuit

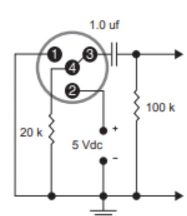


Fig. C5 Specifications of SM.

Fig. C6 Specifications of AMP.

Performance Specifications

Microphone Inputs	
Dynamic Range	106 dB (A-weighted)
Frequency Response	20 Hz to 20 kHz ±0.1 dB
THD+N	<0.002% (minimum gain, -1 dBFS input with 22 Hz/22 kHz bandpass filter)
Noise EIN	>-126 dB (A-Weighted)
Maximum Input Level	+4 dBu
Gain Range	50 dB
Line Inputs	
Dynamic Range	106 dB (A-weighted)
Frequency Response	20 Hz to 20 kHz, ±0.1 dB
THD+N	<0.003% (minimum gain, -1dBFS input with 22 Hz/22 kHz bandpass filter)
Maximum Input Level	+22 dBu
Gain Range	50 dB
Instrument Inputs	
Dynamic Range	106 dB (A-weighted)
Frequency Response	20 Hz to 20 kHz, ±0.1 dB
THD+N	<0.02% (minimum gain, -1 dBFS input with 22 Hz/22 kHz bandpass filter)
Maximum Input Level	+13 dBu
Gain Range	50 dB
Line and Monitor Outputs	
Dynamic Range Outputs (1-2)	106 dB (A-weighted)
Dynamic Range Outputs (3-4)	106 dB (A-weighted)
Maximum Output Level (0 dBFS) Balanced Line/TRS Outputs	+10 dBu
Maximum Output Level (0 dBFS) Unbalanced Line/RCA Outputs	+5.5 dBu
THD+N Outputs (1-2)	<0.001% (minimum gain, -1 dBFS input with 22 Hz/22 kHz bandpass filter)
THD+N Outputs (3-4)	<0.008% (minimum gain, -1 dBFS input with 22 Hz/2 2kHz bandpass filter)

Fig. C7 Specifications of SC.

Appendix D

Neurological assessment questionnaire from the Institute of Neuroscience of the University of Guadalajara

Cuestionario de evaluación neurológica del Instituto de Neurociencias de la Universidad de Guadalajara.

Cuestionario Neurológico

Datos de identificación. Fecha: / /

Nombre del paciente: ______________________________ Código: __________

Fecha de nacimiento: __________ Edad: ________ Grado: ________ Manualidad: ________

Teléfono(s): ______________________________

Calificación del grado anterior en matemáticas: __________ En español: ______________

Ha repetido año escolar: Si No ¿Cuál? y ¿Por qué?: __________________

Desarrollo

Considera que fue normal el desarrollo:

Del lenguaje: ____________________

Motor: ____________________

Adaptación a la escuela: ______________

____

Ha recibido tratamiento de

Terapeuta del aprendizaje: __________

Psicólogo: ________ Neurólogo: ________

Psiquiatra: _______ Neurocirujano: _______

Motivo y duración: ______________

____

Antecedentes patológicos

Al momento del nacimiento presentó hipoxia o ictericia: ____________________

Ha presentado

Traumatismo craneoencefálico SI___ NO___

Pérdida de conciencia SI___ NO___

Cefalea SI___ NO___

Crisis convulsivas SI___ NO___

Si presentó algunos de los eventos indique

Edad al momento del evento: __________

Duración: ________ Secuelas: ________

Frecuencia: ________ Tipo: ________

Tratamiento: ____________________

¿Actualmente toma algún medicamento? Si ______ No ______ ¿Cuál? ______________

Diagnóstico: ______________ Tipo de tratamiento: ______________________

Específicamente ha sido diagnosticado con:

Trastorno por déficit de atención: SI___ NO___ Especialista: ________ Tratamiento: ________

Hiperactividad: SI___ NO___ Especialista: ______________ Tratamiento: ______________

Trastorno en el aprendizaje de la lectoescritura SI___ NO___ Especialista: ______________

¿Necesita lentes, aparatos para oír o tiene dificultad para mover o usar alguna de sus extremidades? ______________________________

¿Algún familiar directo presentó en su infancia dificultades de aprendizaje o problemas de atención?

Antecedentes escolares

¿En qué escuelas ha estado? Indique grado escolar ______________________

Edad a la que ingresó a la escuela: ______________ ¿En qué grado escolar?: __________

Edad a la que aprendió a leer y escribir: ______________________

Tuvo alguna instrucción adicional para aprender a leer y escribir (en casa o con tutor): ________

Último grado de estudios del Padre: ________________ Madre: ________________

Appendix E

Scenarios in 5-FC

C: ATVIO. S: SHURE. A: APPLE.

'CCC'
'CAA'
'CCA'
'CAC'
'CSS'
'CCS'
'CSC'
'CAS'
'CSA'
'SSS'
'SAA'
'SSA'
'SAS'
'SCC'
'SSC'
'SCS'
'SAC'
'SCA'
'AAA'

'ASS'
'AAS'
'ASA'
'ACC'
'AAC'
'ACA'
'ASC'
'ACS'
'CCC'
'CAA'
'CCA'
'SAS'
'SCC'
'SSC'
'ACA'
'ASC'
'ACS'

Appendix F

Table F1 Words in audios.

Day	Words				
1	Pescado	Vaca	Morado	México	
2	Verde	Oro	Manos	Libro	Pared
3	Mesa	Planta	Semilla	Tela	León
4	Lápiz	Vestido	Letras		
5	Luna	Fuego	Mujer	Niño	
6	Océano	Blanco	Carro		
7	Playa	Pollo	Mar		
8	Limón	Planeta	Arena	Amor	
9	Dama	Abeja	Tacos		
10	Pelo	Piedra	Melón		
11	Ciudad	Nopal	Puerta		
12	Mamá	Dulce	Amarillo	Juego	Pelota
13	Caballo	Piano	Foto	Notas	
14	Café	Música	Pulpo	Corazón	Libreta
15	Tenis	Ropa	Árbol		
16	Cuerpo	Manzana	Plata		
17	Tigre	Ruido	Gorra		
18	Reloj	Niña	Cuadrado	Hombre	

19	Gato	Negro	Pluma	
20	Tierra	Balón	Azul	
21	Sol	Lengua	Lluvia	
22	Papá	Lago	Imagen	Dedos
23	Agua	Pizza		
24	Río	Casa		
25	Número	Silla		
26	Ojos	Coco		
27	Canción	Rojo		
28	Pipa	Aire	Estrella	Ventana
29	Flor	Té		
30	Cara	Jugador	Pera	
31	Pescado	Vaca	Morado	México

Appendix G

Statistical Data and Neural Activity

Table G1 Correct answers and RTs.

