# Loudness Threshold as a Function of Sound Source Location Using Circum-Aural Headphones in Noisy and Sound-Proof Acoustic Environments

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***Abstract*- We compared custom-made headphones (designed to capitalize on the directional filtering capability of the external ear) with standard consumer headphones in a loudness threshold task, and had shown that the location of the speakers was essential to auditory perception. The results revealed that the equal loudness contour profiles were significantly changed using the customized headphones. Furthermore it was discovered that an everyday noisy acoustic environment as compared to a sound-proof room does not diminish the advantage of the customized headphones in an auditory threshold task. Future investigation of the filtering process that the external ear provides could lead to more ergonomic acoustic equipment and hearing aid design.**

***Keywords*- *Loudness Threshold; Circum-aural Headphones; Noise***

## I. INTRODUCTION

The contribution of the location of the sound source and of the expanded utilization of the external ear to the loudness threshold using circum-aural headphones was the main objective of the present investigation. As sound travels through the structure of the external ear it undergoes a filtering process by which frequencies that comprise the normal range of human speech are amplified. Numerous empirical studies and reviews [1, 2, 3] support the functional importance of the external ear in processing sound. The design principles of the majority of circum-aural headphones utilize the functionality of the pinnae [4]. However, most modern headphone design solutions ignore important components of the external ear, either by pressing on and deforming the outer ear or are inserted directly into the ear canal, leaving the pinnae unemployed. The aim of the present project was to construct a pair of headphones that exploit the natural transfer functions of the external ear as much as possible. The method of the present study was based on previous experiments in which investigators mapped out the frequency specific direction dependent amplification functions of the external ear [2, 5, 6].

The importance of the pinna's role in sound perception has been described by several authors [2, 6, 7, 8]. The external ear is not just passively transferring sound into the ear canal but it is also a significant component of auditory perception [9]. One of the most researched properties of the external ear is its influence on the perception of the sound source's location [2, 6, 7]. Putting the process of sound localization into contrast with visual space perception might help us to gain a better understanding of auditory space perception. The process of auditory localization is very different from locating an object visually. Visual perception has the advantage of direct representation of the environment on the retina, where the retinal position of each object corresponds to the actual location of that object. However the auditory system cannot rely on such direct representation of surrounding sound sources. The acoustic information that arrives to the ear canal contains all the data that is currently available in our environment and the direction of sounds must be computed from the neural representation of the incoming sound waves [6].

According to [9], the external ear can block some frequency components of incoming sound waves. As such the structure of the pinnae can be thought of as analogous to an electronic wave filter capable of attenuating and amplifying certain frequencies. Moreover, acoustic cues provided by the outer ear play an important role in externalizing the perceived acoustic event. The externalized, out-of-head experience means that the listener perceives the sound source as coming from a natural (external) environment [10]. The importance of the pinnae for producing an auditory experience in three-dimensional space underlies recent research which attempted to simulate this effect [11, 12, 13]. The applied methods included the artificial synthesis of ear canal waveforms, that is the actual waves recorded within the ear canal when the sound source was located in a free field [10], controlling the azimuth and range of waves reaching the listener [11], and the use of ambisonic technique to reproduce the spatial sound experience [13, 15]. The main purpose of these projects was to recreate a natural environment for the listener by using a pair of headphones or a set of loudspeakers. The practical importance of the above mentioned studies is reflected in today's 3D capable audio systems built to simulate the natural acoustic environment. Many of these commercially available 3D capable audio sound systems widen the virtual auditory space by expanding the acoustic event beyond the original sound sources, such as left and right speakers [12]. Regardless of whether the utilized system was the real thing or simply a system which mimicked the real 3D technology, the objective was always to imitate auditory processing as it occurs in a natural environment. In the natural environment the external ear always participates in the process of shaping the acoustic information that reaches the middle and inner ear. Just as in the natural environment, during simulations of free field listening, the acoustic signals first interact with the external ear. This fact necessitates the incorporation of the pinnae's transfer function into the structural design of headphones.

