# Frequency limitation for optimized perception of local active noise control

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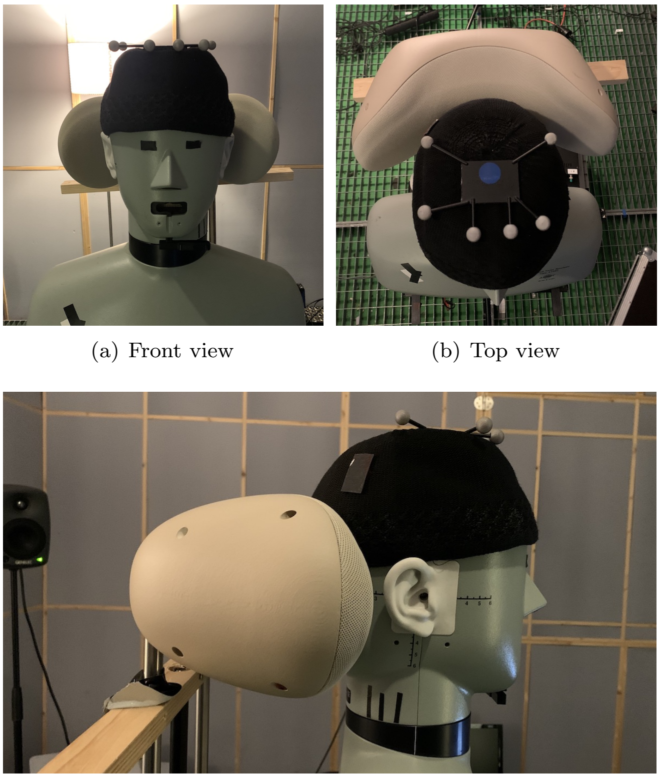
## Introduction

Local active noise control (ANC) is an emerging technique for the reduction of unwanted disturbances. Loudspeakers, in this case also called secondary sources, generates signals, which cancel or reduce the primary noise through destructive interference. In contrast to global ANC, a local approach reduces noise at a limited number of specific positions, not throughout the whole space. This brings the advantage of an extended controlled bandwidth with less secondary sources [1].

An inherent property of local ANC is its limited spatial extent. Several analytical studies deal with the size of the *zone of quiet* (ZoQ), meaning the area around the point of cancellation where −10 dB attenuation can be achieved. One of the earliest and most prominent investigations states, that the ZoQ in a pure tone diffuse field has a spherical shape with a diameter of about $^1/_{10}$-th of the wavelength [2]. This theory can be expanded for multiple ZoQ [3] and broadband disturbances with secondary sources in the acoustic near- and far-field [4]. However, due to the knowledge of the authors, there has not been a study assessing the *perceived* area of effect, in the following referred to as *zone of comfort* (ZoC). In order to do so, a listening experiment has been carried out with different types of disturbances, controlled bandwidths and primary source directions.

## Experiment setup

The participants are seated in the center of a circular loudspeaker array ($r = 1.5\,\mathrm{m}$), consisting of 8 equiangular distributed Genelec 8020B as primary sources. Two loudspeakers, embedded in a headrest, are located behind the head as secondary sources. Markers for an optical tracking system (OptiTrack Motive, 6 Flex3 cameras, with a mean error $\leq 0.4\,\mathrm{mm}$) are placed on the participants heads. The arrangement is exemplified in figure 1. Starting from the point of cancellation, the listeners are instructed to rotate (clock- and counterclockwise) or move their head to the front until their perceived ZoC is left. At this position, a button on a tablet-PC should be pressed. Its screen is mirrored to a display, placed at eye level in front of the participants. An alternative answer ("out of bounds" - labeled as "Inf" in the evaluation) is available, if no position can be found. Also an option to temporarily disable ANC is provided. Playback is stopped, if the position is set, and starts again if the point of cancellation is reached (X/Y translation with ±1 cm and yaw/pitch with ±3° tolerance). To assist participants finding this location between trials, their current location is monitored at the tablet-PC. The optimal reference position has to be found by the participants in a pre-trial in order to calibrate the tracking marker placement.



