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# VERTICAL SOUND LOCALIZATION: PRECISION AND ROBUSTNESS TO REVERBERATION IN A LARGE-SCALE STUDY

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### ABSTRACT

Vertical sound localization, the ability to perceive the elevation of a sound source, is a fundamental aspect of human auditory perception, yet it remains far less understood than horizontal localization. Existing studies rely on small sample sizes, limiting the generalizability of findings. The presented study bridges that gap by examining vertical sound localization precision in a cohort exceeding 150 participants, making it the largest investigation of its kind to date. Participants are exposed to broadband noise stimuli from various elevations under controlled anechoic conditions. The elevation localization error is measured by comparing perceived sound source elevations to actual positions of speakers of a curved array. Azimuth angles of arrival are altered between $-45°$, $0°$, and $90°$. For a smaller group of test subjects, the experiment is repeated in echoic conditions, to gain insight into reverberation and reflection robustness of vertical sound localization. This large-scale study establishes benchmarks for vertical sound localization precision and robustness, advancing our understanding of human auditory spatial perception. These findings have implications for audio technology development, such as spatial audio rendering and hearing aid design, and lay the groundwork for further exploration into the neural and anatomical underpinnings of vertical localization.

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

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## 1. INTRODUCTION

### 1.1 Motivation

Traditionally, sound localization has been studied primarily in the horizontal plane (azimuth angle), where binaural cues such as interaural time differences (ITDs) and interaural level differences (ILDs) play a dominant role in pinpointing sound sources [1].
Vertical sound localization primarily relies on monaural cues, including the frequency-dependent filtering effects of the outer ear (pinna) and the body [2]. The unique shape and structure of the pinna alter the spectral content of incoming sounds, creating cues that are specific to the elevation angle of the source [3]. Despite its importance, research on vertical sound localization is limited compared to horizontal localization, particularly in terms of precise quantitative measurements and understanding how different factors, such as reverberation or anthropometric data are related to localization precision and robustness. This gap in research presents an opportunity to explore how the human auditory system copes with complex acoustic environments and whether these mechanisms can be leveraged to enhance applications ranging from artificial localization systems to virtual reality and hearing aids.

### 1.2 Goals

The primary aim of this study is to provide quantitative data on acoustic localization in the vertical (elevation) plane. To explore potential demographic and pathological effects, metadata on age, sex, hair length (covering the ear), ear size, and self-reported hearing disorders is collected. Due to practical constraints, the research primarily concentrates on sources within the subject's field of view, varying between three azimuth directions. Within this contribution, the following questions are investigated:

If subjects are presented with a sound source in their field of view,

- how far off is their estimation of the elevation angle of arrival?
- is there a tendency to over- or underestimate the elevation angle?
- is this the same for different azimuth angles of arrival?
- how does reverberation affect the performance?

## 2. EXISTING LITERATURE

One of the most cited sources on elevation angle spatial hearing accuracy is a paper from 1969 [4], where localization performance in the median plane for signals directly presented by human speakers in different elevation angles, was compared to performance while using recordings from an artificial head in the same scenario. The subjects identified sound sources with a probable error of around $\pm 14°$. The study tested seven human subjects for directional hearing (ages 20–30, both trained and untrained listeners).

A study from 1989 [5], testing four subjects, found the minimum audible elevation angle to be around $3.65°$. As a signal, a 52 dB click train was used and subjects were tasked to estimate whether the source is above or below a reference source with varying angle difference.

In [6], the difference between the minimum audible angle and sound localization precision is described, where the latter is a better measure for how good a subject can actually localize an object. Six subjects were placed in a hoop of loudspeakers, which played sounds from different directions. Vertical localization absolute deviation was found to be between $3.5°$ and $9°$ for sources in front of the previously trained test subjects (open loop conditions - no feedback during the experiment).

## 3. METHOD

### 3.1 Experimental Setup

For the tests, a curved array of 16 coaxial loudspeakers (numerically labeled) is used, spanning a $60°$ section of a circle (elevation angle from $-15°$ to $45°$) with speakers placed every four degrees, as shown in figure 1. Subjects are seated on a chair with a positioning headrest, ensuring the head is centered within the array circle, which has a diameter of 1.7 m. For shorter subjects, the seat height is adjusted with cushions to maintain consistent ear positions and distances from the array, verified with a fixture on the chair.

Each test involves playing one second of white noise from each of the 16 loudspeakers in a random order. The volume is set to 50 ± 1.5 dB SPL at the listener's position, resembling similar sound pressure levels as expected in conversations and daily life situations (birds chirping, traffic, footsteps etc.).

