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VERTICAL SOUND LOCALIZATION: INFLUENCE OF AGE, EAR SIZE, SEX, AND HAIR

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ABSTRACT

Sound localization in the vertical plane is a vital aspect of human auditory perception and has implications for everyday life. Previous studies have explored factors influencing sound localization, but mainly in the horizontal plane or with a small number of subjects. This study stands out due to the large cohort of 150 participants, providing a robust data set that enhances the reliability and generalizability of the findings. Participants underwent a series of vertical sound localization tests with broadband noise stimuli under free-field conditions, measuring the localization error between the actual sound source position and the subjects' estimations. Certain factors were documented to investigate their influence on localization precision, including age, ear size, sex, and the hair length, whether it covered the ears or not. The comprehensive analysis conducted in this study aims to provide a more nuanced understanding of the factors affecting the accuracy of vertical sound localization. The findings can contribute to a better understanding of spatial hearing and hence to improvements in virtual reality applications or hearing aid development.

Keywords: *sound localization, spatial hearing, vertical sound localization, elevation hearing, psychoacoustics*

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1. INTRODUCTION

Sound localization is a critical aspect of human auditory perception, enabling individuals to navigate and interact with their environment effectively. While more research has been conducted on sound localization in the horizontal plane, focusing on its primary localization cues, interaural time differences (ITD) and interaural level differences (ILD), the vertical plane has received comparatively less attention. Localization in elevation is influenced by spectral cues, caused by the shape and features of the head, torso, and external ear.

This study aims to clarify sound localization in the vertical plane, which is vital for everyday life and has significant implications for various applications. Previous studies have often been limited by small sample sizes or have focused predominantly on horizontal localization. In contrast, this research stands out due to its large cohort of 150 participants, providing a robust dataset that enhances the reliability and generalizability of the findings.

The paper is organized as follows: The literature review section discusses previous findings related to sound localization. The methodology details the experimental setup and procedures. The results section presents the outcomes of the study and a discussion on the influence of age, ear size, sex, and hair length. Finally, the conclusion and outlook summarizes the findings and suggests directions for future research.

2. LITERATURE

In [1], the focus is on the horizontal plane, determining the minimum audible angle in azimuth. In [3], the use of spectral cues in resolving the localization of sounds originating in the front or rear along the horizontal plane was demonstrated with seven participants. Factors influencing vertical localization have been studied with a small number of subjects, such as in [2] with six participants, where it was found that complex stimuli and frequencies above 7000 Hz must be present for accurate vertical localization. In [4], both horizontal and vertical localization were examined with four participants regarding the minimum audible angle, showing that auditory cues significantly improve the efficiency of visual search tasks.

It was found that the pinna significantly affects sound localization, particularly within the cone of confusion, depending on the frequencies [5,6]. In [5], it was discovered that the shape of the outer ear channels sound through multiple pathways, enhancing directional hearing and in [6] specific frequency bands perceived in particular directions were identified, highlighting the role of the pinna in sound localization.

Furthermore, the influence of hair on sound localization was investigated, revealing its impact on auditory perception [7]. Additionally, sex differences in sound localization were explored, highlighting variations in auditory processing between males and females [8], although vertical sound localization was not explicitly examined. According to the study, females are more sensitive to sound, but males have a tendency to be better at sound localization.

3. METHODOLOGY

In the following the experimental setup is described, as well as the data that were recorded from each subject.

3.1 Experimental Setup

The experimental setup was constructed in an anechoic chamber using a curved array consisting of 16 coaxial loudspeakers, spanning a total of 60° in elevation, with one loudspeaker every 4°, as shown in Figure 1. The subject was seated on a chair at a distance of 1.7 m from the center of the head to each loudspeaker, with the lowest loudspeaker positioned at -15° and the highest loudspeaker +45° elevation angle. The chair had a headrest to minimize head motion. White noise at 50 dB SPL was played for one second from a random loudspeaker, and the subject had to estimate from which loudspeaker, numbered 1 for the highest and 16 for the lowest position, the sound originated. The sound was played only once for each estimation. Additionally, there were no prior tests, nor did the subjects receive feedback about their choice, ensuring no training effect. The test was conducted with three different azimuth positions relative to the right ear's position to the array. These azimuth positions, -45°, 0°, and +90°, were also selected randomly. Each loudspeaker played only once per azimuth angle. Further details can be found in [9]. In the following, the influencing factors in relation to the mean absolute deviation and mean signed deviation of these 3 azimuth positions are analyzed.