	Correct Answers (%)			RT (s)		
Group	S1	SF	D	S1	SF	D
Global	92.014	92.245	-0.231	1.795	1.576	0.219
ATVIO	94.444	94.841	-0.397	1.684	1.343	0.342
SHURE	89.444	88.889	0.556	1.817	1.628	0.189
APPLE	93.254	94.444	-1.19	1.875	1.739	0.136

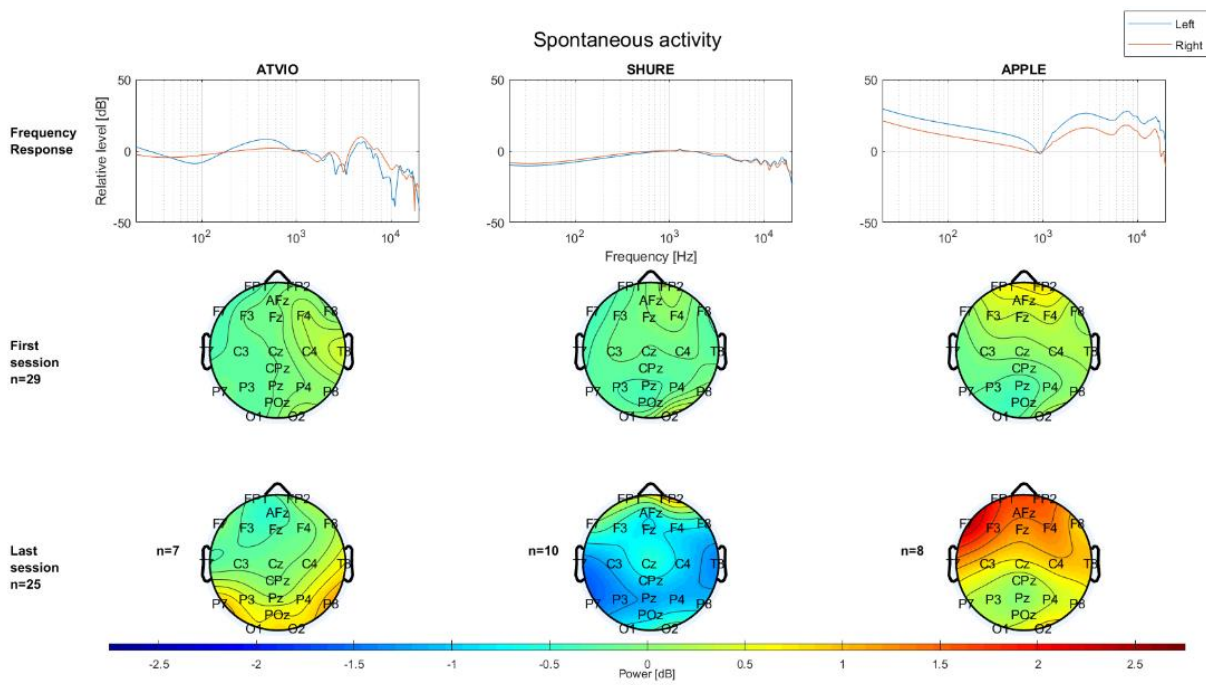


Fig. G1 GAP in delta band. First row shows the frequency response of every headphone. Second row presents GAP in first session. Third row presents GAP in last session.

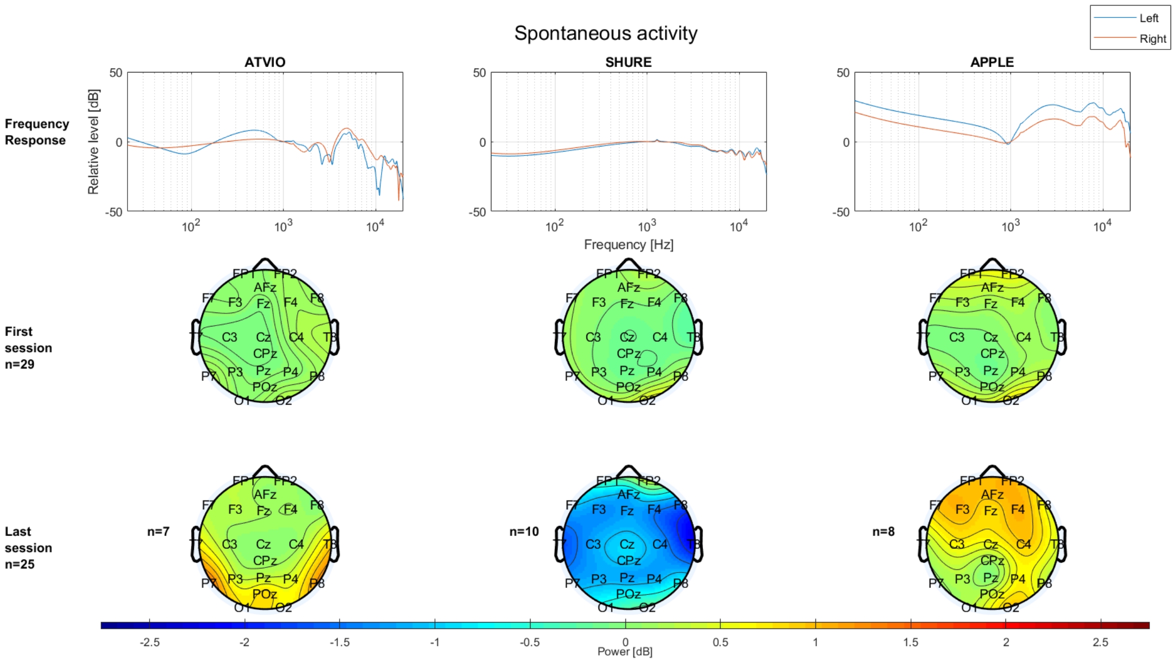


Fig. G2 GAP in theta band. First row shows the frequency response of every headphone. Second row presents GAP in first session. Third row presents GAP in last session.