(a) Front view (b) Top view

(c) Side view

**Figure 1:** Positioning of the participants and the tracking markers.

In order to calculate the ANC filters, impulse responses between all primary and secondary sources and a Brüel & Kjær 4128C head and torso simulator (HATS) are recorded beforehand at the center position at 44.1 kHz sample rate. The impulse responses are windowed, so that only the direct sound is further processed. An additional delay of 2048 taps is applied to the direct path to ensure a sufficiently causal filter. This delay is also applied to the played back disturbances during the experiment. With the $2 \times 8$ primary path $\mathbf{P}_e$, a static $2 \times 8$ control filter $\mathbf{W}$ with 8192 taps is calculated. In frequency domain, the $k^{\mathrm{th}}$ frequency bin of the latter is computed as

$$\mathbf{W}_k = -\mathbf{G}_{e,k}^{-1}\mathbf{P}_{e,k} \tag{1}$$

with the $2 \times 2$ secondary path $\mathbf{G}_e$. Care is taken to ensure a causally constrained filter design. In the investigated scenario, the problem was conditioned well enough to omit regularization.

Two different kinds of stimuli are chosen for the listening experiment - lowpass-filtered white noise, using a $32^{\mathrm{rd}}$ order Butterworth filter as in [4], and a recording of the interior noise in a car at 80 $^{\mathrm{km}}/_{\mathrm{h}}$ speed (cf. figure 2)

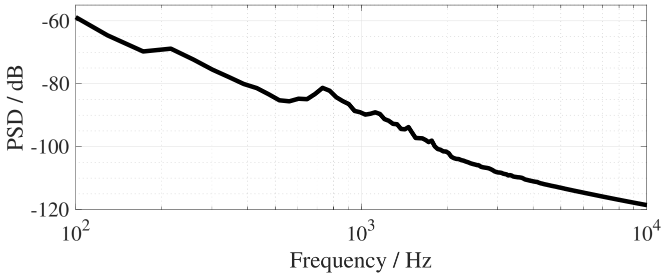



**Figure 2:** Power spectral density of the recorded road noise.

with wide-sense stationary signal properties. For the former, cutoff-frequencies at 500 Hz, 1 kHz, 2 kHz and 10 kHz are selected, whereas for the latter the control filter is processed with a 6$^{\text{th}}$ order Butterworth filter using a forward-backward method at the mentioned cutoff-frequencies to preserve the phase response. The achieved noise reduction for the road noise stimulus with varying upper control frequency, measured with the HATS at the reference (center) position, is displayed in figure 3.

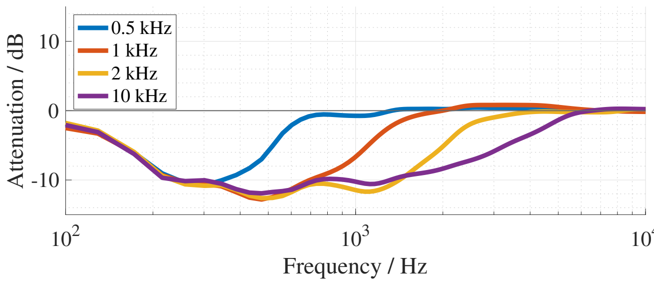



**Figure 3:** Noise reduction with $^1/_3$-octave smoothing at the center position with varying upper control frequency for the diffuse road noise stimulus.

The stimuli are played from the front, the back, as well as in a diffuse scenario. To achieve this, the mono signals are processed with a granular synthesizer and encoded to the Ambisonic domain using the GranularEncoder as presented in [5]. Apart from the default settings, a grain length of 0.841 s with 31.5 % modulation, a time between grains of 0.001 s, a buffer position at 1.125 s with 1.112 s modulation as well as a circular grain distribution and 360° spread are chosen. The signal is decoded to the loudspeakers using the AllRAD approach [6] with two zero-gain imaginary loudspeakers at ±90° elevation. Both programs are part of the IEM Plug-in suite [7]. A comparable interaural coherence to reference recordings in a car is reached with this approach. All primary disturbances are leveled to roughly 58 dB(A) at the listening position.