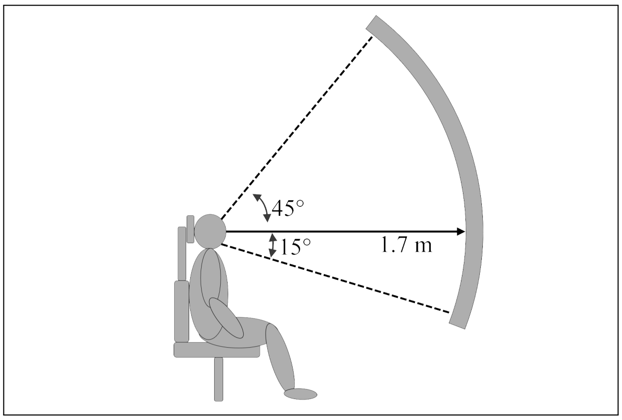

Figure 1. Experimental setup in a anechoic chamber.

3.2 Subjects and Recorded Data

The research included a total of 150 valid subjects, aged between 16 and 65, comprising 61 female and 89 male participants. All participants were volunteers.

In addition to the data recorded during the measurements, participants were asked to provide further information. This data was collected to investigate the correlation between these factors and the precision of sound localization in the vertical plane. The documented information included sex, hair, categorized as covering or not covering the ears, as well as age, and ear size, which was split into ear height and ear width. Furthermore, medical information related to the ear was collected to ensure that the participants' hearing conditions were suitable for the sound localization requirements. The date and time of the measurements were also noted.

The medical condition of each subject's ear was assessed, specifically whether any hearing loss had been diagnosed or if the participant had noticed any issues. Subjects with diagnosed hearing loss were excluded from the evaluation of the study. To achieve a total of 150 subjects, 157 individuals were initially measured, with seven excluded due to hearing loss. Two of the remaining 150 subjects suffer from tinnitus. However, they were included in the study because the measurements were conducted using a broadband signal, specifically white noise.

Due to a significantly higher rate of choosing the first three edge loudspeakers on each side, these loudspeakers were excluded to ensure there was no bias towards the edges. Consequently, the statistics are based on the results from loudspeakers 4 to 13. This adjustment was made to maintain the integrity of the data and ensure a more uniform distribution of choices.

4. RESULTS AND DISCUSSION

Considering the exclusions, the results for the mean absolute deviation, mean signed deviation, and standard error for all subjects are shown in Table 1. The mean absolute deviation is $5.27°$, indicating that, on average, the subjects' estimations were more than one loudspeaker away from the actual speaker. The mean signed deviation was $0.00°$, showing that, on average, there was no offset in the upward or downward direction. The standard error for all subjects is $\pm 0.14°$. Therefore, a random subject made an error within the range of $5.27° \pm 0.14°$.

This data will serve as a reference when analyzing individual binary influence factors, such as sex and hair. The influence of age, ear size, sex, and hair length will be discussed in the following sections. The influence is considered significant if its p-value is below the significance level $\alpha = 0.05$. Any p-value higher than α confirms the null hypothesis H_0, which asserts that there is no influence. The p-values are determined by calculating the correlation coefficients and the linear or multiple linear regression.

Table 1. Mean absolute deviation, mean signed deviation and standard error of sound localization in elevation for all subjects.