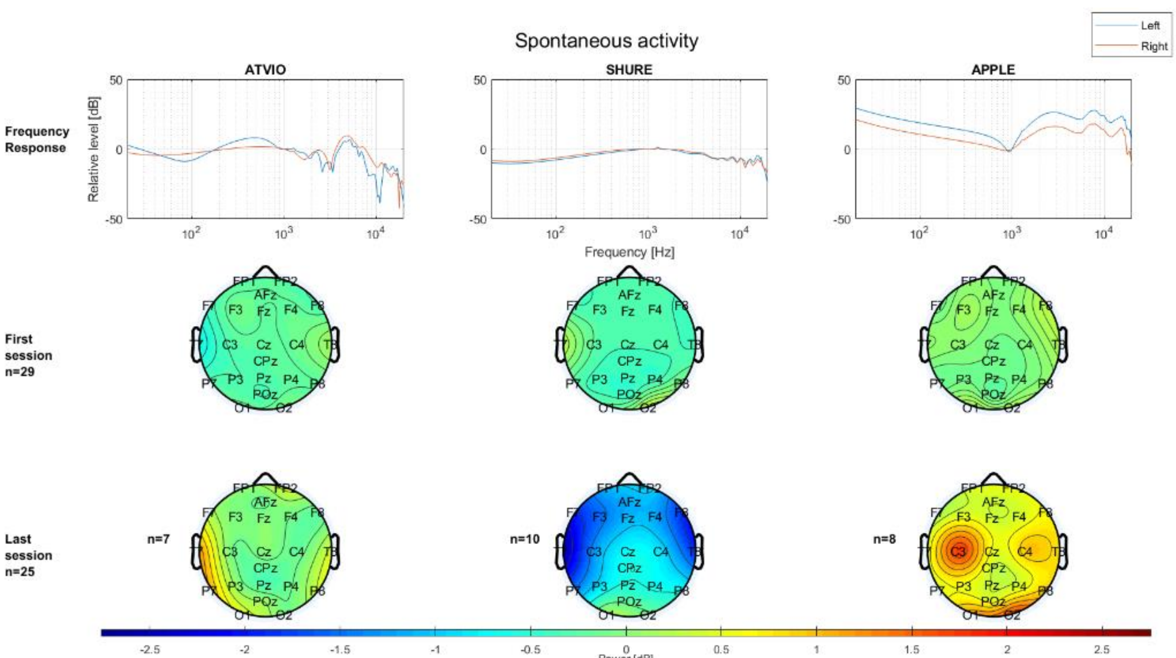


Fig. G3 GAP in beta band. First row shows the frequency response of every headphone. Second row presents GAP in first session. Third row presents GAP in last session.

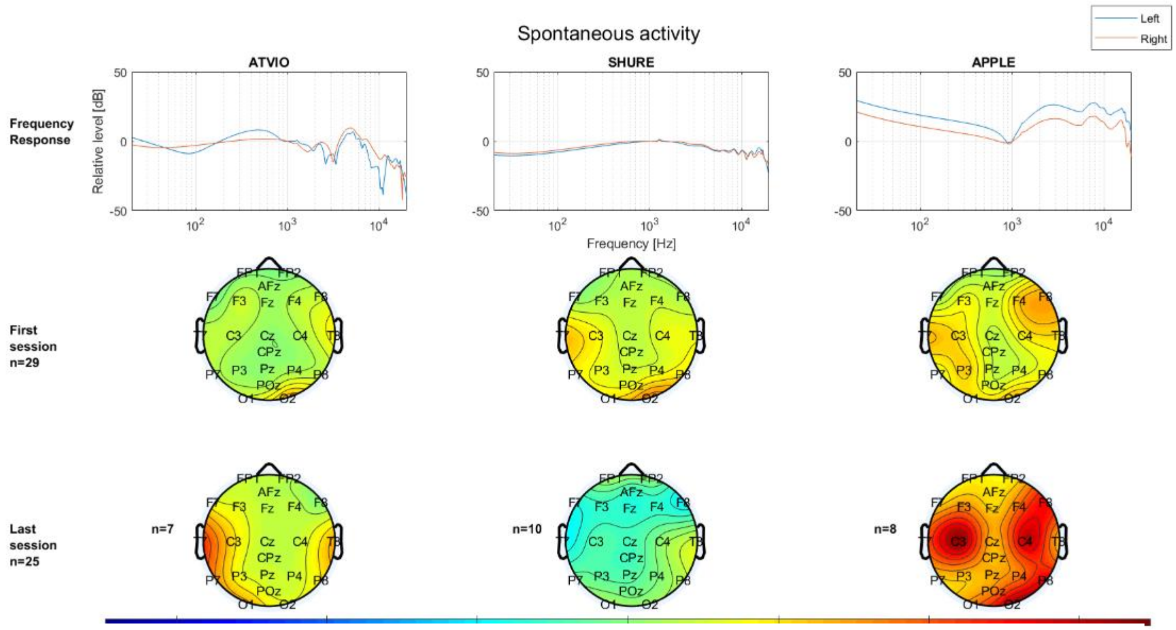


Fig. G4 GAP in gamma band. First row shows the frequency response of every headphone. Second row presents GAP in first session. Third row presents GAP in last session.