The pinnae's frequency amplification function is direction dependent [1]. By systematically changing the elevation and angle of the sound source, the sound pattern differentially interacts with the notches of the outer ear. This phenomenon was demonstrated by [5] when they presented participants with a series of auditory signals arranged at as many as 325 to 393 different locations within a spherical space with the head at its center. The observed changes in amplitude for the tested frequencies within the ear canal revealed that air pressure changes are maximized for higher frequencies (12 kHz and 14 kHz) if they are presented from very specific locations in space. It was also discovered that for some frequencies (e.g. 9.9 kHz at 50˚ azimuth and -40˚ and 60˚ elevation) there is more than one position that achieves maximum amplification of the external ear. Further analysis showed that for higher frequencies the best amplification always occurred when the sound source was positioned in front of the subject. Similar results were also obtained by [15]. In this study computer generated sound stimuli were presented from a circular array of 36 speakers positioned around the listener. Changes in sound pressure levels were measured within the ear canal for each direction. Results showed that the maximum amplitude for higher frequencies (10-14Hz) was observed when the sound source's azimuths were located in the frontal horizontal plane between 0 and 40 degrees. These results were consistent with the findings from several other researchers [5, 7, 16].

We hypothesized that projecting sound waves onto direction specific sites of the external ear with the use of a circum-aural headphone would utilize the natural amplification of higher frequencies and result in a listening experience in that frequency range that is of higher sensitivity. In addition to that, we wanted to increase the ecological validity of our measurements by testing acoustic thresholds in both sound-proof rooms and everyday noisy acoustic environments.

## II. METHOD

### A. Participants

43 undergraduate students (mean age M=23 years) at the University of Southern Mississippi participated in the study. Experimental procedures were approved by the local Institutional Review Board. Participants were asked to report any kind of hearing deficits. Three participants reported hearing problems such as tinnitus, mild hearing loss in the left ear due to playing on a musical instrument, and major hearing loss in the left ear that existed from birth, respectively. We did not exclude these three participants from the statistical analyses. 19 participants were assigned to a soundproof acoustic environment (quiet room), and 24 participants were tested in a laboratory room with typical everyday noise levels (noisy room). One participant's data in the soundproof condition was lost due to instrument malfunction.

### B. Materials and Apparatus

Participants were seated in front of an LCD monitor and used a computer mouse to press a virtual button on the screen. Each participant was tested with both the experimental and control headphones. The control headphones was a SONY MDR-NC7/WHI model which comprised two 30 mm closed dome type dynamic speakers with a frequency response of 30 Hz - 20,000 Hz, impedance of 33 ohms at 1 kHz (when the power is on), 35 ohms at 1 kHz (when the power is off). During the experiment the headphones' power was always turned on in order to include the effect of the headphones' built-in noise cancellation feature. According to the official technical description of the device provided by SONY the total noise suppression is approximately 9 dB when power is on. The experimental headphone was constructed from the same SONY MDR-NC7/WHI type model with the exception that the position of the speakers had been modified. The positioning of the sound source within the headphones (that is, the speakers) was based on direction dependent frequency responses of the external ear [5, 7, 16]. Based on the results of the aforementioned studies, the maximum amplification for higher frequencies (4 kHz-12 kHz) can be best achieved from the frontal hemi-field with the sound source's elevation within 10-30 degrees with an azimuth of 10-40 degrees. The speakers of the experimental headphones were positioned approximately 1-2 cm from the ear canal with the elevation of 20 degrees depending on the variability of the subject's anatomical distinctiveness. The azimuth was controlled with a plastic strip that measured approximately 40×30×1 mm which was attached to the base of the speaker at a 10 degree angle. The strip served as a guide for sound waves arriving from the speaker to the top of the external ear canal (see details of the experimental headphones in Fig. 1).