Mean abs. dev.	Mean sig. dev.	Std. error
$5.27°$	$0.00°$	$\pm 0.14°$

4.1 Influence of Age on Localization

Figure 2 shows the elevation angle error for all subjects and the linear regression line for increasing age. There is a recognizable trend indicating that the error rate increases with age. However, when calculating the correlation coefficients and corresponding p-values, the resulting p-values for the mean absolute deviation (p = 0.1567) and the mean signed deviation in elevation angle (p = 0.5535) was found not to be significant. Note that for simplification, the former deviation will also be referred to as error and the latter deviation as offset in the following.

The reason why the observed trend is not significant could be the age distribution of the test subjects. The majority of participants were between 17 and 31 years old, with only 5 subjects older than 50 years and just 3 participants older than 58. It has been found that noticeable hearing loss due to age increases significantly after 60 years, which is why regular hearing tests are recommended for individuals no older than 60 years [10].

Therefore, the limited number of older participants may have influenced the overall findings, suggesting that further research with a more balanced age distribution is necessary.

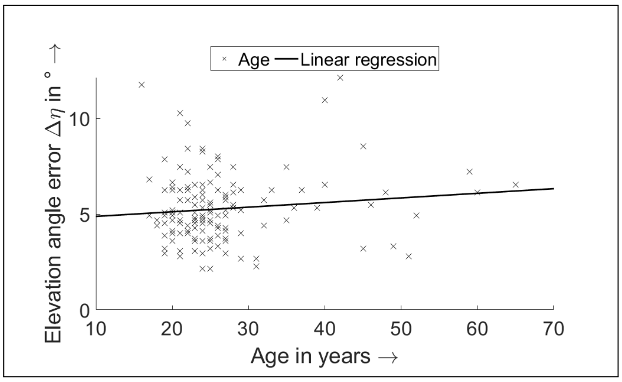

Figure 2. Absolute elevation deviation $\Delta\eta$ in ° for every subject according to their ages with the calculated regression line, showing is a slight trend towards greater deviation with increasing age.

4.2 Influence of Ear Size on Localization

The ear size of each subject was recorded by measuring the height, from the lowest edge of the lobule to the highest part, and the width from the tragus to the outer edge of the ear, as shown in Figure 3. First, the ear area will be considered, followed by a separate analysis of the measured values for height and width.

4.2.1 Ear Size in Ear Area

Looking at Figure 4, there is a clear trend indicating that subjects with a larger ear area made a smaller error. Each "x" represents a subject's estimation error in degrees, and

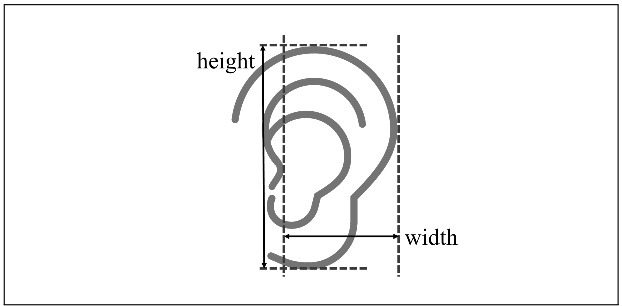

Figure 3. Ear measurement in width and height.

the line shows the calculated regression line for the distribution. Ear areas ranged from $1311\,\text{mm}^2$ to $2482\,\text{mm}^2$. An increase in this is inversely proportional to the magnitude of the elevation error angle.

Examining the statistics, there is a significant influence. The p-value for the mean signed deviation is $p = 0.0461$, and for the mean absolute deviation, $p = 4.16 \cdot 10^{-3}$, with a significance level of $\alpha = 0.05$.