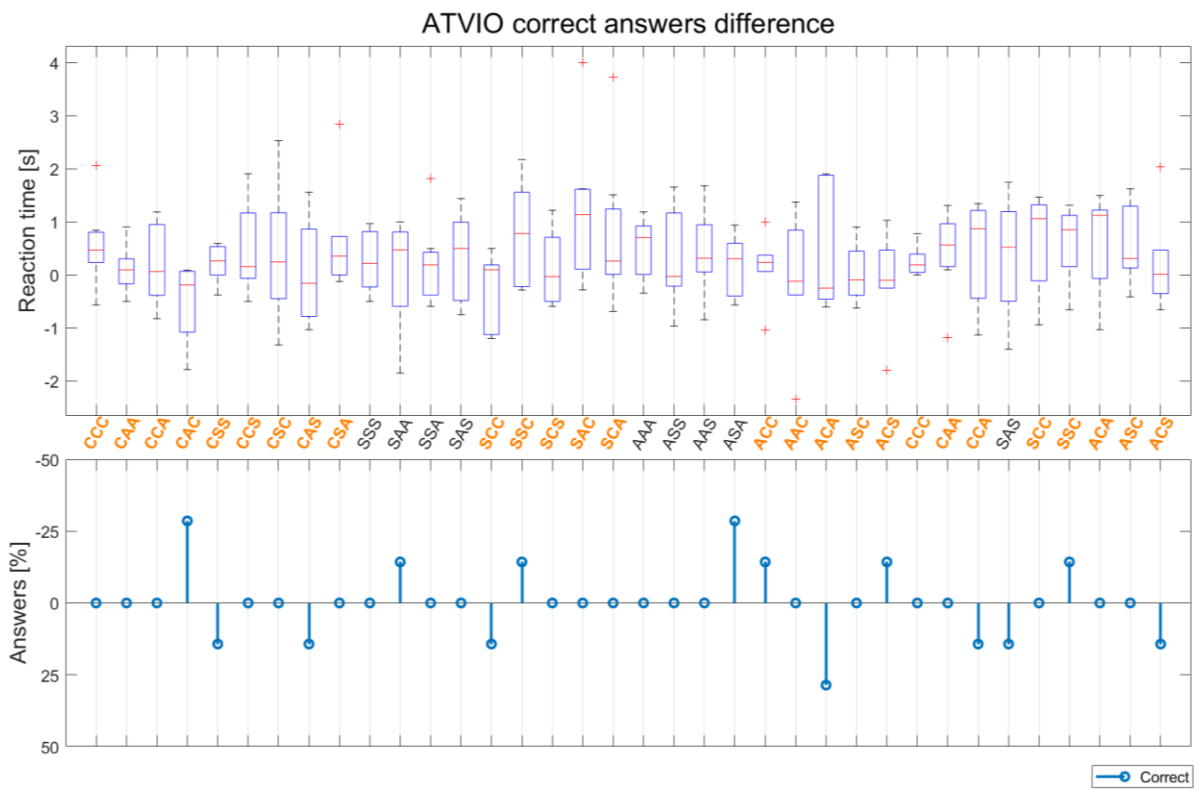


Fig. G5 Difference in answers of first and last session for ATVIO.

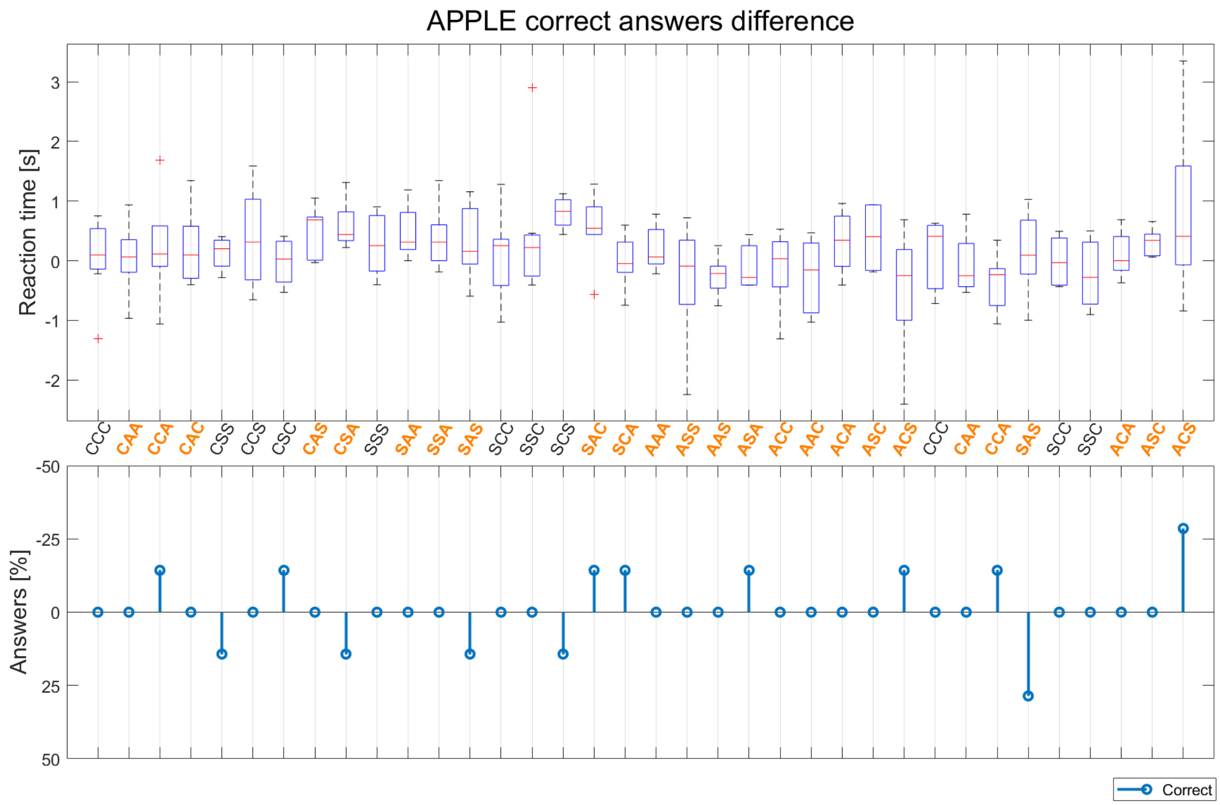


Fig. G6 Difference in answers of first and last session for APPLE.

Bibliography

[1] WATSON, J., TINNITUS: Epidemiology, Causes and Emerging Therapeutic Treatments. Nova Science Publishers, Inc. 2016.

[2] FERNANDES, F. L., ROCHA, V. B. C., GUIMARÃES, A. C., STOLER, G., AND GUSMÃO, R. J., in: Watson, J. (Ed.), Tinnitus: Epidemiology, Causes and Emerging Therapeutic Treatments. Nova Science Publishers, Inc. 2016, pp. 11–24.

[3] IBARRA-ZARATE, D., AND ALONSO-VALERDI, L. M., Acoustic therapies for tinnitus: The basis and the electroencephalographic evaluation. Biomed. Signal Process. Control 2020, 59, 101900.

[4] ALONSO-VALERDI, L. M., IBARRA-ZARATE, D. I., TAVIRA-SÁNCHEZ, F. J., RAMÍREZ-MENDOZA, AND R. A., RECUERO, M., Electroencephalographic evaluation of acoustic therapies for the treatment of chronic and refractory tinnitus. BMC Ear, Nose Throat Disord. 2017, 17, 1–15.

[5] STEIN, A., WUNDERLICH, R., LAU, P., ENGELL, A., WOLLBRINK, A., SHAYKEVICH, A., KUHN, J. T., HOLLING, H., RUDACK, C., AND PANTEV, C., Clinical trial on tonal tinnitus with tailor-made notched music training. BMC Neurol. 2016, 16, DOI: 10.1186/s12883-016-0558-7.

[6] PAPE, J., PARASKEVOPOULOS, E., BRUCHMANN, M., WOLLBRINK, A., RUDACK, C., AND PANTEV, C., Playing and listening to tailor-made notched music: Cortical plasticity induced by unimodal and multimodal training in tinnitus patients. Neural Plast. 2014, 2014, DOI: 10.1155/2014/516163.