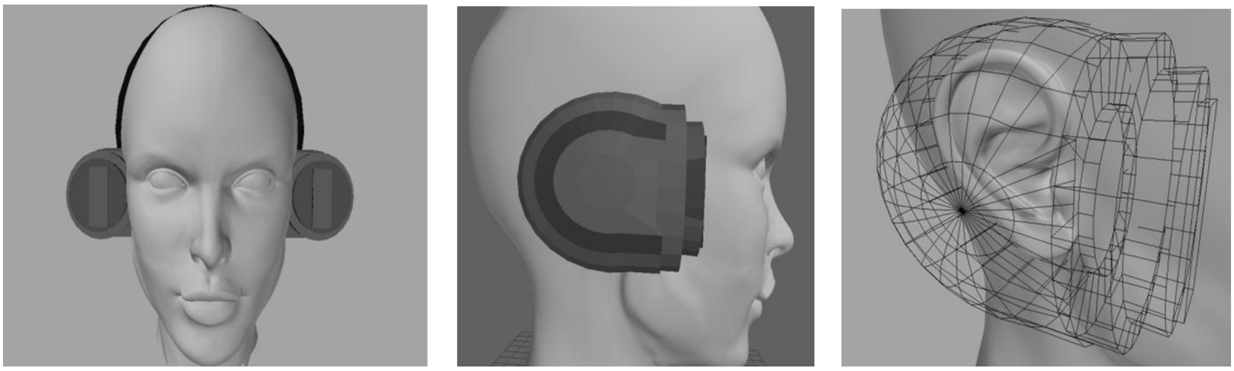

Fig. 1A Frontal and side view of the headphones along with a transparent view

The outer shell (indicated by the dark polygons in the transparent view) completely covers the entire external ear without interfering with its surface structure and shape.

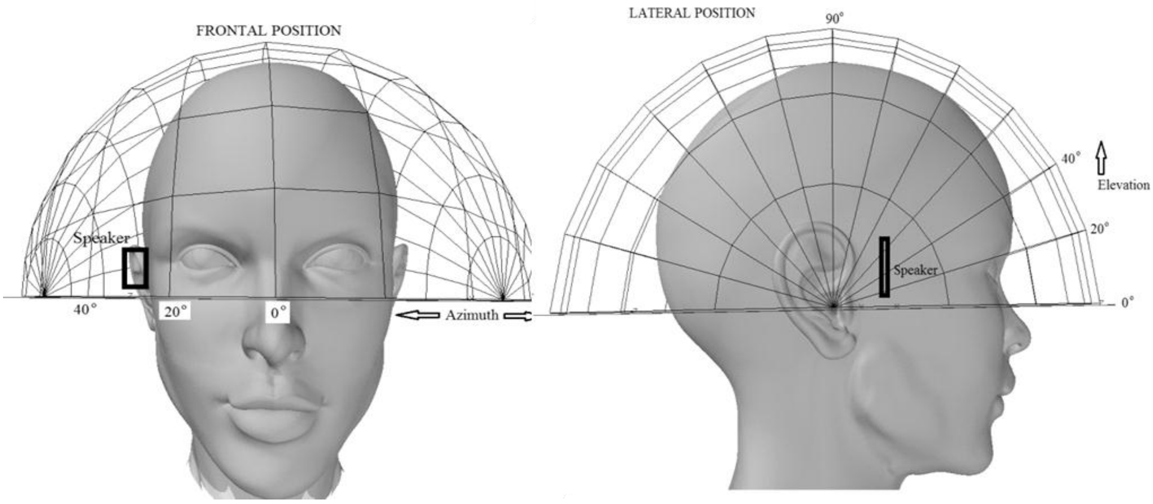


Fig. 1B Frontal and lateral view of the position of the speakers in the experimental headphones

The speakers of the experimental headphones were positioned approximately 1-2 cm from the ear canal with the elevation of 20 °depending on the variability of the subject's anatomical distinctiveness.