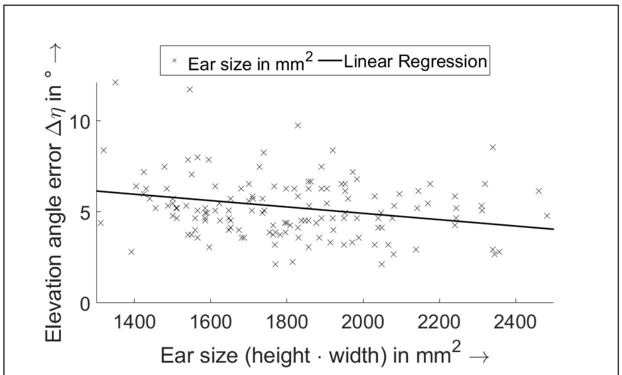

Figure 4. Absolute elevation angle error $\Delta\eta$ in $^\circ$ for every subject according to their ear area size with the calculated regression line, showing a trend towards smaller deviation with larger ear area.

4.2.2 *Ear Width Individually*

The ear width of the subjects varied between 22.5 mm and 40 mm. When analyzing the this factor, it was found that it has no significant influence on neither the mean absolute deviation (p = 0.0606) or the mean signed deviation (p = 0.1064). However, the linear regression analysis revealed a clear tendency that accuracy increases with ear width.

This suggests that while the statistical significance is not strong enough to reject the null hypothesis, there is an observable trend indicating that wider ears may contribute to better sound localization accuracy.

4.2.3 *Ear Height Individually*

Subjects' ear height varied between 49 mm and 83.4 mm. Considering the influence of ear height on the error in locating a sound in the elevation plane, the p-value is $4.9843 \cdot 10^{-5}$, indicating clear significance. In contrast, the offset shows no significance with a p-value of 0.0804.

This significant correlation suggests that ear height plays a crucial role in the accuracy of vertical sound localization. The lack of significance in the offset implies that while ear height affects the precision of localization, it does not introduce a consistent directional bias.

4.2.4 *Interrelated Influence Ear Height and Width*

When performing the multiple linear regression analysis, it was determined that ear height continues to have a significant impact on the mean absolute deviation in elevation, with a p-value of p = 0.0003 and a coefficient of -0.2760. As illustrated in Table 2, the corresponding correlation coefficients and p-values are presented for the mean absolute deviation across all subjects concerning ear height. The same table also shows these values for ear width, based on a point-biserial correlation coefficient calculation for the interrelated influence of ear height and ear width. Conversely, ear width remains non-significant, with a coefficient of -0.0952 and a p-value of p = 0.5264, leading to the acceptance of the null hypothesis (H_0). Furthermore, Table 3 displays the same parameters for the average offset, where no significance was observed for either ear height or ear width. While ear height significantly influences localization accuracy, ear width does not exhibit a similar effect and neither parameter impacts the offset. The trend that was determined for the individual ear width can probably be explained by the correlation that the ear width also increases with increasing ear height.

Table 2. Correlation coefficients and p-values for interrelated ear height and ear width in mean absolute deviation in elevation angle.

Mean abs. dev.	Ear height	Ear width
Coefficients	-0.2760	-0.0952
p-value	0.0003	0.5264

Table 3. Correlation coefficients and p-values for interrelated ear height and ear width in mean signed deviation in elevation angle.

Mean sig. dev.	Ear height	Ear width
Coefficients	0.1823	0.3155
p-value	0.1961	0.2687

4.3 Influence of Sex and Hair on Localization

In the following the influence of sex and hair on sound localization in the elevation plane is discussed. First, they are considered individually and then the interrelated influence is examined.

4.3.1 Sex Individually

The influence of biological sex is shown in Table 4, which includes the mean absolute deviation, mean signed deviation, and standard error for both female (F) and male (M) participants. Compared to the general results found in Table 1, it is clear that women perform slightly worse than the average, with a mean absolute deviation of $5.83°$ and tend to localize lower elevation angles than the acutal ones, indicated by the mean signed deviation of $-1.09°$. Men perform slightly better than the average with a mean absolute deviation of $4.89°$, showing a slight tendency to localize higher elevation angels than the acutal ones, indicated by the mean signed deviation of $+0.74°$. By calculating the point-biserial correlation coefficients and corresponding p-values, it was discovered that this performance is significant for both the error (mean absolute deviation, p = $9.6584 \cdot 10^{-4}$) and the offset (mean signed deviation, p = $4.2249 \cdot 10^{-4}$). The standard error appears to remain within a similar range. Aligning with the findings in [8], this study confirms that male participants perform better at localizing sound sources, and this advantage extends to localization in the elevation plane.