For each subject, the test is repeated at three chair angles: $-45°$, $0°$, and $90°$ azimuth, in randomized order. This results in a total of 48 localization estimations per subject. To compare results in echoic and anechoic conditions, the array can be placed in either a reverberant room (RT60 = 1.5 s) or an anechoic chamber.

No prior training or feedback is given during the test. The sound is played once, and subjects must localize the single event. Subjects are informed that speakers are played randomly and exclusion processes can not be used. For lateral incidence angles, subjects are instructed to remain facing straight, while the sound is played. Afterwards, they may turn their head to read the speaker labels and provide their estimation to the supervisor, who then plays the next sound.

To avoid boundary value problems, responses for the highest and lowest speakers (1-3 and 14-16) are not considered in the evaluation.

Under the assumption, that the data follows a normal distribution, repeated measures ANOVAs are used to determine whether there are statistically significant differences between conditions, while accounting for variability within subjects. A 95% level of significance ($\alpha = 0.05$) was used for all statistical tests.

### 3.2 Test Subjects

A total of 157 subjects participated in the study. Seven are excluded from the following evaluation, due to diagnosed hearing loss. Subjects with tinnitus are not excluded, as prior research shows that tinnitus significantly affects sound localization with pure tones but not with wideband signals such as white noise [7]. Two participants reported tinnitus, but only one had a formal diagnosis. Both performed well within the standard deviation. Participants' ages ranged from 16 to 65, with a median of 24 years. Of the 150 valid participants measured in anechoic conditions, 61 (41%) are female, and 89 (59%) are male. All subjects were recruited on the campus and participated voluntarily.

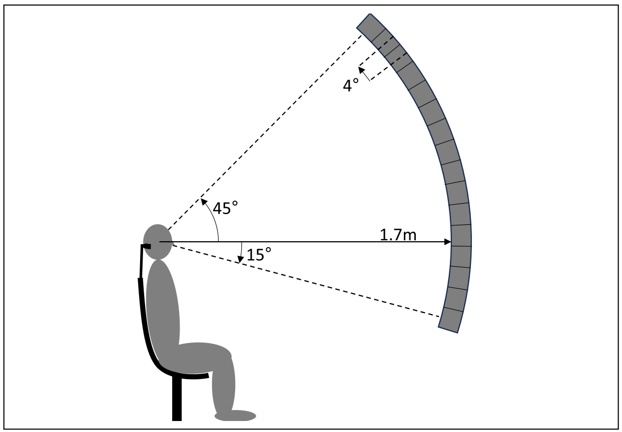


**Figure 1**. Circular array used in the experiment.

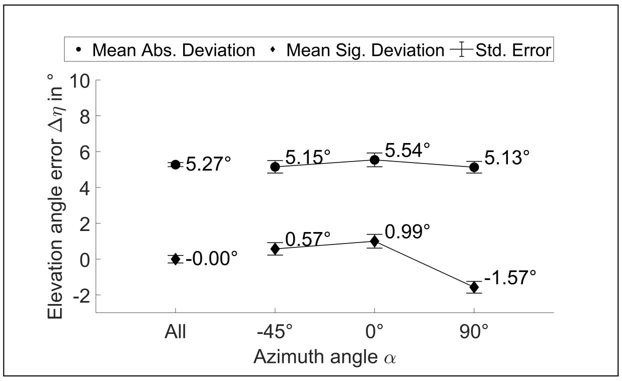


**Figure 2**. Mean absolute and signed deviation and standard errors for different azimuth angles.

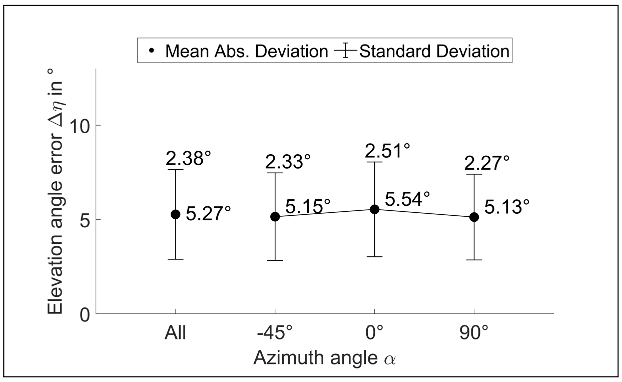


**Figure 3**. Mean absolute deviation and standard deviation for different azimuth angles.

For each subject, age, sex, hair length (covering the ear or not) and ear size are documented. The date and time of the test are also recorded. Subjects are also asked if their hearing is compromised in any way (e.g. diagnosed hearing loss).
For the comparison between echoic and anechoic conditions, 11 subjects have been tested in both conditions with at least two weeks between tests, to avoid training effects.