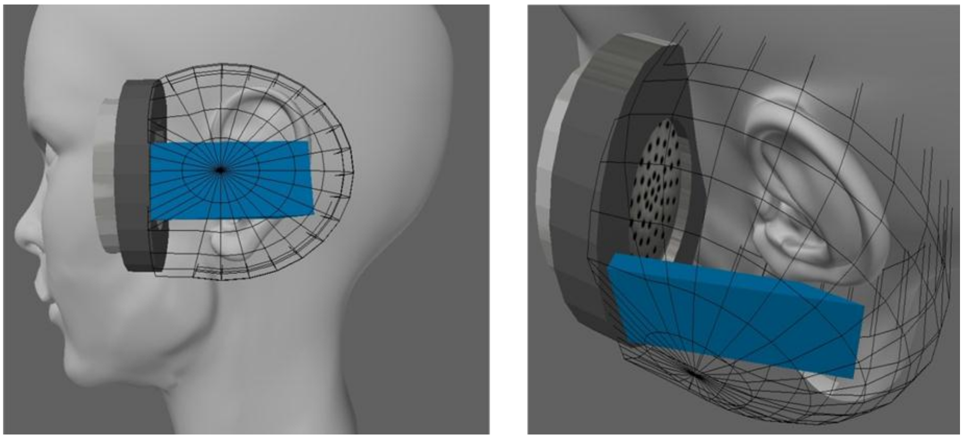

Fig. 1C The azimuth was controlled by a 40×30×1 mm plastic strip (indicated by the shaded rectangle) attached to the base of the speaker at a 10 degree angle

The strip served as a guide and reverberation surface for sound waves reaching from the speaker to the top of the external ear canal.

The hardware of the headphones was constructed from hard plastic parts measuring approximately 2mm width and covered the whole external ear. Stimuli were presented via MATLAB software using a modified version of source code downloaded from MATLAB Central [17]. A screenshot of exemplary results is presented via a MATLAB Graphical User Interface (GUI) in Fig. 2.

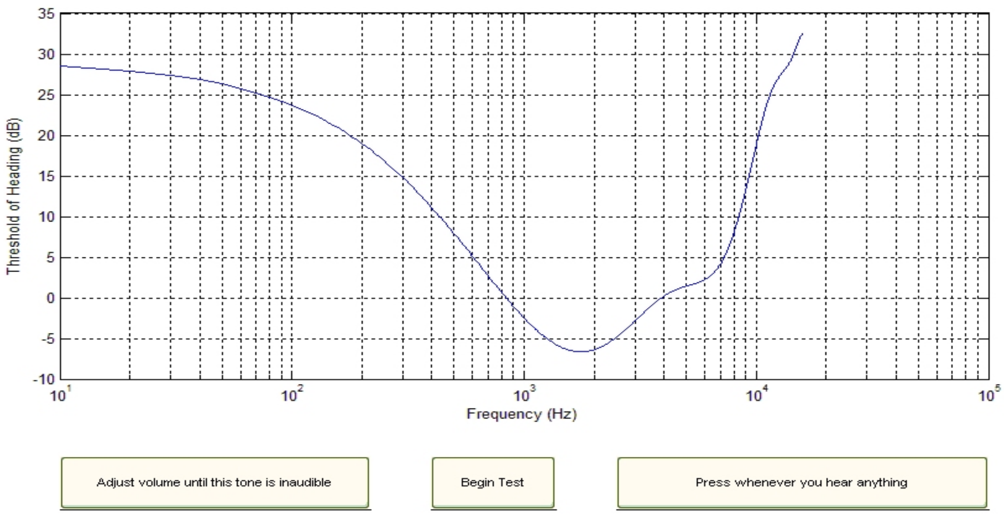


Fig. 2 A screenshot of the MATLAB graphical user interface (GUI) used to measure the equal loudness curves of individual participants

The loudness curve plot portion of the GUI (top) was covered and not visible to participants to prevent them from monitoring their own responses.

