UNIVERZIRA PAVLA JOZEFA ŠAFÁRIKA V KOŠICIACH
PRÍRODOVEDECKÁ FAKULTA

REWEIGHTING OF BINAURAL SOUND LOCALIZATION CUES IN A REAL ENVIRONMENT

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Cieľ:	- Examine the mechanism by which reweighting of binaural localization cues was induced by visually guided spectral reweighting training in real environments in Spisak (2021). - Design and perform an experiment on two subject groups in which the spectral training is replaced 1) by an active localization task in real environment, and 2) by a control condition with no training or localization sessions. - Analyze the weights of the binaural cues in the pretest and postest for both groups. - Describe of change in weighting of spectral and binaural cues by linear regression model. - Combine the collected data with those of Spisak (2021) and analyze the differences in binaural weights across different types of training. - Combine the real-environment data from the current study with those of Spisak (2021) to determine whether the spectral training induced there was stronger for high-frequency or low-frequency training.
Literatúra:	Klingel M, Laback B, Kopco N (2021) Reweighting of Binaural Localization Cues Induced by Lateralization Training. Journal of the Association for Research in Otolaryngology, in press. Ferber M, Laback B, Kopco N (2018) Vision-induced reweighting of binaural localization cues. The Journal of the Acoustical Society of America 143, 1813 (2018); https://doi.org/10.1121/1.5035942 Ferber M (2018) Plasticity of Spatial Processing in Normal Hearing: Reweighting of Binaural Cues. Unpublished MSc. Thesis. University of Vienna. Moore, Travis & Picou, Erin & Hornsby, Benjamin & Gallun, Frederick & Stecker, G Christopher. (2020). Binaural spatial adaptation as a mechanism for asymmetric trading of interaural time and level differences. The Journal of the Acoustical Society of America. 148. 526-541. 10.1121/10.0001622. Thurlow WR, Jack CE. Some determinants of localization-adaptation effects for successive auditory stimuli. J Acoust Soc Am. 1973 Jun;53(6):1573-7. doi: 10.1121/1.1913505. PMID: 4719254. Kumpik DP, Campbell C, Schnupp JWH, King AJ. Re-weighting of Sound Localization Cues by Audiovisual Training. Front Neurosci. 2019 Nov 15;13:1164. doi: 10.3389/fnins.2019.01164. PMID: 31802997; PMCID: PMC6873890.

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Abstrakt v štátnom jazyku:

Ľudia a zvieratá majú schopnosť lokalizovať zdroje zvuku, určovať smer predmetov, ktoré treba nájsť alebo sa im vyhnúť a naznačiť vhodný smer na nasmerovanie zrakovej pozornosti. Na toto všetko používame binaurálne kľúče nazývané interaurálny časový rozdiel (ITD), ktorý určuje časový rozdiel príchodu zvuku medzi oboma ušami, a interaurálny rozdiel v hlasitosti (ILD), ktorý určuje rozdiel v hlasitosti zvuku, ktorý prichádza do obidvoch uší. ILD je frekvenčne závislé a rastie s frekvenciou, čo sa o ITD nedá povedať. ITD u ľudí dominuje pre nízke frekvencie (LF) a ILD dominuje pre vysoké frekvencie (HF). Jedným z možných spôsobov, ako sledovať, ako ITD/ILD ovplyvňujú lokalizáciu, je meranie ich váh. V predchádzajúcej štúdii (Spišák, 2021) bolo zistené že tréning HF vs. LF komponentu s vizuálnou odozvou v reálnom prostredí podporilo váženie binaurálnych lokalizačných kľúčov spôsobom, že sa ILD váha zvýšila nezávisle na trénovanej skupine. Uskutočnili sme experimenty vo virtuálnom anechoickom prostredí a v reálnom prostredí s ozvenou bez tréningu, aby sme zistili, či zmena váženia binaurálnych kľúčov závisí od trénovania jedného komponentu alebo stačí na zmenu váženia jednoduchá zmena prostredia. Výsledky z reálneho prostredia ukazujú, že zmena váženia nastáva tak, ako sme očakávali, pretože chýbal tréning komponentov HF a LF. Vzhľadom na predchádzajúce výsledky z rôznych experimentov sme predpokladali, že experiment v reálnom prostredí môže ovplyvniť spôsob, akým subjekty odpovedali vo virtuálnom prostredí. Výsledky z virtuálneho prostredia však nevykazujú očakávaný efekt a od pretestu po posttest nedochádza k žiadnej významnej zmene váženia. Zistenie princípu zmeny váženia je dôležité pre ľudí, ktorí trpia stratou sluchu a sú odkázaní na kochleárne implantáty alebo načúvacie prístroje, ktorých dizajn je potrebné urobiť tak, aby poskytoval poslucháčom podnety na prispôsobenie sa im rovnakým spôsobom ako sa im prispôsobujú poslucháči so zdravým sluchom.

Abstrakt v cudzom jazyku:

Both humans and animals have the ability to localize sound sources, to determine the direction of objects to seek or avoid and to indicate the appropriate direction to direct visual attention. For all of this we use the binaural cues called interaural time difference (ITD), which determines the time difference of a sound arrival between two ears, and interaural level difference (ILD), that determines the difference in level of sound that arrives in two ears. ILD is frequency dependent and is raising with raising frequency, ITD is not frequency dependent. ITD dominates for low-frequencies (LF) and ILD dominates for high-frequencies (HF). One possible way of observing how the ITD/ILD affects the localization is to measure its weight. A previous study (Spišák, 2021) showed that visually guided training on HF vs. LF components in real environment induces reweighting in the binaural localization cues such that the ILD weight is increased independent of the training type. We performed experiments in virtual anechoic environment and in real reverberant environment without training to find out if re-weighting of binaural cues is dependent on training of one component or simple change of environment is enough to induce the re-weighting. Results from real environment show that change in spectral weighting does not occur, as we expected because no training of HF and LF components was present. Based on previous results we hypothesized that performing an experiment in real room may affect the way subjects answered in virtual environment. However, the results from virtual environment do not show the expected effect and no significant re-weighting occurred from pretest to posttest. Finding out the principle of re-weighting is important for people who suffer hearing loss and are dependent on cochlear implants or hearing aids, which design needs to replicate sound more accurately, increasing the quality of life of disabled people.