[7] BRÜGGEMANN, P., OTTO, J., LORENZ, N., SCHORSCH, S., SZCZEPEK, A. J., BÖCKING, B., AND MAZUREK, B., Long-term changes in multimodal intensive tinnitus therapy: A 5-year follow-up. HNO 2018, 66, 34–38.

[8] SCHAETTE, R., KÖNIG, O., HORNIG, D., GROSS, M., AND KEMPTER, R., Acoustic stimulation treatments against tinnitus could be most effective when tinnitus pitch is within the stimulated frequency range. Hear. Res. 2010, 269, 95–101.

[9] STRAUSS, D. J. J., CORONA-STRAUSS, F. I. I., SEIDLER, H., HAAB, L., AND HANNEMANN, R., Notched environmental sounds: a new hearing aid-supported tinnitus treatment evaluated in 20 patients. Clin. Otolaryngol. 2015, 42, 172–175.

[10] VORLÄNDER, M., Auralization. Springer Berlin Heidelberg 2008, pp. 103–119.

[11] OKAMOTO, H., STRACKE, H., STOLL, W., AND PANTEV, C., Listening to tailor-made notched music reduces tinnitus loudness and tinnitus-related auditory cortex activity. Proc. Natl. Acad. Sci. U. S. A. 2010, 107, 1207–1210.

[12] VANNESTE, S., VAN DONGEN, M., DE VREE, B., HISENI, S., VAN DER VELDEN, E., STRYDIS, C., JOOS, K., NORENA, A., SERDIJN, W., AND DE RIDDER, D., Does enriched acoustic environment in humans abolish chronic tinnitus clinically and electrophysiologically? A double blind placebo controlled study. Hear. Res. 2013, 296, 141–148.

[13] YOUNG KIM, S., YOUNG CHANG, M., HONG, M., YOO, S.-G. G., OH, D., AND KYUN PARK, M., Tinnitus therapy using tailor-made notched music delivered via a smartphone application and Ginko combined treatment: A pilot study. Auris Nasus Larynx 2017, 44, 528–533.

[14] HOFFMANN, P. F., CHRISTENSEN, F., AND HAMMERSHØI, D., Insert Earphone Calibration for Hear-through Options. n.d.

[15] BACKMAN, J., CAMPBELL, T., KLEIMOLA, J., AND HIIPAKKA, M., Convention E-Brief 347 A Self-Calibrating Earphone. n.d.

[16] OGHALAI, J. S., AND BROWNELL, W. E., IN: Lalwani, A. K. (Ed.), Current Diagnosis & Treatment Otolaryngology—Head and Neck Surgery, 4e. McGraw-Hill Education, New York, NY 2020.

[17] STREICHER, R., AND EVEREST, F. A., The New Stereo Soundbook. Audio Engineering Associates 2006, pp. 3.1-3.22.

[18] PURVES, D., AUGUSTINE, G. J., FITZPATRICK, D., HALL, W. C., LAMANTIA, A.-S., MOONEY, R. D., PLATT, M. L., AND WHITE, L. E. (Eds.), Neuroscience. Oxford University Press 2018, pp. 281–304.

[19] MIDDLEBROOKS, J. C., Sound Localization. Elsevier B.V. 2015.

[20] FARNELL, A., Designing Sound. The MIT Press n.d., pp. 9–37.

[21] FASTL, H., AND ZWICKER, E., Psychoacoustics. Facts and Models. Springer Series in Information Sciences 2007.

[22] ABRAMONT, C., AND DE MONTALEMBERT, E., in: Económica, F. de C. (Ed.), Teoría de La Música. Una Guía. 2005, pp. 19–24.

[23] TACKETT, J., ISO 226 Equal-Loudness-Level Contour Signal. 2020.

[24] FLETCHER, H., AND MUNSON, W. A., Loudness, Its Definition, Measurement and Calculation. Bell Syst. Tech. J. 1933, 12, 377–430.

[25] ISO 226:2003 Acoustics - Normal equal-loduness-level contours. 2003.

[26] POWELL, L., 69th Convention of the Audio Engineering Society. Audio Engineering Society 1981.

[27] BLAUERT, J., Spatial Hearing. The MIT Press 1983.

[28] FRANOSCH, J. M. P., KEMPTER, R., FASTL, H., AND VAN HEMMEN, J. L., Zwicker Tone Illusion and Noise Reduction in the Auditory System. Phys. Rev. Lett. 2003, 90, 4.

[29] NATH, A. R., AND BEAUCHAMP, M. S., A neural basis for interindividual differences in the McGurk effect , a multisensory speech illusion. Neuroimage 2012, 59, 781–787.

[30] MCCONNELL, P. A., FROELIGER, B., GARLAND, E. L., IVES, J. C., AND SFORZO, G. A., Auditory driving of the autonomic nervous system : Listening to theta-frequency binaural beats post-exercise increases parasympathetic activation and sympathetic withdrawal. 2014, 5, 1–10.

[31] LOVATI, C., FREDDI, A., MUZIO, F., AND PANTONI, L., Binaural stimulation in migraine: preliminary results from a 3-month evening treatment. Neurol. Sci. 2019, 197–198.

[32] MUNRO, B. A., AND SEARCHFIELD, G. D., The short-term effects of recorded ocean sound with and without alpha frequency binaural beats on tinnitus perception. Complement. Ther. Med. 2019, 44, 291–295.

[33] PERALES, F. J., RIERA, L., RAMIS, S., AND GUERRERO, A., Evaluation of a VR system for Pain Management using binaural acoustic stimulation. Multimed. Tools Appl. 2019, 78, 32869–32890.

[34] HUBER, D. M., Modern Recording Techniques. Routledge 2018.

[35] POLDY, C. A., in: Borwick, J. (Ed.), Loudspeaker and Headphone Handbook. Focal Press 2001, pp. 585–692.

[36] AIRPODS PRO, https://www.apple.com/mx/airpods-pro/?afid=p238%7CsiJQ72FjY-dc_mtid_u3tzk236h0_pcrid_405715095332_pgrid_86577926796_&cid=wwa-mx-kwgo-wearables-slid---productid--Brand-AirPodsPro-Evergreen.

[37] COBO, P., FERNÁNDEZ, A., AND CUESTA, M., Measuring short impulse responses with inverse filtered maximum-length sequences. Appl. Acoust. 2007, 68, 820–830.

[38] IBARRA, D., LEDESMA, R., AND LOPEZ, E., Design and construction of an omnidirectional sound source with inverse filtering approach for optimization. HardwareX 2018, 4, DOI: 10.1016/j.ohx.2018.e00033.

