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Different Headphone Models Modulate Differently Alpha and Theta Brain Oscillations When Listening to the Same Sound*

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Abstract— **The frequency content of a sound changes the perception of acoustic features, but can headphones also change auditory information interpretation? Audio devices such as headphones are factors that have not been taken into consideration at studying sound perception, specifically in acoustic therapies. In particular, alternative treatments based on psychoacoustic effects could be more effective if the frequency response of headphones is found as a determining factor.**

This investigation, therefore, aims to study the brain response (in terms of electroencephalographic activity) produced by listening to pink noise in three different headphone models. Furthermore, not only the immediate response is studied, but the sound habituation (after daily exposure to pink noise for 30 days) is also investigated. The investigation findings reveal that headphones with a flatter frequency response provide more accurate acoustic information to the brain, what in turn, demands a larger number and a wider variety of mental resources, even after a habituation process.

Clinical Relevance—**This investigation establishes that audio devices are a determining factor to achieve specific psychoacoustic effects since they change the auditory information decoding at a cortical level.**

I. Introduction

Audio devices, such as headphones, can alter the frequency content of an audio signal due to their frequency response [1]. It has been documented that the frequency content of a sound changes auditory perception: from the modification of the position of a sound source in space [2] to the perception of an unreal sound equivalent to a gap [3] or increase [4] in the sound frequency spectrum. Headphones and audio interfaces used in the professional audio industry do less modification to sound because they are built with more sophisticated components. As headphones are devices widely used for different purposes (such as acoustic therapies for tinnitus treatment) [5]–[9], where the audio quality is not considered as in the audio industry, their appropriate characterization and calibration are required to guarantee the sound effects of interest. Up to now, the impact of the frequency response of audio devices has not been considered, particularly in conducted researches where headphones are a determining factor such as acoustic treatments. Headphones could be the variable that may increase or reduce the effect of the sound-based treatments. The human perception of sound essentially depends on the ear, the auditory nerve, and the central auditory pathway from the brainstem to the auditory cortex. As some sections in the brainstem, such as the inferior colliculus, the auditory cortex has neurons that process the frequency content of a sound, an important feature to understand music and speech [10]. The auditory cortex also uses previous knowledge to complete missing information from auditory stimuli. Brain oscillations over this region have been related to rhythm, movement, attention, and location in space [11]. In particular, electroencephalography- (EEG) based studies have shown that desynchronization of alpha and theta brain oscillations has been associated with the recognition of acoustic material and auditory memorization such as words; on the other hand, synchronization of those brain oscillations has been observed during the encoding of new acoustic information into the short-term memory [12]–[15].

The present work aims to determine the effect of frequency responses of three different headphones (Atvio® supra-aural headphones (AH), Shure® SRH1840 circum-aural headphones (SH), and Apple® Earpods® intra-aural headphones (EH)) in the modulation of alpha and theta brain oscillations at short and long term, and thus investigating if quality of audio devices modify human auditory perception.

II. Methodology

A. Characterization of Headphones

For this research, the frequency responses of three headphone models were characterized in three auditory stimuli: (1) AH, (2) SH, and (3) EH. The main goal of the characterization was to measure the frequency response of AH and then change it to the response of either SH or EH for headphone emulation by means of inverse filtering. This approach reduced the cost of experimentation since SH and EH are expensive models in comparison to AH. The offline audio processing method is described in [16], [17].

B. Sample

Thirty volunteers who were 21.300±1.841 years old (13 males, 17 females) participated in the study. Participants fulfilled the following criteria: (1) ages from 19 to 24, (2) no musicians or audio experts, (3) have not taken musical lectures or ear training courses for more than five years, (4) undergraduate or recently graduated students (no longer than one year), and (5) no neurological or hearing loss conditions.

C. Recruitment of Volunteers

Participants registered for the study through a survey in Google Forms. Each participant underwent a neurological

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evaluation stated by the Institute of Neuroscience of Guadalajara to exclude any participants with neurological disorders. Afterward, audiometry per participant was taken and assessed by an otolaryngologist to exclude participants with a hearing loss condition.