Contents

List of figures

List of tables

List of abbreviations and symbols

ITD	**I**nteraural **T**ime **D**ifference- the time difference of a sound arriving to both ears
ILD	**I**nteraural **L**evel **D**ifference- the intensity difference of a sound arriving to both ears
HF	**H**igh **F**requency
LF	**L**ow **F**requency
VE	**V**irtual **E**nvironment- environment for first part of experiment
RE	**R**eal **E**nvironment- environment for second part of experiment
OR	**O**culus and **R**eal room group – subjects that did VE and RE part of experiment
O	**O**culus group- subjects that did only VE part of experiment
NoT	**No T**raining group- OR+O group together as a one group without training for comparsion with different experiment
HFI	**H**igh **F**requency **I**nformed- group of people who knew about spectral composition of stimuli

Vocabulary

Anechoic means without reverberation

Reverberant means echoing

Non-target is control sound

Trial is one measurement

Pretest is first part of the experiment

Posttest is second part of the experiment

Introduction

Localization of sound is not that easy, each localized sound can be perceived as coming from any distance and direction and it is defined relative to the position of the head. With studies in sound localization, we often come to two words monaural and binaural. As Moore in his Introduction to Psychology of hearing (2013) defined, “The word “monaural” refers to situations when the sound is delivered to one ear only. The word “binaural” refers to situations where sound is delivered to both ears.”

In our study, we focused on binaural localization cues, ITD and ILD. ITD is an interaural time difference and ILD is an interaural level difference. The main goal was to collect and analyze data from a behavioral experiment where the sound was presented to subjects through headphones in a soundproof room and in a reverberant room through loudspeakers to examine the impact on the weight change of spectral (high frequency and low frequency) and binaural (ITD and ILD) components of sound. We did comparison of the results of our experiment without audiovisual training and an experiment with audiovisual training (Spišák, 2021). All groups from our experiment took a position as no training group and groups from Spišák master degree thesis were training group, meaning all his subjects were trained to increase weight of assigned component.

Our study focuses on understanding how people work with sound in different environments and how they process it. People with healthy hearing tend locate sound more by ITD. This can be important for manufacturers of cochlear implants to improve the design of hearing gadgets because of the fact that people that are using cochlear implants do not focus on ITD component at all. (Klingel, Laback, 2021) This can be due to lack of knowledge how to code represented sound for unhealthy ear. Moreover, deep understanding of sound perception is important in replicating it in virtual reality.

For the analysis, we used a linear regression model to analyze collected data to separate possible distorting effects in form of compression. For all modeling and analysis, we used MATLAB and to evaluate the results we used analysis of variance (ANOVA) computed by UNIX-style command-line program CLEAVE.

Our study is divided into 6 chapters. In the first chapter we describe the theory behind hearing and perception of sound. We have outlined other researches that describe re-weighting important for understanding binaural localization cues. In the second chapter we stated main goals of this study and hypothesis we focus on. In the third chapter we described experiment, experimental groups, setup, stimuli and procedure. In the fourth chapter we focused on methods used for analysis. Fifth chapter draws results of our experiment in detail. Last, sixth chapter contains conclusions and summarizes the results.

1 Theoretical background

1.1 Sound and auditory system

As Moore in his An Introduction to the Psychology of Hearing stated, the easiest way we can characterize what the auditory system is and what it does is to describe it as a relationship between the characteristics of a sound that is entering the ear and the sensation it produces.

First of all, we need to describe what sound is. It originates from the vibration of an object and is transferred by air or a different kind of medium as changes in pressure. The movement of sound waves is due to particles or molecules that get squeezed together and then are pulled farther apart transferring vibrations along an axis that is aligned with the direction in which sound is broadcasted.

To describe a simple sound, three things must be specified: frequency, or the number of times per second the waveform repeats, or the simpler number of vibrations made by the sound wave per second; the amplitude, or the amount of pressure variation about the mean, in different words we can look at it as the measure of height describing the loudness; and the phase is the location or timing of a point of a sound wave in relation to some fixed point in time.

When the soundwave reaches the ear, it meets the first outer part of it called the pinna, which modifies the incoming sound at high frequencies and is important for our ability to localize sounds; and the non-visible auditory canal, where sound causes the eardrum to vibrate. The part that cares for hearing is called the cochlea. The middle ear has to efficiently transfer sound from the air to the fluids in the cochlea, so it works as some kind of transformer. Transmission of a sound through the middle ear is most efficient at middle frequencies (500-5000 Hz). When exposed to intense sounds, muscles in the middle ear are contracted causing middle ear reflex which reduces the transmission of sound for frequencies below about 1.5 kHz.

A membrane called basilar membrane runs along the length of the cochlea, where waves produced by sound travel. There is a maximum pattern of vibration for each frequency at a specific place. In other words, high frequencies produce maximum vibration close to the base (start of the cochlea where the oval window is situated) and low frequencies produce maximum vibration close to the apex (inner tip of the cochlea).

Each auditory nerve carries information from the cochlea to the central nervous system in form of electrical signals. What are the features of the stimulus that produce responses of the cortex to the information given by a set of neurons is very unclear. The cortex is likely concerned with analyzing more complex aspects of stimuli than simple frequencies or intensity. This hierarchical complex system has to be investigated in more detail in the future.

1.2 Space and perception

Direction of sound source in space is relative to the head.

The term “localization“ refers to judgments of the direction and distance of a sound source” (Moore 2013). Since localization takes place in the real environment such as a room, we are not able to use the same word for localization of sound using headphones. “The term “lateralization” is used to describe the apparent location of the sound source within the head. Headphones allow precise control of interaural differences and eliminate effects related to room echoes” (Moore 2013).

The direction of a sound can be described by its azimuth and its elevation. Azimuth is the angle produced by projection onto a horizontal plane, meaning that sounds lying in the median plane have 0° azimuth. The elevation is the angle produced by projection onto the medial plane, meaning that sounds lying in the horizontal plane have 0°elevation.

In binaural perception, both ears receive auditory stimuli and the nuclei compare the sound coming from both ears to make judgments, such as where the sound is coming from. For such judgments, decisions are made based upon either the differences in time parameters of the sound from the two ears (ITD) or the differences in loudness of the sound coming from the two ears (ILD) (Furst, Levine, 2015).

Binaural and spatial perception are important for localization but also for spatial separation of sounds, e.g. for speech perception in complex environments (the cocktail party effect).

1.3 Cues for localization

When we are presented with a sound from any position in azimuth, we can localize it due to two possible cues of the sound source as was stated before: an interaural time difference (ITD) and an interaural level difference (ILD). “For a sinusoidal tone, and ITD is equivalent to a phase difference between two ears, called an interaural phase difference (IPD)" (Moore 2013).

When a sound is presented from the side, the head of the subject is in the path of the source to the far ear. It creates a shadow around the far ear resulting in ILD. The amount of the shadowing depends on the wavelength of each sound compared to the dimensions of the head (Middlebrooks and Green 1991). Thus, ITDs and ILDs are not equally effective at all frequencies due to the physical nature of sounds. Low-frequency sounds have a long wavelength compared to the size of the head and sound can bend easily around it. This process is called diffraction and with ILDs very little or no shadow is cast by the head. On the other hand, higher frequencies have shorter wavelengths than the head's size, creating shadows and little diffraction occurs (Moore 2013). All of this is part of the duplex theory of sound localization (Middlebrooks and Green 1991).