### C. Stimuli and Measurements

The display for the stimulus detection task, demonstrated in Fig. 2, consisted of two buttons that were used by the participants to start the experiment and to indicate their responses. After participants pressed the start button a range of test frequencies (40 Hz-20 kHz) were presented from low to high frequencies in successive order. Each stimulus contained a sequence of repeated presentation of one target tone[1] with amplitude decreasing by decrements of 3dB. The presentation continued until the participant was unable to detect the tone, as indicated by a failure to respond to the presented stimuli. The perceived minimal loudness (minus the 3dB decrement) was recorded as the relative threshold at the given sound frequency.

Each session was started with measuring the participant's relative threshold of hearing. The reference tone against which the threshold was measured was a 3500 Hz tone. The 0 threshold was defined by the decibel rate at which the participant was no longer able to detect the reference tone. We changed the decibel rate by adjusting the PC computer's volume setting until the participant no longer could hear the tone. During each trial this was the decibel rate at which each test tone was presented for the first time. Detection threshold levels were calculated with respect to the previously defined 0 threshold. Negative decibel rates meant that the threshold was below the reference level, whereas positive decibel levels meant that the threshold was above the reference level. The reference tone of 3500 Hz was established for each headphone type and each participant separately, yielding an intrinsic baseline. This procedure was employed for each participant in order to establish an individual's baseline reference threshold (which is a different absolute decibel value for each person). This way we avoided the bias of variations in individual hearing thresholds and frequency responses of the ear.

### D. Design and Procedure

The experiment was conducted with two groups of participants assigned to two different acoustic environments. The experimental group's testing was conducted in a room with an overall unfiltered ambient noise level of 79 dB SPL (Leq: 47 dBA). No audiometric prescreening was conducted for the experimental group, only the participants' self-reports were recorded about hearing deficits. The control group participants were seated in an acoustically insulated room and prescreened with a standard audiometer. Each group was introduced to the same sequence of 29 tones presented with the same 3 dB decrement steps in amplitude for each tone. Participants' responses were recorded for each tone to measure the relative threshold for that frequency. We used a 29 (frequencies) × 2 (acoustic environment: soundproof, noisy) × 2 (headphones: experimental, control) mixed ANOVA design with frequencies and headphones serving as within-subjects independent variables, and acoustic environment as a between-subjects independent variable. The dependent measure was the relative threshold of hearing expressed in decibels (dB).

## III. RESULTS

The acquired threshold levels in decibel were plotted as an average equal loudness curve (see Fig. 3). There were main effects of frequencies, headphones, and acoustic environment. More importantly, there was a three-way frequencies × acoustic environment × headphones interaction, $F(28,1120)=7,8$, $p<0.001$. This showed that the pattern of changes of frequencies for the different headphones differed across acoustic environments. Specifically, the headphones × frequencies interaction, $F(28,1120)=163.4$, $p<0.001$, showed that experimental headphones were more sensitive to high frequencies, thus producing lower thresholds, than the standard headphones, whereas the relationship is reversed for low frequencies. This result basically validated the purposeful design of the experimental headphones that were built specifically for enhancement of high frequencies. The significant frequencies × acoustic environment interaction, $F(28,1120)=44.9$, $p<0.001$, revealed that low frequencies interfered with perception to a larger extent in the noisy environment, because the background noise was mostly composed of strong low frequency components, thus resulting in higher thresholds for low frequencies. In the midrange of frequencies, surprisingly, the noisy room produced lower thresholds of hearing, whereas for high frequencies the two acoustic environments produced essentially the same response profile. We will discuss in more detail the important implications of this finding for how we should reinterpret the classical treatment of noise as separate from the perceptual system, and offer a more ecologically valid explanation. The experimental results are presented in Fig. 3A and 3B in separate plots corresponding to the two acoustic environments.

[1] Due to the imperfections of the sound system of the computer used to generate the tones, every stimulus contained the target tone with maximum amplitude mixed in with a number of other frequencies at lower amplitudes. The intensity profile of each stimulus was measured to list all the spectral components that were present in the sound. The spectral content of all stimulus tones was recorded by a microphone (Audix TR-40, E-Mu 0404 sound card) suspended from the ceiling in the middle of the acoustical chamber.