[39] MATHWORKS, I., MATLAB & Simulink, https://www.mathworks.com/products/matlab.html (last time accessed: July 3, 2020).

[40] PLAKKE, B., AND ROMANSKI, L. M., Auditory connections and functions of prefrontal cortex. Front. Neurosci. 2014, 8, 1–13.

[41] KAISER, J., Dynamics of auditory working memory. Front. Psychol. 2015, 6, 1–6.

[42] BENARROCH, E. E., Basic Neurosciences with Clinical Applications. Elsevier n.d., p. 930.

[43] HARRIS, R., AND DE JONG, B. M., Cerebral activations related to audition-driven performance imagery in professional musicians. PLoS One 2014, 9, DOI: 10.1371/journal.pone.0093681.

[44] MCDONALD, J. J., STÖRMER, V. S., MARTINEZ, A., FENG, W., AND HILLYARD, S. A., Salient sounds activate human visual cortex automatically. J. Neurosci. 2013, 33, 9194–9201.

[45] BAARS, B., AND GAGE, N. M., Fundamentals of Cognitive Neuroscience. Elsevier 2018.

[46] ABHANG, P. A., GAWALI, B. W., AND MEHROTRA, S. C., Introduction to EEG- and Speech-Based Emotion Recognition. Elsevier 2016, pp. 51–79.

[47] KLIMESCH, W., The frequency architecture of brain and brain body oscillations: an analysis. Eur. J. Neurosci. 2018, 48, 2431–2453.

[48] KRAUSE, C. M., Chapter 13 Cognition- and memory-related ERD/ERS responses in the auditory stimulus modality. Prog. Brain Res. 2006, 159, 197–207.

[49] PFURTSCHELLER, G., AND ANDREW, C., Event-Related Changes of Band Power and Coherence: Methodology and Interpretation. J. Clin. Neurophysiol. 1999, 16, 512.

[50] KLIMESCH, W., EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. Brain Res. Rev. 1999, 29, 169–195.

[51] ZOEFEL, B., AND VANRULLEN, R., Oscillatory mechanisms of stimulus processing and selection in the visual and auditory systems: State-of-the-art, speculations and suggestions. Front. Neurosci. 2017, 11, 1–13.

[52] WEISZ, N., HARTMANN, T., MÜLLER, N., LORENZ, I., AND OBLESER, J., Alpha rhythms in audition: Cognitive and clinical perspectives. Front. Psychol. 2011, 2, 1–15.

[53] RAJENDRAN, V. G., TEKI, S., AND SCHNUPP, J. W. H., Temporal Processing in Audition: Insights from Music. Neuroscience 2018, 389, 4–18.

[54] LENZ, D., SCHADOW, J., THAERIG, S., BUSCH, N. A., AND HERRMANN, C. S., What's that sound? Matches with auditory long-term memory induce gamma activity in human EEG. Int. J. Psychophysiol. 2007, 64, 31–38.

[55] BEDNAR, A., AND LALOR, E. C., Neural tracking of auditory motion is reflected by delta phase and alpha power of EEG. Neuroimage 2018, 181, 683–691.

[56] SCHADOW, J., LENZ, D., THAERIG, S., BUSCH, N. A., FRÜND, I., AND HERRMANN, C. S., Stimulus intensity affects early sensory processing: Sound intensity modulates auditory evoked gamma-band activity in human EEG. Int. J. Psychophysiol. 2007, 65, 152–161.

[57] MCFARLAND, D. J., KRUSIENSKI, D. J., AND WOLPAW, J. R., Chapter 26 Brain-computer interface signal processing at the Wadsworth Center: mu and sensorimotor beta rhythms. Prog. Brain Res. 2006, 159, 411–419.

[58] HOTS, J., RENNIES, J., AND VERHEY, J. L., Loudness of sounds with a subcritical bandwidth: A challenge to current loudness models? J. Acoust. Soc. Am. 2013, 134, EL334–EL339.

[59] LUCK, S., An Introduction to the Event-Related Potential Technique, Second Edition. The MIT Press 2014.

[60] HU, L., AND ZHANG, Z., EEG Signal Processing and Feature Extraction. 2019, pp. 23–42.

[61] LI, S. A., BAO, L., AND CHROSTOWSKI, M., Investigating the effects of a personalized, spectrally altered music-based sound therapy on treating tinnitus: A blinded, randomized controlled trial. Audiol. Neurotol. 2016, 21, 296–304.

[62] MANABE, Y., SATO, K., FUKUDA, S., AND MIYASHITA, T., Unpleasantness of amplified environmental sound used in tinnitus sound therapy: A preliminary study of clinical assessment. J. Int. Adv. Otol. 2019, 15, 94–98.

[63] SERQUERA, J., SCHLEE, W., PRYSS, R., NEFF, P., AND LANGGUTH, B., Music technology for tinnitus treatment within tinnet. Proc. AES Int. Conf. 2015, 2015-June, 76–80.

[64] AYTAC, I., BAYSAL, E., GULSEN, S., TUMUKLU, K., DURUCU, C., MUMBUC, L. S., AND KANLIKAMA, MU., Masking treatment and its effect on tinnitus parameters. Int. Tinnitus J. 2017, 21, 83–89.

[65] MAHBOUBI, H., HAIDAR, Y. M., KIUMEHR, S., ZIAI, K., AND DJALILIAN, H. R., Customized Versus Noncustomized Sound Therapy for Treatment of Tinnitus: A Randomized Crossover Clinical Trial. Ann. Otol. Rhinol. Laryngol. 2017, 126, 681–687.

[66] SCHAD, M. L., MCMILLAN, G. P., THIELMAN, E. J., GROON, K., MORSE-FORTIER, C., MARTIN, J. L., AND HENRY, J. A., Comparison of acoustic therapies for tinnitus suppression: a preliminary trial. Int. J. Audiol. 2018, 57, 143–149.

[67] HAN, L., YAWEN, L., HAO, W., CHUNLI, L., PENGFEI, Z., ZHENGYU, Z., ZHAODI, W., ZHENGHAN, Y., SHUSHENG, G., AND ZHENCHANG, W., Effects of sound therapy on resting-state functional brain networks in patients with tinnitus: A graph-theoretical-based study. J. Magn. Reson. Imaging 2019, 50, 1731–1741.

[68] JASTREBOFF, P. J., AND JASTREBOFF, M. M., Tinnitus Retraining Therapy (TRT) as a Method for Treatment of Tinnitus and Hyperacusis Patients. 2000.