1.4 Localization of sound

The way ITD or ILD contributes to the localization of the sound depends on the frequency content of the sound. At lower frequencies, ITDs are dominant. For higher frequencies, ILDs are dominant (M. Klingel et al. 2021). Due to the clear frequency dependence on the localization, errors occurred at around 3000 Hz and declined at higher and lower frequencies. In another study, a similar frequency dependence in localization occurred, when a subject was asked to adjust the position of a broadband noise source to correspond to the apparent source of the sinusoid. It showed that performance was worst for sinusoids around 1500-3000 Hz. This can be interpreted with duplex theory, that in a particular range, stimuli are too high in frequency to provide usable ITD cues and waves are too long to provide adequate ILD (Middlebrooks and Green 1991).

One possible way of observing how the ITD/ILD affects the localization is to measure its weight. This can be done by using ITD/ILD trading ratios. ITD/ILD trading ratios depend on which cue is adjusted, so it receives greater weight due to the attention shifted toward it or due to cue-specific adaptation (M. Klingel et al. 2021).

1.5 Re-weighting of binaural cues

In Kumpik et al.'s (2019) study they used virtual acoustic space stimuli, and measured changes in subjects' sound localization biases and binaural localization cues after audiovisual training in which visual stimuli was informative or not about the location of broadband sound. In their experiments, ILDs were weighted more than ITDs before training, when they used uninformative stimuli, some subjects showed a reduction in auditory localization bias, and the weighting of ILDs increased after training. With ILDs, they increased too with informative visual training and congruent binaural cues, thus the largest improvements were spotted when both binaural cues were matched to visual stimuli. Some subjects with consistently misaligned binaural and visual cues produced the ventriloquism aftereffect. “Repeated pairings of spatially mismatched visual and auditory stimuli produce a shift in a perceived sound location that persists when the sound is presented alone” (Kopco et al.,2009). Kumpik et al. reflected changes in the relative weighting of ITD and ILD cues by calculating the binaural weighting index (BWI) for each subject, negative value where ITD or ILD dominated, or positive value when they represented equal weighting between the cues. In almost all experiments, the BWI was positive indicating that localization responses were more dependent on ILDs. They also observed higher ILD than ITD weights. The training consisted of randomizing one cue within each sound sequence while keeping the other constant. The group with informative visual cues that were either congruent or displaced from the spatially consistent binaural cues showed that the visual “teacher” signal induces corrective changes in auditory localization. Even in the absence of informative visual cues, some subjects reduced error in localization when binaural cues were consistent with each other or when they were exposed to spatially-consistent ITDs with ILDs that were randomized. When binaural cues were congruent, both ILDs and ITDs were up-weighted.

In Klingel et al.’s (2021) study we can see another approach to re-weighting of binaural cues by lateralization training in a virtual audio-visual environment. The lateralization consisted of 500-ms bandpass-filtered noise bursts with various combinations of binaural cues supplemented by audiovisual cues during training. This method might seem similar to that of Kumpik et al. (2019) but they used a stimulus spectrally focused at an intermediate frequency region, to ensure that neither ITD nor ILD is used by default. A variety of combinations of ILDs and ITDs were used to prevent strategic responses such as memorizing specific stimuli or azimuths. As a result of ITD and ILD being dependent on frequency, Klingel et al. chose a frequency range of 2-4 kHz that is typical for either ITD- or ILD dominance so neither would be weighted particularly strongly increasing weight. The overall lateralization performance was calculated using the root-mean-square error (RMSE) between response and stimulus azimuth. The practice stimuli had either consistent ITD/ILD combinations or one of them was fixed at zero. In training, the head-pointing technique was used and auditory stimuli included both inconsistent and consistent ITD/ILD combinations. One group focused on re-weighting ITD and the other on re-weighting ILD. The training procedure was the same, except for that which cue was visually reinforced and presented. Experiments show a decrease in ILD weights for the ITD group and an increase of ILD weights for the ILD group in posttest compared to the pretest. Following studies showed a potential implication of apparently asymmetric binaural cues due to the overall stronger weighting of ITD cues.

To sum up the experimental groups: “The ITD group showed less reweighting from the pretest to the training which then remained stable through the posttest, the ILD group showed stronger reweighting from the pretest to the training, part of which then got lost from the last training session to the posttest.”

In Spišák (2021) master degree thesis we see another approach of reweighting cues. Behavioral experiment was performed in two environments, virtual (VE) and real (RE). The main point of this study was to train the subjects to induce a change in spectral weight with dynamic cues in real environment, and test whether the reweighting will generalize to binaural reweighting. Given that based on the duplex theory, ITDs will dominate for LF group and ILDs for HF group.

In the RE, the pretest, training and posttest were performed. Sound was coming from 11 loudspeakers (9 in the middle were target and 2 at the edges were non-target only) placed in semicircle around the subject with spacing 11.25°between them, in range from -56.25° to 56.25°. 5 types of sounds differed in frequency, 0.35kHz and 0.7kHz as low-frequency sounds, 2.8kHz as mid-frequency, 5.6kHz and 11.2kHz as high-frequency sounds. At the start and the end of each stimuli was ramp to make it sound more naturally. Visual stimuli was presented with projector on the white paper above loudspeakers and orientation of the head was monitored with headband on the head of subject. On the other hand, in VE, pre-training, pretest and posttest, identical to Klingel at al. (2021), were performed. Experiment took part in double-walled soundproof booth with Oculus headset, which displayed virtual room and visual stimuli and also monitored orientation of the head. ILD/ITD combinations were presented from headphones to one from 40 possible positions in horizontal plane in range from -70.2°to 70.2°with spacing 3.6° between them.

Pre-training and pretest were first performed in VE. Each trial started with subject orienting his head straight ahead. After pressing button on the keyboard, sound stimulus was presented. The task of the subject was to indicate the position of the incoming sound in horizontal plane and turning his head to that position and then pressing the answering key on keyboard to submit response. Then subject turned its head back to the 0°azimuth and another trial followed. In VE, pretest was preceded by a short pre-training similar to pretest but visual feedback was presented to show position of incoming sound. Another pretest, but in RE was performed with the same principle as in VE. Each trial began with subject facing 0°azimuth and after pressing button on the keyboard, sound was played. His task was to turn his head towards incoming sound and after pressing button to record answer his head turned back to 0°azimuth and another trial followed.

Training was performed in RE consisting of 3 sessions during 3 consecutive days. HF group was trained for high frequency component. HFI group was too trained for high frequency component but they were informed about spectral composition of sound. LF group was trained for low frequency component. but Procedure was similar to the pretest. At the beginning of each trial, subject faced 0°azimuth. After pressing button on the keyboard, sound was presented making subject turn his head to the perceived position of sound source. Pressing button on the keyboard he confirmed this position and visual feedback was provided at the position of high frequency component for HF and HFI group and the position of the low frequency component for the LF group, and simultaneously the repeated sound was played from the same position as in the trial. Subject ‘s task was to turn his head to the position of the visual feedback, confirm this position by pressing button, return his head back to 0° azimuth. Next trial followed.