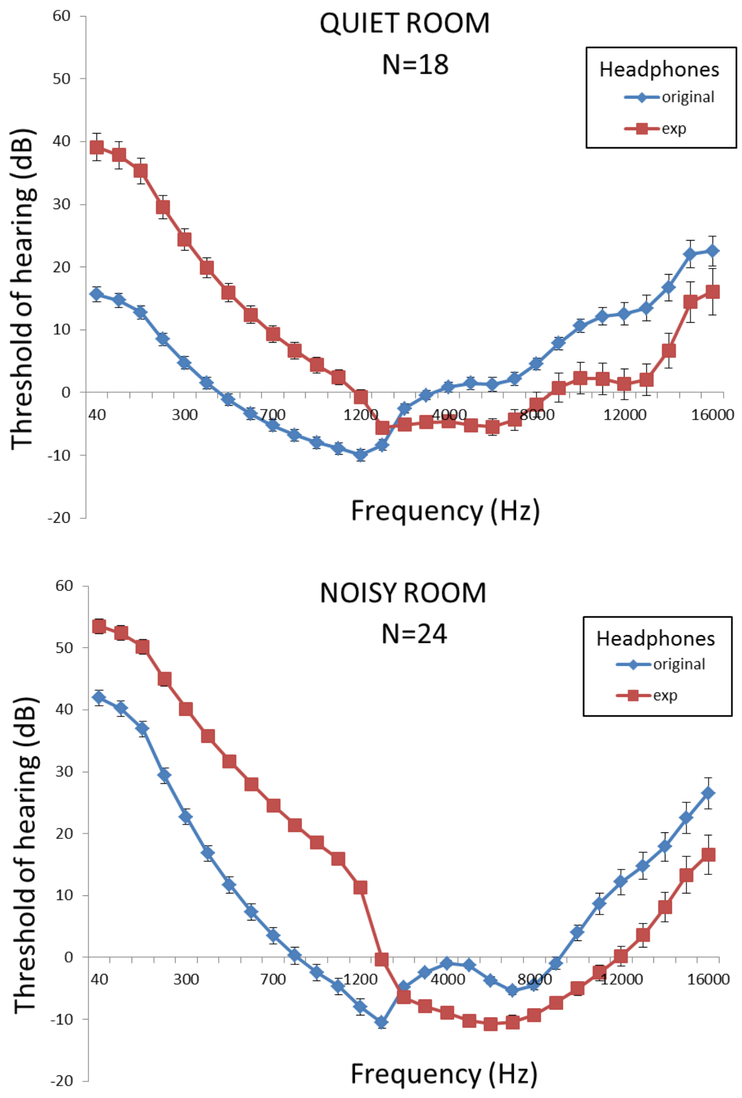


Fig. 3 A, B Auditory thresholds (presented as average equal loudness curves) as a function of sound frequency, headphones and acoustic environment

The error bars represent ±1 standard error. The reference tone was a 3500 Hz sound. Zero dB threshold corresponds to the perceived threshold that is identical to the threshold assessed for the 3500Hz tone. In the figure legend 'original' indicates the standard SONY headphones, whereas 'exp' labels the custom-made headphones. *Panel A* shows the soundproof condition (quiet room), whereas *Panel B* presents the noisy room condition.

It is interesting to note that the 3500 Hz threshold tone did not correspond to complete silence. Even in the soundproof room, the adjustments to the standard headphone that had built in noise cancellation resulted in a measured threshold of -0.4 dB. The thresholds were even lower for both headphones in the noisy room (-2.4 dB for the standard headphone and -7.9 dB for the experimental headphone). Apparently, participants turned the volume lower to compensate for the growing amount of environmental noise that was seeping in from the noisy room through the experimental headphones.