The main experiment control (stimuli selection, playback commands, saving of results) is programmed in Pure Data [8]. The audio signals are played back by the digital audio workstation REAPER [9], a user interface on the tablet-PC is created with MobMuPlat [10]. Communication between those applications happens via OpenSoundControl [11]. White noise stimuli and the control filters are calculated in MATLAB.

The residual disturbances are recorded for various off-center positions. The achieved attenuation of the white noise stimulus with 10 kHz cutoff-frequency is displayed in figures 4 and 5.

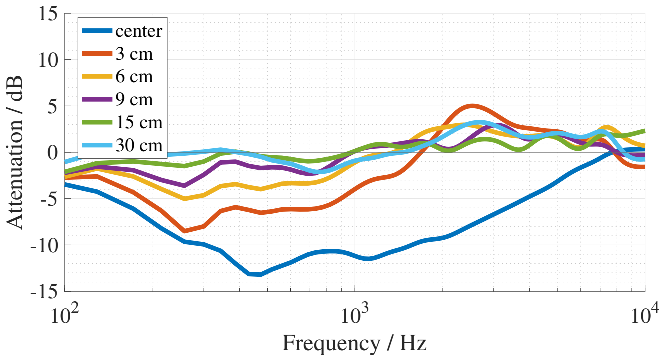
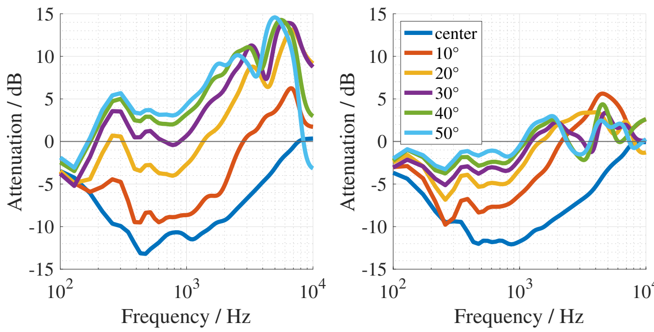



**Figure 4:** $^1/_3$-octave smoothed noise reduction for different head rotations with the diffuse white noise stimulus at 10 kHz cutoff-frequency.




(a) Ipsilateral ear (b) Contralateral ear

**Figure 5:** $^1/_3$-octave smoothed noise reduction for different head rotations with the diffuse white noise stimulus at 10 kHz cutoff-frequency. The ear directions are chosen with regard to the secondary source location.

To evaluate the participant's reliability and consistency, a selected trial (white noise, cutoff at 1 kHz, diffuse) is presented four times. Every other combination is presented once, resulting in 81 trials in total.