To find out whether this change of weighting will generalize to change of weighting of the untrained component, in their case mid-frequency.

On the last day of experiment, the training session was followed by a posttest firstly in RE and after that in the VE. Posttest was identical to pretest.

To sum up the results, change in weight occurred during training sessions rather than between them. Difference between HF and HFI group showed that information about spectral composition of sound and exact instructions to follow this sound was not useful for reweighting. In RE all groups significantly changed weighting according to training procedure. In VE all groups increased their weighting of ILD, independent on the type of the training. LF group was supposed to increase weighting of ITD component but increased weighting of ILD, in opposite way it was trained. This interesting fact is what made us write this study.

2 Goals

Localization of sound is dependent on our way of weighting and re-weighting binaural cues. Reweighting can happen both in an anechoic, soundproof room or an reverberant room, where sound is reflected from the objects located in the room. Important question is, whether change in the environment affect the re-weighting of cues, and if yes, is this change comparable to the change conducted by the training?

From the previous analysis from master's degree thesis (Spišák 2021) we observed the same way of re-weighting in real environment in two groups that were trained opposite way. One group, called LF group was trained to increase weight of LF components and HF group that was trained to increase weight of HF components. HFI group has the same training as HF group, but subjects were informed about spectral composition of stimuli and were instructed to answer on position of HF sound. Both groups (LF, HF and HFI) increased weighting of component they were trained to. Furthermore, they examined whether reweighting of spectral components is exclusive for sounds used during training or whether it will generalize to mid-frequency sounds which were not presented during training. However, this change in real environment did not generalize to change in virtual environment. In virtual environment all training groups increased weight of ILD component. We wanted to test whether change in the weight of ILD component is due to training or change of environment.

In our study we work with two groups that differ in experimental sessions. We expected that both groups would not increase their weighting of spectral components due to no training. Moreover, we hypothesized that the RE posttest that was performed before the VE posttest, but not before the VE pretest, caused the increased ILD weighting because the ILD weights are weighed more in reverberation than in anechoic environment (since ITDs are distorted by reverberation), as was shown in Kumpik (2019). We expected that OR group would increase ILD weighting and O group would not.

Hypotheses that we are trying to confirm:

1. Weights of high frequency and low frequency spectral components in real environment will not increase because training of components is omitted.
2. Re-weighting of binaural components ITD and ILD in virtual environment is affected by prior posttest in real environment.

3 Experiment

3.1 Setup and stimuli

3.1.1 Setup and stimuli in a real environment

For our experiment, we chose the same experimental setup in the real room as in Spišák (2021). In a dark reverberant experimental room with dimensions of 5.5 x, 4.7 x 2.7 m were placed 11 loudspeakers in a semicircle around the subject with 11.25° spacing between each other in the range from -56.25°to 56.25° (Figure 1).

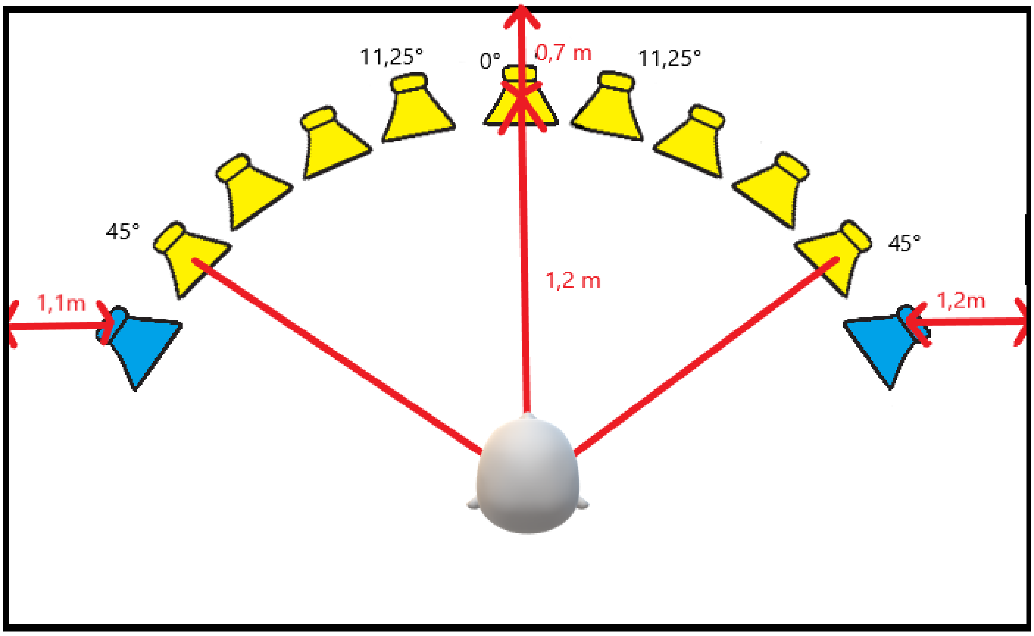

Figure 1: Sketch of RE. Yellow-colored loudspeakers represent the possible position of the target loudspeaker and blue color represents the non-target loudspeaker. Part of the experiment from the master thesis by Spišák (2021).

Loudspeakers were covered with acoustically transparent cloth to prevent subjects from giving biased answers by knowing specific locations of the speakers. Subjects were seated on the chair in the middle of the semicircle with their head directed to 0° azimuth. On the top of the loudspeakers was a white paper strip to display visual stimuli from the head tracker on the subjects' head. Current orientation of the head was generated by projector. 0°azimuth was displayed as a red cross in the middle of the paper. To indicate whether the position of the head should be recorded by headtracker, subjects used small numeric keyboard (Figure 2).