## IV. DISCUSSION

In our experiment we replicated the classic findings that demonstrate the directional sensitivity of the auditory system using custom-made headphones. The novel design allowed the external ear to filter acoustic information in the same way as it happens in unobstructed auditory perception in real 3D space. The aim was to accomplish a design that is capable of reproducing the findings of past research that tested the directional dependent amplification of the human external ear. Our hypothesis was that using a specific setting of a sound source the experimental headphone will be able to harness the external ears' directional dependent amplification for higher frequencies that are related to the given sound source direction.

One disadvantage of the testing method was the reverberation of the experimental headphone caused by the lack of professional construction materials. Due to the nature of the constructed circum-aural device the applied insulation did not entirely absorb the reverberant noise within the headphones. The spectral analysis of the output indicated that the target frequency was presented with the highest amplitude but it also confirmed the occurrence of additional frequencies (see Footnote 1). As a consequence of these confounding variables, on each trial participants were exposed to a mixture of frequencies (including the target frequency with the highest dB) instead of a pure tone. The presence of additional frequencies was a considerable source of error regarding the interpretation of the results because they can compete with the actual frequency that the participants were responding to. The presence of this type of error was anticipated to be manifested as an increase in variability between individual participant responses. However, the error rates (represented by standard error bars in Figure 3) on the plotted equal loudness contours indicated consistent responding to target frequencies in both conditions and across participants. Had the additional frequencies significantly interfered with the perception of the target frequency, response variability would have been consequently larger for the experimental headphones, especially in the acoustically insulated room condition where the interference would have been much more pronounced. Interestingly, our results indicated that in the noisy room the experimental headphones required even less amplification of higher frequencies to present detectable stimuli compared to the acoustically insulated condition. The differential sensitivity of the customized headphones in the noisy room is especially striking for the 4 kHz -12 kHz range (see Figure 3). This result is possibly an artifact of the interaction between the nature of the environmental noise (which was in the lower range of frequencies) and the position of the sound source inside the headphones. One possible explanation for the observed enhancement of auditory perception in the noisy condition is related to the spectral difference between the stimuli and the noise itself. Because the stimuli were presented onto specific sites of the external ear they gained more amplification compared to the environmental noise and, thus, became even more salient. The saliency of the high frequency stimuli in a low frequency noisy environment can be analogous to seeing a white horse among lots of brown and black horses. However, this salience was not so prominent in the case of the original headphones which can lead to further implications of the results. One promising interpretation could be that the experimental headphones were capable of taking advantage of the external noise which is of considerable benefit if we think of the fact that people usually use headphones in noisy environments instead of an acoustically insulated room. The extended range of amplified frequencies was likely the by-product of the physical proximity of the sound source to the external ear. Previous experiments [5] used a distance of 1.2 meters to test directional amplification of a variety of frequencies. In the case of our experimental headphones the distance was approximately 2-3 cm from the external ear.

Measurements of the direction dependent amplification in both conditions showed significant differences between the experimental and the original headphones. Based on our results we can conclude that it is possible to incorporate the external ear's transfer function into the design of circum-aural headphones. Despite the disadvantages of the experimental headphone's construction it was able to produce a measurable and significant difference as compared to the standard headphones. These results serve as a preliminary investigation of a new headphone design which, we hope, will be capable of providing a more natural listening experience due to the involvement of the external ear. The customized headphones performed as well or even better than standard headphones in a noisy environment in detecting high frequencies. The surprising resistance of the custom-made headphones to background noise suggests that classical distinctions in cognitive science and engineering between signal and noise need to be revised in view of our present findings. Noise and signal in natural environments can be genuinely considered parts of the same organism-environment system, a basic tenet of the ecological approach to perception and action [18]. There is mounting evidence from a variety of empirical findings in precision motor tasks [19], postural stability [20], and exploratory behavior in dynamic touch [21], to name just a few, that support the idea of noise as an integral part of perception-action systems that shapes goal-directed behavior. This is yet another reason to harness the inherent complex nature of acoustic noise for the understanding of auditory perception and to use it to design better and more functional hearing devices that provide a natural, high-fidelity auditory experience.

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