## 4. RESULTS

### 4.1 Anechoic Conditions

In anechoic conditions the 150 subjects localized sources with a mean absolute deviation of $5.27°$ and a mean signed deviation of $0.00°$. Results are similar to what has been measured in [6] and in unison with the minimum audible angle as measured by [5].
While the standard errors are very small (see figure 2), indicating a representative sample mean, the standard deviation shown in figure 3, reflects the relatively large performance difference between subjects. This is also evident in the distribution, shown in figure 4.
Regarding different azimuth angles, figure 2 shows, that differences in the mean absolute deviation are very small (not significant). So even though ITDs and ILDs are available for lateral sources, precision does not seem to increase.
For the mean signed deviation, lateral sources, especially at $90°$ azimuth, are localized significantly lower (significant difference between the $90°$ condition and the other two conditions).

### 4.2 Echoic Conditions

Figure 5 shows the comparison of localization performances for a group of 11 subjects in both echoic and anechoic conditions. Due to the high inter-subject difference in performance, the comparison is conducted using the same group of subjects, meaning that a subject's results in anechoic conditions are directly compared to that subjects results in the echoic condition. This ensures that the relatively large individual differences are controlled for, as participants serve as their own baseline.
The mean absolute deviations are very close in both conditions (no significant difference), with the performance in echoic conditions being minimally worse. The mean signed deviation in echoic conditions differs insignificantly, with a stronger tendency of lateral sources being localized lower than frontal sources, compared to the

results in anechoic conditions.

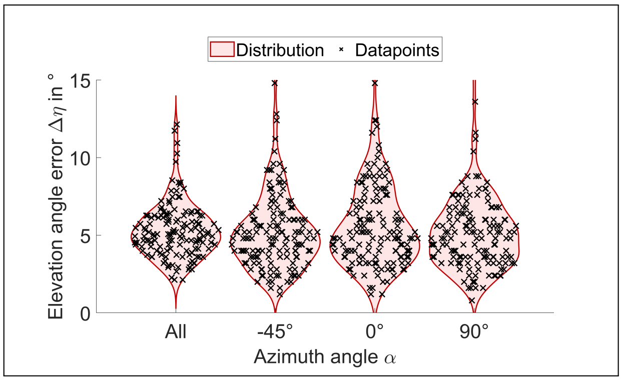


**Figure 4**. Distribution of the mean absolute deviation results and datapoints per subject.

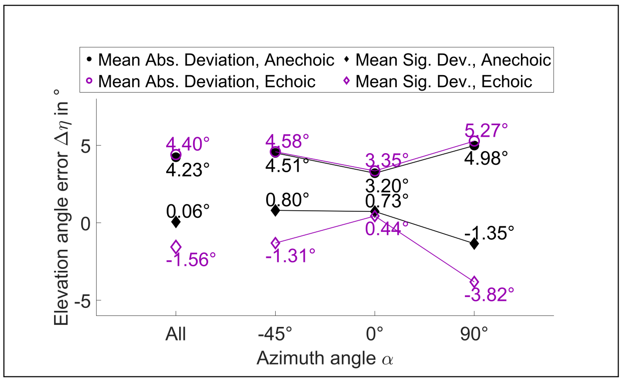


**Figure 5**. Comparison of mean deviations in anechoic and echoic conditions with a reduced set of subjects.

## 5. CONCLUSIONS

This study confirms that vertical sound localization is generally precise, with a mean absolute deviation of 5.27° in anechoic conditions. Differences across azimuth angles are minimal, though lateral sources tend to be localized lower.
Comparing anechoic and echoic conditions, localization remains robust, with minimal performance degradation in reverberation. While absolute deviation is nearly unchanged, signed deviation shifts indicate a stronger localization bias for lateral sources.
All in all this study delivers a reliable benchmark for the vertical sound localization without training. The comparison between anechoic and echoic conditions demonstrates impressive robustness of spatial hearing to reverberation. The findings show the immense potential in virtual audio and bio-inspired localization algorithms.
A further analysis of the data with a more detailed look into inter-subject performance difference, also including the documented metadata, is published in [8]. Also, cases with different forms of hearing loss will be discussed in further publications.

## 6. ACKNOWLEDGMENTS

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