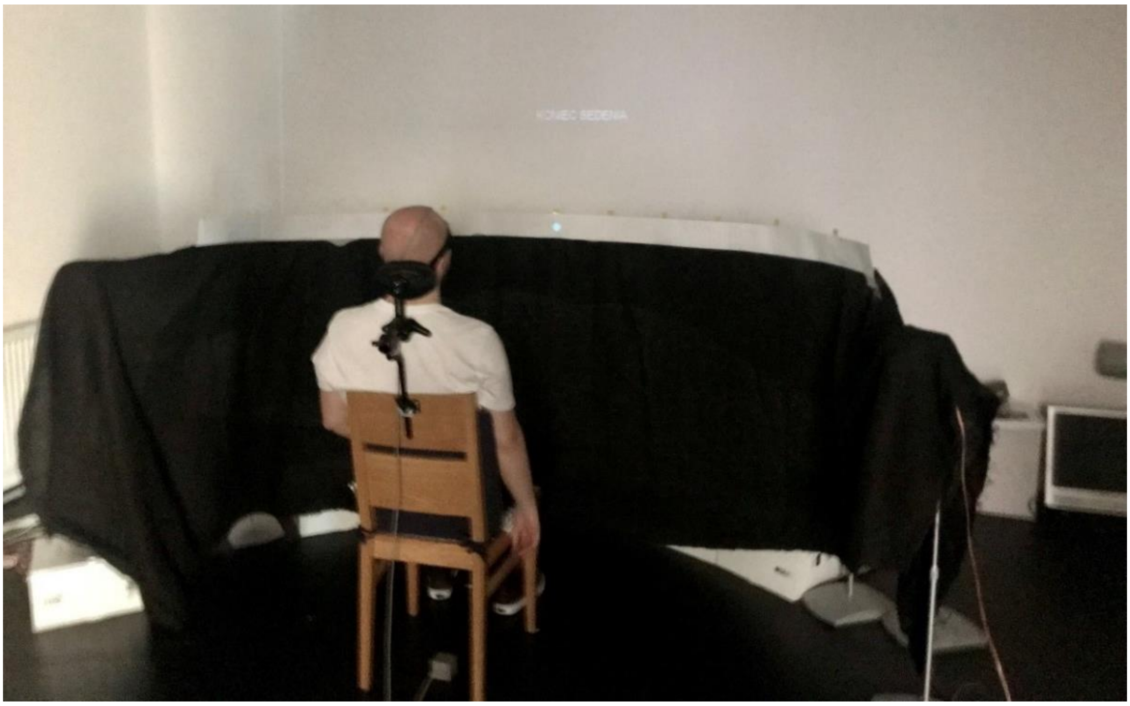

Figure 2: Room for RE part of the experiment. Chair in the middle of a semicircle of loudspeakers covered with black cloth and with a stripe of paper on top of them for presenting visual stimuli.

5 types of sounds, that were different in frequency from each other, were presented through loudspeakers. Stimuli with frequencies 0.35kHz and 0.7kHZ are low-frequency (l-f) sounds, 2.8kHz is mid-frequency sound (m-f), 5.6kHz and 11.2kHz are high-frequency (h-f) sounds. Nine loudspeakers in the middle were used as target and non-target, while 2 on the sides were non-target only. All stimuli were pre-generated and consisted of 0.5-octave noise bands with a duration of 0.3s. The ramp at the beginning and the end of each stimuli made them sound more natural. Moreover, we divided stimuli into 3 types.

2-channel trials, where played stimuli consisted of one h-f and one l-f component. Trials could be played from the same loudspeaker or 2 different loudspeakers, one or two positions apart (Tab.1).

In 4-channel trials, sounds consisted of two h-f components and two l-f components, where two h-f sounds or two l-f sounds made consistent pair playing from the same loudspeaker and other pair played from three different positions apart from consistent pair: from the same loudspeaker, one or two positions away in the same direction (Tab.2).

In 2-channel with mid-frequency trials, sound consisted of an m-f component and one h-f or l-f component one position apart from m-f speaker (Tab.3).

To distinguish when different sounds are coming from different loudspeakers, we assigned them to big and small separations. In big separations, 2-channel trials were sounds coming from loudspeakers 2 positions apart. For 4-channel trials, two sounds-consistent pair is playing from one loudspeaker and other two sounds from two different loudspeakers. In small separations, 2-channel trials are sounds played from loudspeakers one position apart and for 4-channel trials is sound from consistent pair played from the same loudspeaker as one other sound. For 2-channel trials with sounds coming from the same loudspeaker, the type of separation is referred to as zero.

Table 1: Example of 2-channel trials. Numbers in the table express the position of loudspeakers numbered from left to right from 1 to 11 that played in a specific trial.

Frequency	0.35 kHz	0.7 kHz	5.6 kHz	11.2 kHz	2.8 kHz	Type of separation
Trial						
1.	6	-	4	-	-	Big
2.	9	-	-	9	-	0
3.	-	7	5	-	-	Small

Table 2: Example of 4-channel trials. Numbers in table express the position of a loudspeaker that played in specific trial.

Frequency	0.35 Hz	0.7 kHz	5.6 kHz	11.2 kHz	2.8 kHz	Type of separation
Trial						
1.	4	4	3	2	-	Big
2.	8	8	8	4	-	Small

Table 3: Example of 2-channel with mid frequency trials. Numbers in table express position of loudspeaker that played in specific trial.

Frequency	0.35 kHz	0.7 kHz	5.6 kHz	11.2 kHz	2.8 kHz
Trial					
1.	7	-	-	-	8
2.	-	5	-	-	6
3.	-	-	-	4	5
4.	-	-	4	-	3

3.1.2 Setup and stimuli in virtual environment

Design of VE was the same as in Ferber et al. (2018) using ITD/ILD combination corresponding to one of 40 possible positions in horizontal plane in range from -70.2° to 70.2° with spacing of 3.6°. Positions from -45°to 45° were target positions, the rest were non-target only (Figure 3). The experiment took part in anechoic, double-walled soundproof booth in front of the computer, with headphones and Oculus Development Kit 2 headset, which displayed virtual room made of black and white stripes. Orientation of the head was monitored with Oculus sensor located on the top of the monitor. Oculus displayed current position of head represented by yellow triangle. The sound pressure level of the stimuli was in the range of 62.5bB to 67.5dB SPL, randomly roved on each trial. The stimuli were 1-octave noises with center frequency 2.8 kHz. The stimuli were generated by multi I/O processor TDT RX8 and played through headphones Sennheiser HD 800 S (Figure 4).

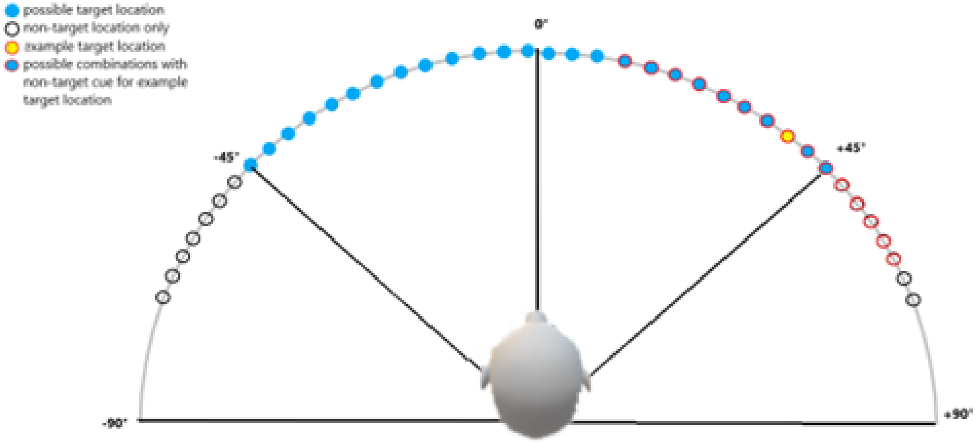

Figure 3: Sketch of VE. Dots representing possible positions of sounds. Part of the experiment from study Ferber (2018).