D. *Experimental Procedure*

The experimental procedure involving human subjects was approved by the ethics committee of Tecnologico de Monterrey. Upon arrival, each participant filled-in an informed consent authorizing his/her participation in the study. Then, the heart rate was measured with a pulse oximeter to calculate his/her individual alpha frequency, and thus, personal frequency bandwidths of brain oscillations in accordance with the Brain Body Coupling theory [18]. Afterward, the brain responses of each participant were recorded using EEG technique. On the first session, the brain responses were recorded in four conditions lasting five minutes with closed eyes: (1) in a resting state (baseline), (2) at listening to pink noise through AH, (3) at listening to pink noise through SH, and (4) at listening to pink noise through EH. At the end of the session, each participant was given a pair of AH models along with 30 audio files (sample rate = 44100 Hz) in WAV format of pink noise with a length of 20 minutes. Audio files frequency content was compared to the inverse response of headphones with frequency graphs and perceived auditory sensation to verify correct calibration. Participants were equally divided into three groups: AH, SH (AH calibrated to emulate the SH frequency response), and EH (AH calibrated to emulate the EH frequency response). Audio devices sound level (e.g., computers, smartphones) were adjusted to 60±2 dB with a sound level meter, and equalizers in devices were deactivated. Participants were instructed to listen in AH to one sound emulating AH, SH, or EH every day for 30 days at home. To monitor that they heard the assigned sound, a set of random words were inserted along with the file. The words were different every day, and so the number of words. After listening to the audio file, the participant had to write the words in a survey in Google Forms, indicating the number of the file, the assigned group, and any other comments. After listening to the 30 audio files, a second and last EEG recording session following the same procedures as the first session was conducted to evaluate sound habituation.

E. *Signal Acquisition*

A 24-channel Easycap electrode cap in line with the 10/20 international system and a Smarting EEG Bluetooth amplifier were used. Data were recorded using OpenViBE software. The sample rate was 250 Hz.

F. *Signal Analysis*

EEG signals were processed in MATLAB and EEGLAB toolbox. Preprocessing steps were: (1) Baseline removal. (2) Data were bandpass filtered in 0.1-100 Hz with an 8th-order IIR Butterworth design. (3) The 60 Hz component was removed with a 2nd-order bandstop IIR design. (4) Monopolar referencing was performed against the average between left and right mastoids. (5) EEG signals were visually inspected to reject artifacts due to participant motion and electrode displacement. (6) Individual component analysis was applied to remove cardiac and ocular electrical activities, and electrode pop-ups. On the other hand, the processing of EEG signals was conducted as follows: (1) EEG signals of each participant were filtered with an 8th-order IIR Butterworth bandpass filter according to their individual theta (f_{Low}=3.968±0.732 Hz, f_{High}=6.062±1.119 Hz) and alpha (f_{Low}=7.935±1.464 Hz, f_{High}=12.125±2.238 Hz) frequency bands. (2) EEG signals were squared to calculate the band power of adjacent windows of one second long. (3) EEG signals were normalized by dividing band power at listening to pink noise (EEG^2_{PN}) against the mean band power at resting state ($\overline{EEG}^2_{baseline}$) to obtain normalized brain oscillations for both frequency bands, alpha and theta. (4) The mean absolute band power (AP) of each participant was estimated, and it is expressed as follows:

$$AP = \left(\sum_{i=1}^{t} EEG^2_{PN} / \overline{EEG}^2_{baseline} \right) / t, \quad (1)$$

where t is the sample of the power signal in the time domain. This analysis was followed for the three study cases: AH, SH and EH. As time signals were filtered in frequency, a decibel conversion of the grand average power (GAP) to reduce the effect of power-law [19] was calculated using (2):

$$GAP = 10\log_{10}\left(\sum_{i=1}^{n} AP_i \ / n \right), \quad (2)$$

where n is the number of subjects. IIR filters were applied with the filtfilt function, turning them into zero-phase. Fig. 1 shows the GAP of subjects for each condition and session.

G. *Statistical Analysis*

The level of significance for all study cases was set to 0.05.

First Session. The Shapiro-Wilk normality test (SW) rejected the hypothesis of normality in the residuals of data ($p < 0.05$) for both bands. Levene's test (LT) for homogeneity of variances failed to reject homogeneity in alpha brain oscillations ($p > 0.05$) but not for theta ($p < 0.05$). Assumptions of analysis of variance test (ANOVA) were not accomplished. Therefore, the non-parametric Friedman test (FT) was selected to investigate if the means of the GAP in decibels registered by 22 electrodes differ. Then, a post-hoc two-sided Eisinga test (ET) for pairwise comparison was performed.