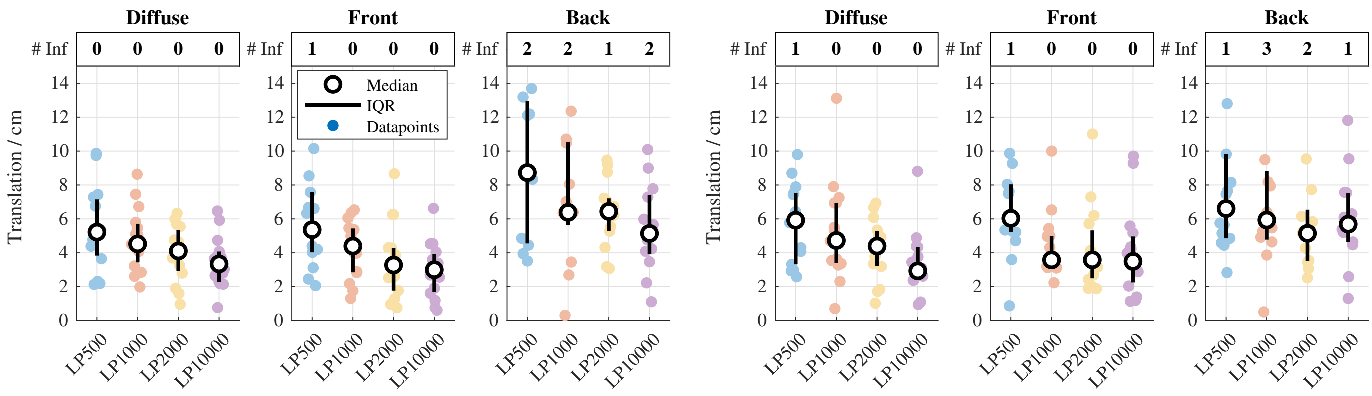
## Results

24 healthy hearing persons, 3 females 21 males, took part in the experiment with age between 21 and 60 years (median 29 years). Experiment durations of 11 min to 64 min are documented with a median of 21 min. All participants are students, staff or alumni of our institute. 20 persons have experience in previous listening experiments, 22 have a self-proclaimed background in acoustics/audio engineering.

With the variance of the repeated trial $\sigma^2_{\text{rep}}$ and the overall variance $\sigma^2_{\text{all}}$, an index for the intra-subject reliability

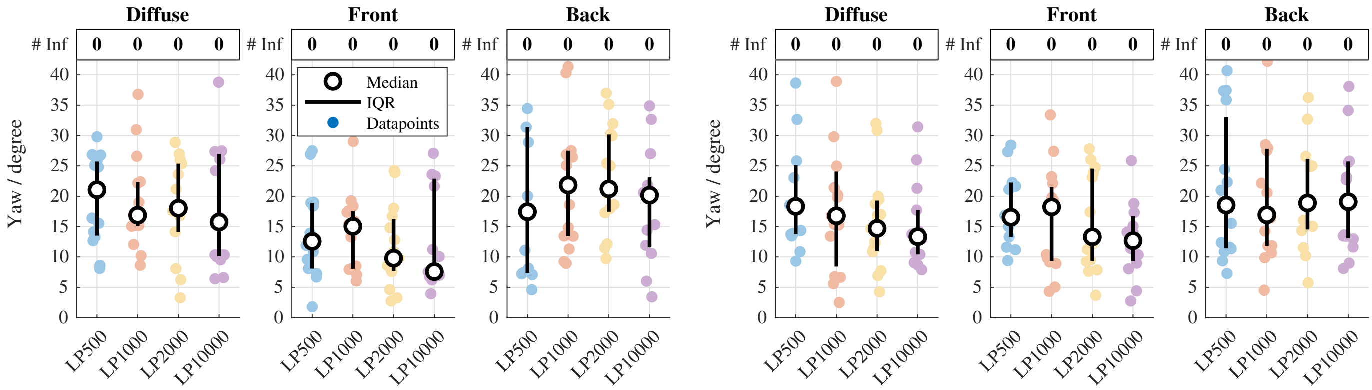
$$rel = 1 - \frac{\sigma^2_{\text{rep}}}{\sigma^2_{\text{all}}} \tag{2}$$

similar to [12, p. 127][13] is calculated for both translation and rotation. 9 participants are excluded of further evaluation because of a low reliability over several moving




(a) White noise (b) Road noise

**Figure 6:** Median, IQR, individual answers and number of “out of bounds” (# Inf) for the **translation** trials along the x-axis for diffuse, frontal and dorsal disturbances. The labels on the abscissa refer to the cutoff-frequencies in Hz.