Figure 4: Virtual room with headset and headphones.

3.2 Experimental design

To show the effect of weighting in real (RE) and virtual environment (VE) we divided the experiment into two parts. One was in the echoic room with loudspeakers- RE and the second was in an anechoic, soundproof room with headphones- VE. Experiments in both environments consisted of 2 parts, pretest, and posttest. The training part from the experiment which we followed up (Spišák 2021) was omitted. Depending on the group, the structure of the experiment varied.

Outline of the experiment:

a. OR GROUP
    i. 1st day: Audiogram, VE pre-training, VE pretest, RE pretest,
    ii. 2nd day: free
    iii. 3rd day: free
    iv. 4th day: RE posttest, VE posttest.
b. O GROUP
    i. 1st day: Audiogram, VE pre-training, VE pretest,
    ii. 2nd day: free
    iii. 3rd day: free
    iv. 4th day: VE posttest

Participants in the OR group started on the first day with an audiogram. During audiogram, subjects were seated in a soundproof room with headphones and an answering device. They were presented with 3 short sounds. Their task was to press the button whenever they heard sounds.

After they finished audiogram, experiment started. They were seated in the soundproof room and instructed how to answer in experiment. After instructions, pre-training in VE followed, consisting of about 80 measurements with Oculus Rift, headphones, and keyboard for answers. Pre-training was with visual feedback, which appeared on position of sound origin, for a better understanding of sounds coming from a different location. Visual feedbacks were presented with sound coming from a specific location and their task was to turn their head to the position of sound location in the horizontal plane and record the location with the keyboard, after that, they turned their head back to the starting position at 0°. Next was the pretest in VE, consisting of 466 measurements with the same principle as pre-training but without visual feedback. This was followed with a pretest in RE, build on the same principle as the pretest in VE, except the sound was coming from loudspeakers, and the oculus was exchanged for a head tracker located on the middle of the forehead of the participant. Overall, 396 trials were played. After pretest, there was 2-day break. On the third day, participants undertook the RE posttest and VE posttest, in reversed order from pretest. Posttests are the same as pretests and both without visual feedback.

All participants in the O group started also with an audiogram and pre-training in VE followed by a pretest in VE. The next two days were free and the third day was the posttest in VE.

3.3 Experimental groups

For better observation of the main goal, we divided a total number of 14 participants into two groups. 7 people called the oculus group (O group) participated in the shorter experiment, only VE part of the experiment, so they can be a control group and 7 people called the oculus + real group (OR group) participated in RE and VE part of the experiment. In total, 3 women and 11 men participated in the experiment with average age 22. At the beginning of the first experimental session, all 14 participants took place in an audiogram, whether they have normal hearing. We tested hearing thresholds in different frequencies. All our participants had hearing thresholds under 20 dB, which was considered as normal hearing.

Nevertheless, all the participants signed informed consent which have been approved by the ethical committee of UPJŠ.

4 Multiple linear regression model (MLR)

The multiple linear regression model is a statistical technique for relating a set of two or more variables (Jobson 1991). This model gives us weights without compression, where compression is an effect when subjects tend to localize sound source closer to the central position in lateral plane. Simple subtraction of position of high frequency and low frequency component is not enough because it would be affected by the compression. By using linear regression model, we can filter compression and transfer it into an additional parameter. All analysis were done for each azimuth separately.

4.1 MLR in real environment

We used same model as Klingel at al. (2019), where cue weights from pretest and posttest were estimated separately for each participant based on a regression analysis fitted separately for each azimuth. The model equation is as follows:

$$R = (\alpha, \Delta_{LF}) = k_{LF}(\alpha) \cdot \Delta_{LF} + Q_{(\alpha)} \qquad (1)$$

$$R = (\alpha, \Delta_{HF}) = k_{HF}(\alpha) \cdot \Delta_{HF} + Q_{(\alpha)} \qquad (2)$$

$$w_{HL} = \frac{atan\frac{k_{LF(\alpha)}}{k_{HF(\alpha)}}}{90} \qquad (3)$$

R is a subject’s response azimuth with LF and HF components at positions

$\alpha + \Delta_{LF}$ and $\alpha + \Delta_{HF}$. α is between -56.25° and 56.25° with 11.25° spacing. k_{LF}, k_{HF} and Q are estimated parameters of a linear regression model, where k_{LF} , k_{HF} are regression slopes determining the weights of the frequency components estimated at each azimuth by considering azimuthal offsets of the cue, $\Delta_{LF}(\Delta_{HF})$, while setting the offset of the other cue $\Delta_{LF}(\Delta_{HF})$ to zero. Q is the overall bias of azimuth α, computed as mean of Q_{LF} and Q_{HF}, where compression is filtered.

w_{HL} is estimated weight of HF vs. LF components, where 1 means that subject oriented only according to HF component and 0 that subject oriented only according to LF component. For further analysis using model (1) an (2) we will be considering w_{HL} and change in weights of spectral components.

All errorbars are standard error of the mean (SEM) characterized with equation:

$$SEM = \frac{\sigma}{\sqrt{n}} \qquad (4)$$

Where σ is a standard deviation and n is the size of a sample (subjects).

Assuming left-right symmetry in perception, all the raw data (Figure 5) for targets located off-center (away from 0°) were collapsed from left to right side and averaged before fitting over *y*-axes. Example is in Table 4. This approach gives smoother raw data and makes model more accurate. Azimuths after collapsing data were 0°, 11.25, 22.5°, 33.75°, 45° and 56.25°. However, we did not include 56.25° because it was not a target azimuth for any stimuli, nor did we include 45°because for 4-channel stimuli was non-target azimuth. This means that all analysis were done only on 4 azimuths: 0°, 11.25°, 22.5° and 33.75°.