Last Session SW failed to reject the hypothesis that data followed a normal distribution in alpha ($p > 0.05$) but not in theta ($p < 0.05$). Bartlett's test for homogeneity of variances failed to reject homogeneity in alpha ($p > 0.05$). LT showed significant evidence to reject homogeneity in theta ($p < 0.05$). Data were then separated into groups: AH, SH, and EH. Therefore, independence can be considered. Assumptions of ANOVA were accomplished only for alpha, and hence, One-Way ANOVA was selected to investigate if the means 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 theta, the non-parametric Kruskal-Wallis test (KW) and a post-hoc two-sided Wilcoxon rank-sum test (WRS) were selected.

First vs. Last Session. SW failed to reject the hypothesis that the difference of data followed a normal distribution ($p > 0.05$) for both bands. Therefore, a two-sided t-test on the difference between the means of the first session and last sessions per band and per group was selected.

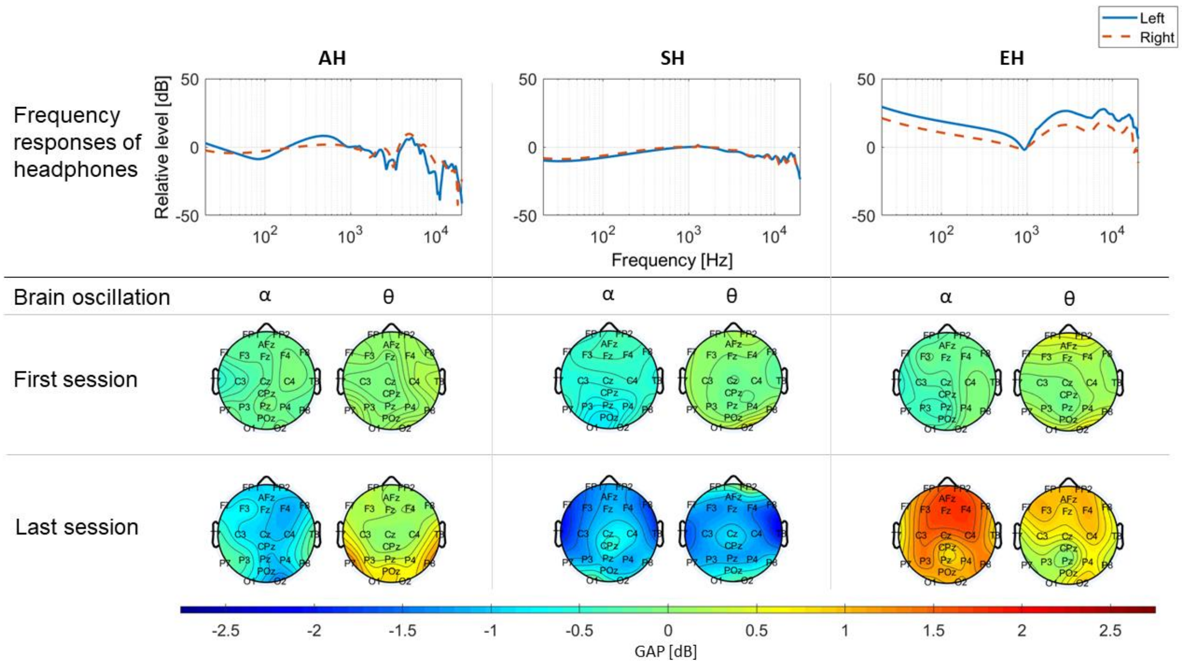

Figure 1. Frequency responses of AH, SH, and EH; and GAP of subjects in alpha (α) and theta (θ) brain oscillations in the first and last sessions. The curves of the frequency responses are adjusted to 1 kHz. Solid line depicts left headphone and dotted line right. Negative values of GAP represent desynchronization and positive values synchronization. The letters and numbers in the topographic map indicate the positions of electrodes.

III. RESULTS

A. *First session: Before Habituation*

For the first session, significant differences in the means of the GAP for alpha and theta ($p < 0.05$) were reported in FT. In ET results, SH showed significant differences compared to AH ($p < 0.025$) and EH ($p < 0.025$) in alpha. Differences between AH and EH were not significant ($p > 0.05$). In theta, EH showed significant differences compared to AH ($p < 0.025$) and SH ($p < 0.025$). AH and SH did not show significant differences ($p > 0.05$). EH showed higher power values in the frontal and right occipital regions.