[69] AAZH, H., AND MOORE, B. C. J., A comparison between tinnitus retraining therapy and a simplified version in treatment of tinnitus in adults. Audit. Vestib. Res. 2016, 25, 14–23.

[70] JAIN, S., AND JAIN, C., Effectiveness of Clinical Trial of Tinnitus Retraining Therapy on Temporal Processing and Perceptual Judgment in Tinnitus. JAIISH 2016, 35, 44–57.

[71] KIM, S. H., BYUN, J. Y., YEO, S. G., AND PARK, M. S., Tinnitus retraining therapy in unilateral tinnitus patients with single side deafness. J. Int. Adv. Otol. 2016, 12, 72–76.

[72] BAROZZI, S., AMBROSETTI, U., CALLAWAY, S. L., BEHRENS, T., PASSONI, S., AND BO, L. DEL, Effects of tinnitus retraining therapy with different colours of sound. Int. Tinnitus J. 2017, 21, 139–143.

[73] LEE, K., MAKINO, K., AND YAMAHARA, K., Evaluation of tinnitus retraining therapy for patients with normal audiograms versus patients with hearing loss. Auris Nasus Larynx 2018, 45, 215–221.

[74] PARK, J. M., KIM, W. J., HA, J. B., HAN, J. J., PARK, S. Y., AND PARK, S. N., Effect of sound generator on tinnitus and hyperacusis. Acta Otolaryngol. 2018, 138, 135–139.

[75] LEE, S. Y., RHEE, J., SHIM, Y. J., KIM, Y., KOO, J. W., DE RIDDER, D., VANNESTE, S., AND SONG, J. J., Changes in the Resting-State Cortical Oscillatory

Activity 6 Months After Modified Tinnitus Retraining Therapy. Front. Neurosci. 2019, 13, DOI: 10.3389/fnins.2019.01123.

[76] SCHERER, R. W., AND FORMBY, C., Effect of Tinnitus Retraining Therapy vs Standard of Care on Tinnitus-Related Quality of Life: A Randomized Clinical Trial. JAMA Otolaryngol. - Head Neck Surg. 2019, 145, 597–608.

[77] KIM, S. H., JANG, J. H., LEE, S. Y., HAN, J. J., KOO, J. W., VANNESTE, S., DE RIDDER, D., AND SONG, J. J., Neural substrates predicting short-term improvement of tinnitus loudness and distress after modified tinnitus retraining therapy. Sci. Rep. 2016, 6, DOI: 10.1038/srep29140.

[78] BAUER, C. A., BERRY, J. L., AND BROZOSKI, T. J., The effect of tinnitus retraining therapy on chronic tinnitus: A controlled trial. Laryngoscope Investig. Otolaryngol. 2017, 2, 166–177.

[79] BRÜGGEMANN, P., OTTO, J., LORENZ, N., SCHORSCH, S., SZCZEPEK, A. J., BÖCKING, B., AND MAZUREK, B., Erratum to: Long-term changes in multimodal intensive tinnitus therapy: A 5-year follow-up (HNO, (2018), 66, S1, (34-38), 10.1007/s00106-017-0463-4). HNO 2018, 66, 211.

[80] SWEETOW, R. W., AND SABES, J. H., Effects of acoustical stimuli delivered through hearing aids on tinnitus. J. Am. Acad. Audiol. 2010, 21, 461–473.

[81] BARROS SUZUKI, F. A. DE, SUZUKI, F. A., YONAMINE, F. K., ONISHI, E. T., AND PENIDO, N. O., Effectiveness of sound therapy in patients with tinnitus resistant to previous treatments: Importance of adjustments. Braz. J. Otorhinolaryngol. 2016, 82, 297–303.

[82] TYLER, R. S., DESHPANDE, A. K., LAU, C. C., AND KUK, F., The effectiveness of the progression of widex zen tinnitus therapy: A pilot study. Am. J. Audiol. 2017, 26, 283–292.

[83] TASS, P. A., ADAMCHIC, I., FREUND, H. J., VON STACKELBERG, T., AND HAUPTMANN, C., Counteracting tinnitus by acoustic coordinated reset neuromodulation. Restor. Neurol. Neurosci. 2012, 30, 137–159.

[84] HAUPTMANN, C., WEGENER, A., POPPE, H., WILLIAMS, M., POPELKA, G., AND TASS, P. A., Validation of a mobile device for acoustic coordinated reset neuromodulation tinnitus therapy. J. Am. Acad. Audiol. 2016, 27, 720–731.

[85] WURZER, H., AND HAUPTMANN, C., Adapted acoustic CR neuromodulation in patients with chronic tonal tinnitus and hearing loss. Front. Med. 2018, 5, DOI: 10.3389/fmed.2018.00288.

[86] WIDEX, Soluciones para el tinnitus, https://mx.widex.com/es-mx/audifonos/soluciones-para-el-tinnitus (last time accessed: July 3, 2020).

[87] DESYNCRA, Desyncra for Tinnitus, https://www.desyncra.com/product-page/desyncra-for-tinnitus (last time accessed: July 3, 2020).

[88] ARGSTATTER, H., GRAPP, M., PLINKERT, P. K., AND BOLAY, H. V., “Heidelberg Neuro-Music Therapy” for chronic-tonal tinnitus - Treatment outline and psychometric evaluation. Int. Tinnitus J. 2012, 17, 31–41.

[89] KRICK, C. M., ARGSTATTER, H., GRAPP, M., PLINKERT, P. K., AND REITH, W., Heidelberg neuro-music therapy restores attention-related activity in the angular gyrus in chronic tinnitus patients. Front. Neurosci. 2017, 11, DOI: 10.3389/fnins.2017.00418.

[90] DAVID, J. BEN, NAFTALI, A., AND KATZ, A., Tinntrain: A multifactorial treatment for tinnitus using binaural beats. Hear. J. 2010, 63, 25–28.

[91] REAVIS, K. M., ROTHHOLTZ, V. S., TANG, Q., CARROLL, J. A., DJALILIAN, H., ZENG, F. G., Temporary suppression of tinnitus by modulated sounds. JARO - J. Assoc. Res. Otolaryngol. 2012, 13, 561–571.

[92] HENRY, J. A., FREDERICK, M., SELL, S., GRIEST, S., AND ABRAMS, H., Validation of a novel combination hearing aid and tinnitus therapy device. Ear Hear. 2015, 36, 42–52.

[93] TAO, Y., CHANG, X., YE, S., CHU, G., GUAN, T., WANG, J., AND ZENG, P., Multiple-frequency matching treatment strategy for tinnitus. J. Int. Adv. Otol. 2017, 13, 221–225.