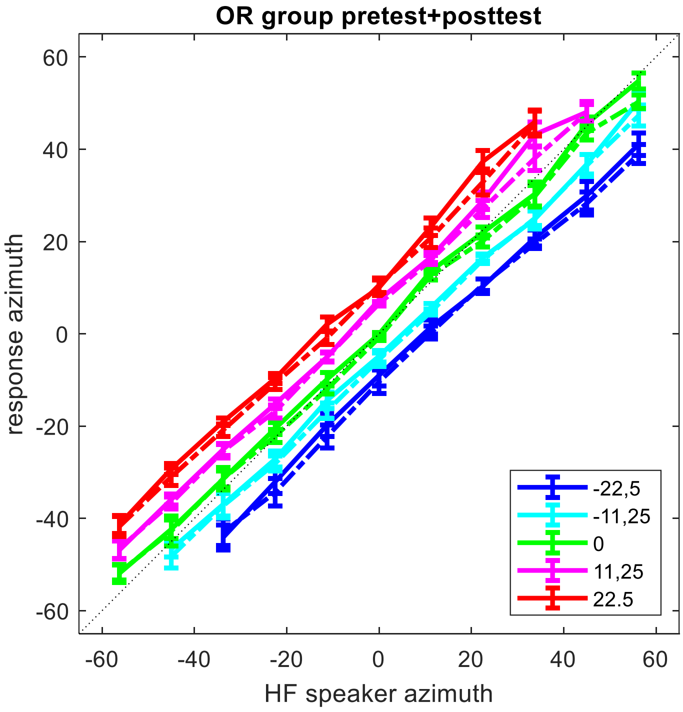

Figure 5: Raw data as response azimuth for OR group for 2-channel data from RE as a function of position of high frequency loudspeaker. Thick continuous lines are data from pretest and dashed lines are data from posttest. Each line represents trial with different spacing of loudspeakers explained in the legend.

Table 4. Example of left-right collapsed data

HF response before collapsing	LF response relative to HF position before collapsing	HF response after collapsing	LF response relative to HF position after collapsing
-22.5°	11.25°	22.5°	-11.25°

4.2 MLR in virtual environment

We used the same linear regression model as in real environment:

$$R = (\alpha, \Delta_{ITD}) = k_{ITD}(\alpha) \cdot \Delta_{ITD} + Q_{(\alpha)} \qquad (5)$$

$$\mathrm{R} = (\alpha, \Delta_{ILD}) = k_{ILD}(\alpha) \cdot \Delta_{ILD} + Q_{(\alpha)} \qquad (6)$$

$$w_{LT} = \frac{atan\frac{k_{LF(\alpha)}}{k_{HF(\alpha)}}}{90} \qquad (7)$$

R is a subject's response azimuth with ITD (low frequencies) and ILD (high frequencies) components at positions $\alpha + \Delta_{ITD}$ and $\alpha + \Delta_{ILD}$. α is between -56.25° and 56.25° with 11.25° spacing. k_{ITD}, k_{ILD} and Q are estimated parameters of a linear regression model, where k_{ITD}, k_{ILD} are regression slopes determining the weights of the ITD and ILD components estimated at each azimuth by considering azimuthal offsets of the cue, $\Delta_{ITD}(\Delta_{ILD})$, while setting the offset of the other cue $\Delta_{ITD}(\Delta_{ILD})$ to zero .Q is the overall bias of azimuth α, computed as mean of Q_{ITD} and Q_{ILD}, where compression is filtered.

w_{LT} is estimated weight of ILD to ITD components. For further analysis using model (5) and (6) we will be considering w_{LT} only, where 1 means that subjects oriented only according to ILD component and 0 that subjects oriented only according to ITD component and change in weights will be expressed in w_{LT}.

All errorbars are standard error of mean (SEM) characterized with equation:

$$SEM = \frac{\sigma}{\sqrt{n}} \qquad (8)$$

Where σ is a standard deviation and *n* is the size of a sample (subjects).

Assuming that the perception is left-right symmetric, we collapsed the data over y-axis in belief to reduce noise and power up the statistics (Figure 6). That gave us data on 13 azimuths, from 1.8°to 45°with 3.6° step.

For the evaluation of results, we used the analysis of variance (ANOVA).

4.3 ANOVA

ANOVA is a technique used for univariate data. It determines and quantifies the effect of different experimental factors on the observed results of the experiment. ANOVA starts by estimating these effects for each factor and for possible interactions, furthermore, the significance of these effects is inferred (Hoefsloot et al. 2009). The level of significance was when value p in ANOVA was less than 0.05.

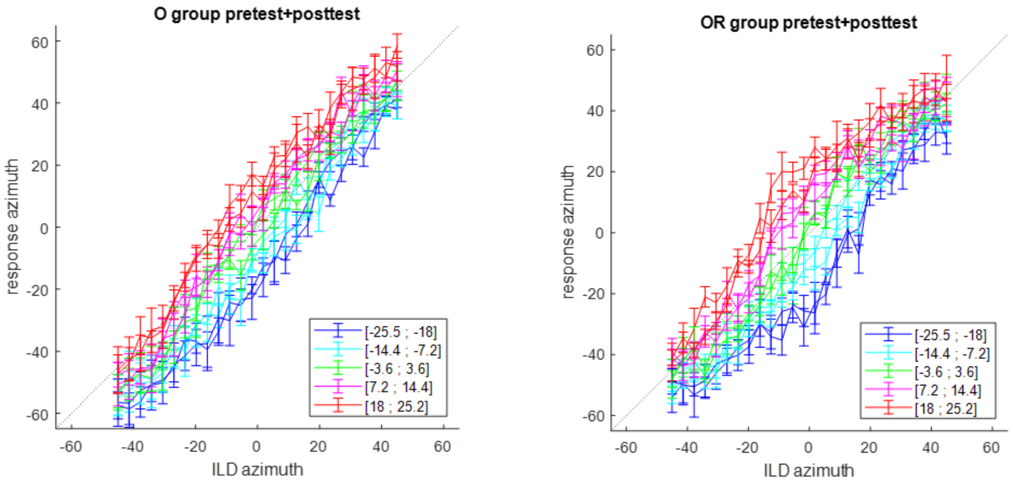

Figure 6: Raw data as response azimuth for O and OR groups for oculus data from VE as a function of position of ILD component. Continuous lines are data from pretest and dashed lines are data from posttest. Each line represents trial with different spacing of loudspeakers explained in the legend.

5 Results

5.1 Real environment

As we hypothesized that relative weight of HF component to LF component from pretest to posttest will not increase because the training part in RE was omitted.

On the Figure 5 we can see raw data, green line represents that there is no compression (or very little). The offset of the other colors that both HF and LF components were used by the subjects. Figure 5 shows responses of each subject as azimuth of HF speaker towards LF speaker position. To get stronger data without compression figures 7,8,9 shows how it is done.

On Figure 7 we can see a first step, we subtracted responses on 0° azimuth (green line) from all responses away from the middle line.