B. *Last Session: After Habituation*

For the last session, ANOVA and KW showed enough evidence to reject the hypothesis that there are no differences in the GAP in alpha and theta, respectively ($p < 0.05$). In alpha, all pairwise comparisons between AH, SH, and EH differed significantly ($p < 0.025$). In theta, WRS showed significant differences between AH and SH ($p < 0.05$), and SH and EH, but not between AH and EH ($p > 0.05$).

C. *First vs. Last Session*

In alpha, there were significant differences in the GAP between the first and last sessions in all groups ($p < 0.025$). In theta, there was enough evidence to conclude that there is a difference in GAP between the first and last session in AH and EH ($p < 0.025$). Differences in SH were not significant ($p > 0.05$). EEG recordings of all participants and the audio files used for the experimental procedure can be accessed in [20].

IV. DISCUSSION

The present work aimed to determine the effect of frequency responses of three different headphone models in the modulation of alpha and theta brain oscillations in the short and long term, and thus investigating if quality of audio devices modifies human auditory perception.

Previous investigations have shown that brain responses in alpha band are related to most of the cognitive states of human beings [21]. The encoding of acoustic material is observed as widespread synchronization in the brain cortex [12]. The recognition of acoustic material, the complexity of a task, and attention level are observed as desynchronization [22]. Theta-band activity is found primarily in sleep states [21] and prominence is observed in auditory disorders [23]. Finally, there is evidence reporting that desynchronization and synchronization change levels with experience and learning [12], where synchronization increases in task demands [14]. The first session analysis aimed to determine differences in the electrical activity of the brain while people listened to the same sound in different headphone models. Desynchronization was observed in the whole brain cortex in SH. This model has a flatter response due to its high quality in comparison to AH and EH. In fact, SH is a specialized model for audio professionals. As the auditory stimuli were sent to the listener as complete as possible, the brain seemed to use fewer resources to encode the auditory information and directly interpreted what was being listened to [22]. On the other hand, the desynchronization levels observed over the topographic map were lower than those in the last session due to sound habituation reached after one month of exposure. Finally, synchronization in alpha and theta brain oscillations was observed in AH and EH widespread over the brain cortex, possibly indicating auditory information encoding. It seems that AH and EH produced loss of information due to their irregular frequency responses (Fig. 1, first row), and the brain required completing the missing information, which was reflected as increased synchronization. In EH, synchronization was observed in a larger area than AH, interpreted as the brain being forced to complete much more auditory information.

The analyses of the last and between sessions aimed to determine differences in the electrical activity of the brain before and after sound habituation. In Fig. 1 (third row), there was a significant change in alpha and theta synchronization/desynchronization levels in the whole cortex compared to the first session for all headphone models. Both AH and SH showed lower GAP values, but SH showed the lowest values. This phenomenon could mean that after sound habituation, the stage of encoding acoustic material is skipped, and the brain goes directly to the retrieval and recognition of sound [12], related to cognitive processes [14]. The opposite effect is observed in EH. An explanation could be that, as this model has a reduction in the low-mid range of sound frequencies, the brain is continually trying to recreate or complete sound features. Therefore, the brain is not wholly focused on recognizing sound. On the contrary, while listening to pink noise in SH, the brain had to complete less information because the sound was already registered in the long-term memory. It used all of its resources to interpret the sound rather than encode new information. Moreover, this study focused on alpha and theta brain oscillations. However, it would be expected to observe changes in delta, beta, and gamma brain oscillations, which show evidence of modulation due to learning (delta)[12], attention and memory (beta and gamma, respectively)[21]. Lastly, current methodologies of acoustic treatments lack standard procedures including optimal devices and processing techniques [24]. Thus, acoustic treatments using headphones that accurately reproduce sound are expected to improve the effectiveness of acoustic treatments in patients because (1) they transmit complete auditory information and (2) lead to sound habituation.

V. Conclusion

This study demonstrated the effect of frequency responses of different headphone models in alpha and theta brain oscillations before and after sound habituation. When the frequency response of an audio device attenuates some frequencies of the transmitted sound, the brain will first complete the missing information reflected as synchronization of alpha and theta brain oscillations. If the audio device accurately reproduces sound, the brain will then use mental resources to recognize and interpret the auditory stimuli, reflected as desynchronization.

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