4.3.2 Hair Individually

Considering the individual influence of hair length, whether the ears are covered (C) or not covered (NC), are shown in Table 5. The mean absolute deviation with hair covered ears is $5.80°$ and not covered ears is $4.82°$. The mean signed deviation is towards a lower elevation angle for C ($-0.88°$), and towards a higher elevation angle for NC ($+0.75°$). The differences between covered and uncovered ears in terms of mean absolute deviation are significant, with p = $4.7072 \cdot 10^{-4}$, as well as for the mean signed deviation, with p = 0.0016. This large-scale study supports the findings, that hair does influence auditory localization [5].

Table 4. Mean absolute deviation, mean signed deviation and standard error of sound localization in elevation for female (F) and male (M) subjects.

	Mean abs. dev.	Mean sig. dev.	Std. error
F	$5.83°$	$-1.09°$	$\pm0.15°$
M	$4.89°$	$+0.74°$	$\pm0.13°$

Table 5. Mean absolute deviation, mean signed deviation and standard error of sound localization in elevation for subjects with hair covering the ears (C) and not (NC).

	Mean abs. dev.	Mean sig. dev.	Std. error
C	$5.80°$	$-0.88°$	$\pm0.15°$
NC	$4.82°$	$+0.75°$	$\pm0.12°$

4.3.3 Interrelated Influence Sex and Hair

Comparing the results of sex and hair, there seems to be a very similar influence on the vertical localization capabilities. Since these two factors cannot be entirely separated, a deeper look into the correlation between these factors was warranted since they are closly interlinked.

Calculating the point-biserial correlation coefficients of these two influence factors with the resulting mean absolute and signed deviation, there appears to be no significant influence. For the mean absolute deviation, the calculated p-values for sex and hair are p = 0.0913 and p = 0.5132, respectively. For the mean signed deviation, the p-values are p = 0.3609 and p = 0.1415, respectively. According to these calculations, it cannot be determined if the influence on the elevation error comes from hair or sex. This may be due to the lack of a representative number of female participants with short hair (only 4 subjects) and male participants with long hair (only 12 subjects).

Examining the mean absolute deviation of females with short hair, which is $3.6°$, it is not within the standard error range for females ($5.83° \pm 0.15°$) nor within the standard error range of NC ($4.82° \pm 0.12°$). For males with long hair, the mean absolute deviation is $4.92°$, which is within the range for males ($4.89° \pm 0.13°$) but not for C ($5.80° \pm 0.15°$).

While the influence of hair coverage and sex individually show some influence on localization accuracy, the interaction between sex and hair on the localization accuracy requires further investigation.

5. CONCLUSION AND OUTLOOK

This study investigates the factors influencing vertical sound localization, focusing on age, ear height, ear width, sex, and hair coverage of the ear. The results show that there is a slight trend towards greater deviation with increasing age, but it is not significant. It was demonstrated that ear height significantly impacts localization accuracy, while ear width does not exhibit a similar effect. Additionally, the influence of sex on localization performance was evident, with male participants generally performing better than female participants. Hair length found to affect localization accuracy, with ears covered by hair showing worse performance compared to uncovered ears.

The interplay between sex and hair length, however, can not be entirely separated due to the limited sample sizes of female participants with short hair and male participants with long hair. Despite this limitation, the data suggestes that females with short hair and males with long hair exhibit different localization accuracies compared to their counterparts with different hair lengths. In summary, while individual factors such as age, ear height, sex, and hair length show some influence on localization accuracy, the interaction between these factors requires further investigation.

A more representative sample to better understand the combined effects of these variables on vertical sound localization is required for a deeper investigation.

6. ACKNOWLEDGMENTS

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