[94] POREMSKI, T., AND KOSTEK, B., Tinnitus therapy based on high-frequency linearization principles - Preliminary results. Arch. Acoust. 2012, 37, 161–170.

[95] BAROZZI, S., DEL BO, L., CROCETTI, A., DYRLUND, O., PASSONI, S., ZOLIN, A., PANICUCCI, E., MANCUSO, A., KAUR, M., AND SEARCHFIELD, G. D., A comparison of nature and technical sounds for tinnitus therapy. Acta Acust. united with Acust. 2016, 102, 540–546.

[96] DURAI, M., AND SEARCHFIELD, G. D., A mixed-methods trial of broad band noise and nature sounds for tinnitus therapy: Group and individual responses modeled under the adaptation level theory of tinnitus. Front. Aging Neurosci. 2017, 9, DOI: 10.3389/fnagi.2017.00044.

[97] NEFF, P., MICHELS, J., MEYER, M., SCHECKLMANN, M., LANGGUTH, B., AND SCHLEE, W., 10 Hz amplitude modulated sounds induce short-term tinnitus suppression. Front. Aging Neurosci. 2017, 9, DOI: 10.3389/fnagi.2017.00130.

[98] NEFF, P., ZIELONKA, L., MEYER, M., LANGGUTH, B., SCHECKLMANN, M., AND SCHLEE, W., Comparison of Amplitude Modulated Sounds and Pure Tones at the Tinnitus Frequency: Residual Tinnitus Suppression and Stimulus Evaluation. Trends Hear. 2019, 23, DOI: 10.1177/2331216519833841.

[98] PEDEMONTE, M., DÍAZ, M., MEDINA-FERRET, E., AND TESTA, M., Impact of sound stimulation during different sleep stages in patients with tinnitus. Loquens 2018, 5, e053.

[100] KUTYBA, J., JEDRZEJCZAK, W. W., AND RAJ-KOZIAK, D., Caso, E. D. E., TINNITUS SOUND THERAPY WITH A MOBILE APPLICATION : CASE STUDY. 2019, 9, 51–56.

[101] LIU, C., LV, H., JIANG, T., XIE, J., HE, L., WANG, G., LIU, J., WANG, Z., AND GONG, S., The Cochleural Alternating Acoustic Beam Therapy (CAABT): A pre-clinical trial. Am. J. Otolaryngol. - Head Neck Med. Surg. 2018, 39, 401–409.

[102] THEODOROFF, S. M., MCMILLAN, G. P., ZAUGG, T. L., CHESLOCK, M., ROBERTS, C., AND HENRY, J. A., Randomized Controlled Trial of a Novel Device for Tinnitus Sound Therapy During Sleep. Am. J. Audiol. 2017, 26, 543–554.

[103] ROCHA, A. V., CAPOANI, M. F., AND MONDELLI, G., Sound generator associated with the counseling in the treatment of tinnitus: evaluation of the effectiveness. Braz J Otorhinolaryngol 2017, 83, 249–255.

[104] KIM, Y., KIM, J., AND KO, S., A parametric model of head-related transfer functions for sound source localization. Audio Eng. Soc. - 122nd Audio Eng. Soc. Conv. 2007 2007, 1, 159–166.

[105] HEAD AND TORSO SIMULATOR (HATS), https://www.bksv.com/en/products/transducers/ear-simulators/head-and-torso/hats-type-4128c.

[106] ORAMUS, T., AND NEUBAUER, P., COMPARISON STUDY OF LISTENERS' PERCEPTION OF 5.1 AND DOLBY ATMOS. Audio Eng. Soc. - 147th Audio Eng. Soc. Conv. 2019 2019.

[107] DOLBY ATMOS FOR HEADPHONES, https://developer.dolby.com/blog/dolby-atmos-for-headphones/#:~:text=How do you get the,positions in the horizontal plane.

[108] ZOTTER, F., AND FRANK, M., Ambisonics: A Practical 3D Audio Theory for Recording. 2019.

[109] NURAPHONE, https://www.nuraphone.com/products/nuraphone.

[110] SILVA, P. B. DA, FIORINI, A. C., AND AZEVEDO, M. F. DE, Otoacoustic emissions in young adults exposed to drums noise of a college band. Rev. CEFAC 2017, 19, 645–653.

[111] SWAIN, S., Snapshots in Ear, Nose and Throat: Head and Neck Surgery. Springer US, Boston, MA 2016, pp. 1–1.

[112] TATE, M., Principles of Hearing Aid Audiology. Springer US, Boston, MA 1994.

[113] QUIZTONES, https://theproaudiofiles.com/quiztones/.

[114] ZHIVOMIROV, H., A method for colored noise generation. Rom. J. Acoust. Vib. 2018, 15, 14–19.

[115] GELFAND, S. A., Hearing: An Introduction to Psychological and Physiological Acoustics. Informa Healthcare 2010, pp. 146–159.

[116] MERTEL, K., in: Thaut, M., Hoemberg, V. (Eds.), Handbook of Neurologic Music Therapy. Oxford University Press 2014.

[117] SAFE LISTENING. Bull. World Health Organ. 2015, 93, 13–24.

[118] COHEN, M., Analyzing Neural Time Series Data : Theory and Practice. The MIT Press 2014, pp. 217–239.

[119] IBARRA, D., TAVIRA-SANCHEZ, F., RECUERO-LOPEZ, M., AND ANTHONY, B. W., In-ear medical devices for acoustic therapies in tinnitus treatments, state of the art. Auris Nasus Larynx 2018, 45, 6–12.

[120] SENNHEISER, HDA 200 Audiometric Headphones.

[121] SONARWORKS, SoundID, https://www.sonarworks.com/soundid (last time accessed: July 3, 2020).

Published works

[1] CEPEDA-ZAPATA, L. K., ROMERO-SOTO, F. O., DIAZ DE LEON, V. A., ROA-HUERTAS, J. L., NAAL-RUIZ, N. E., IBARRA-ZARATE, D., AND ALONSO-VALERDI, L. M., Implementation of a Virtual Reality rendered in Portable Devices for Strabismus Treatment based on Conventional Visual Therapy. Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS, 2019. DOI:10.1109/EMBC.2019.8857222.

[2] NAAL-RUIZ, N.E., ALONSO-VALERDI, L. M., AND IBARRA-ZARATE, D. I., FREQUENCY RESPONSE OF AUDIO DEVICES AND ITS EFFECT IN ELECTROENCEPHALOGRAPHIC PATTERNS. 2020, DOI: 10.13140/RG.2.2.28154.24000/2.

Curriculum Vitae

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