(a) White noise (b) Road noise

**Figure 7:** Median, IQR, individual answers and number of “out of bounds” (# Inf) for clockwise **rotation** trials for diffuse, frontal and dorsal disturbances. The labels on the abscissa refer to the cutoff-frequencies in Hz.

directions, a high overall variance or one or more of the control trials rated as “out of bounds”. If an answer is not recorded correctly, missing values are marked as invalid. As the tracking markers can not be placed at ear height, a correction of the translation

$$\widetilde{tr}_x = tr_x + os_z \cdot \sin(pitch) \tag{3}$$

is applied with a vertical offset $os_z = 0.13\,\mathrm{m}$. This value corresponds to the vertical distance from the top of the head to the ear canals of the Brüel & Kjær 4128C HATS.

As some differences in the rotation in clockwise and counterclockwise direction are statistically significant with $\alpha = 0.05$, the results are not combined and only the answers for clockwise rotation are presented. An explanation for this behavior could be a slightly asymmetric setup of the monitoring display. For the repeated trials, the median of each participant is used for analysis.

The results of the listening experiment are shown in figures 6 and 7 in form of the median, the interquartile range (IQR) and individual answers. Although differences between the conditions are rarely statistically significant (with $\alpha = 0.05$), certain trends can be observed. Unsurprisingly the tendency can be seen, that disturbances from the front yield in a narrower ZoC, whereas sound from the back enlarges the ZoC compared to a diffuse scenario. This can be easily explained as the control signals come from roughly the same direction as the disturbances in these scenarios, resulting in a bigger area where they are in opposite phase. Also a larger IQR (and therefore variance) of the answers can be noticed with dorsal disturbances. In accordance to literature [2, 4], the ZoC shrinks toward higher (controlled) frequencies in general. A greater number of participants struggled assessing the translation with disturbances from the back, indicated by the number of selected “out of bounds”.

A general indicator of the size of the ZoC can be the 25 % quantile, describing a valid area for 3/4 of the participants. With frontal or diffuse disturbances, an extent for the translation of roughly 3 cm can be found up to 2 kHz. For the cutoff-frequency at 10 kHz (and with 2 kHz for frontal noise in figure 7(a)), the area is about 50 % smaller with 2 cm. In most cases, the median and the 25 % quantile of signals with 500 Hz cutoff-frequency are notably higher that in other conditions, resulting in a larger ZoC. A saturation effect, starting at 1 kHz, can be observed in figure 6(b) for frontal disturbances, meaning that the ZoC stays constant for increasing controlled bandwidth. An explanation might bring the power spectral density of the road noise signal in figure 2 with notably less energy towards higher frequencies, meaning that at this range are less disturbances to reduce in the first place.

The 25 % quantiles of the rotation trials are located in most cases between 10° to 15°. This indicates, that the ZoC is relatively independent of the controlled frequency range and primary disturbance direction. An exception represent frontal white noise disturbances, where the limits are at 7° over all conditions. The distribution of individual datapoints in some rotational trials suggests, that there are distinct groups of more or less strict listeners, for example in figure 7(a) with frontal and diffuse disturbances at 10 kHz.

## Conclusion and outlook

To evaluate the perceived zone of comfort for local ANC, a listening experiment has been conducted. For different disturbance types and directions, participants were instructed to rotate or move their head in frontal direction until the ZoC is left. For the used setup, a conservative limit of roughly 3 cm frontal translation can be found in most cases. A reduction of the upper controlled frequency increases the spatial extent of the ZoC in most cases, resulting most likely in higher acceptance. The ZoC in terms of head-rotation is relatively independent of the controlled bandwidth and direction of the disturbances with 10° to 15°.

To enlarge the ZoC, even towards broader controlled bandwidths, head-tracking techniques have been used recently [14]. The limits presented in this study can provide valuable insights for the necessary accuracy of such systems, especially when using nearest-neighbor interpolation.
As this experiment has been conducted with a specific hardware configuration, there might be differences with other setups. Future studies might verify or adjust the found spatial limits for different setups or find a valid, quantitative connection to analytical works [2–4]. Some participants stated, that their decision was influenced by the localization of the primary disturbances. To the knowledge of the authors, the impact of this effect has not been dealt with in literature yet.

## Open data

The experiment data, setup and supplementary scripts are provided online [15].

## Acknowledgement

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