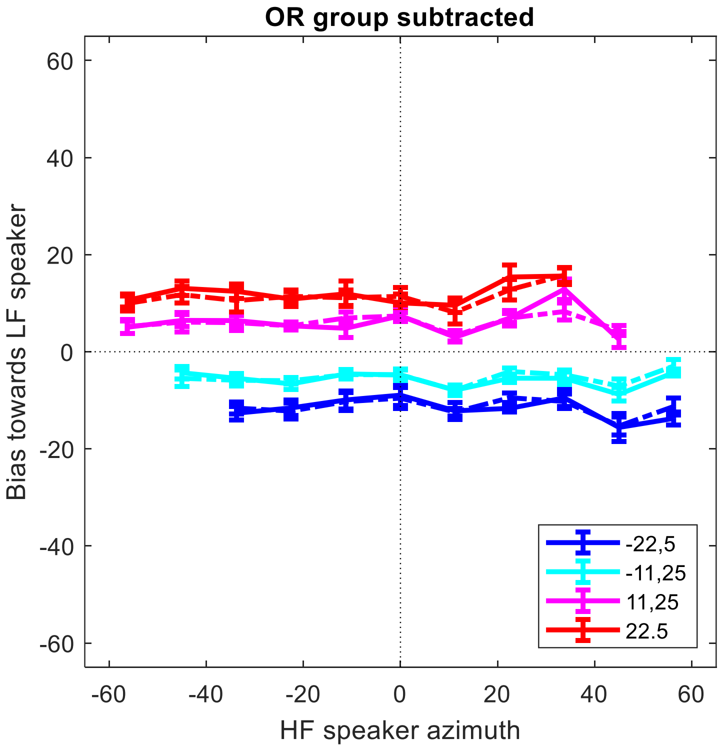

Figure 7: Raw data as bias towards LF speaker as a function of HF speaker azimuth.

Supposing, that data are left-right symmetrical we collapsed them from one side to another. For example, the blue point on azimuth 22.5 was averaged with red point on azimuth -22.5. This was done for every point in a way that blue was collapsed to red and cyan to magenta. Final result is on Figure 8.

To make data even stronger, we multiplied by two the magenta data, HF speaker 11.25° away from LF speaker and added them to red data, HF speaker 22.5° away from

LF speaker and averaged them. Red lines are approximately flat at around 11°, meaning that HF and LF components were approximately equally weighted at all azimuths. Dashed and solid lines are on top of each other, meaning that there was no change from pretest to posttest.

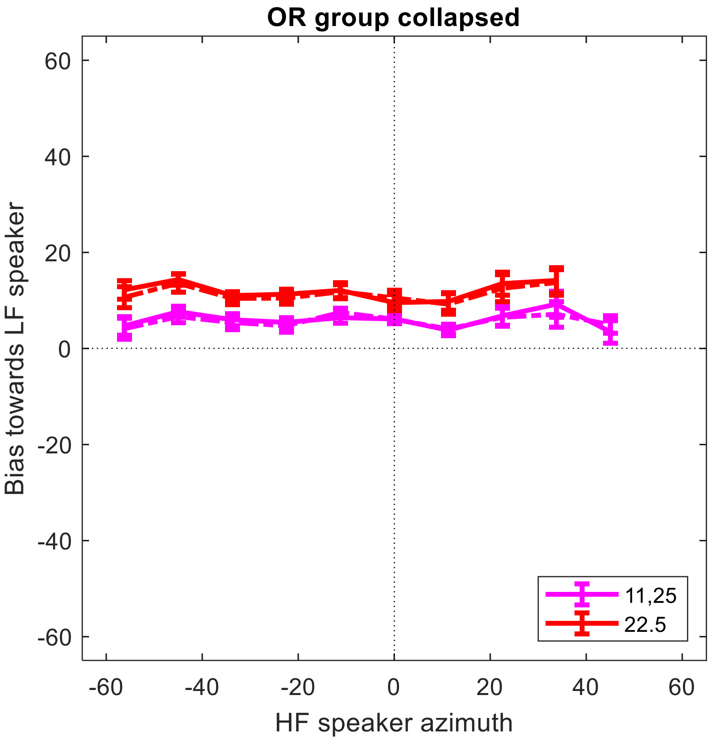

Figure 8: Raw data as bias towards LF speaker as a function of HF speaker azimuth.

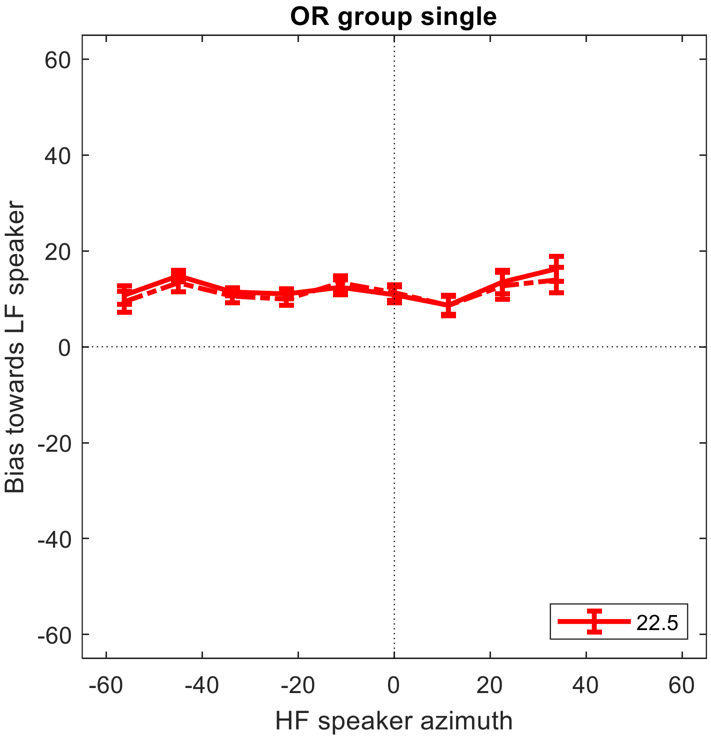

Figure 9: Raw data as bias towards LF speaker as a function of HF speaker azimuth.

5.1.1 Results in RE for w_{HL} for big and small separations

In the Figure 11 is w_{HL} as a function of target azimuth.

Partial ANOVA for w_{HL} for OR group with factors azimuth (0°, 11.25°, 22:5°, 33.75°) and time (pretest,posttest) have shown significant effect of azimuth (F (3,18)=5.78, p<0.01) but not time (F (1,6)=0.1, p>0.05). Furthermore, the interaction time X azimuth showed no significance (F (3,18) = 2.48, p>0.05).

Mixed ANOVA for w_{HL} for training and no training groups with factors azimuth (0°, 11.25°, 22:5°, 33.75°), time (pretest,posttest) and group (HF,LF,NoT) gave significant effect of azimuth (F(3,117)=58.69, p<0.01), time (F(1,39)=6.22, p<0.05), but not for group (F(2,39)=2.13, p>0.05), and significant effect of interactions time X group (F(2,39)=10.98, p<0.01), but not for azimuth X time (F(3,117)=1.81, p>0.05), azimuth X group (F(6,117)=1.44, p>0.05) and azimuth X time X group (F(6,117)=1.59, p>0.05).

Change in weights from pretest to posttest for no training group showed no significance. Training groups changed their weighting from pretest to posttest in a way they were trained. Again, no re-weighting is happening without training, which supports our hypothesis.

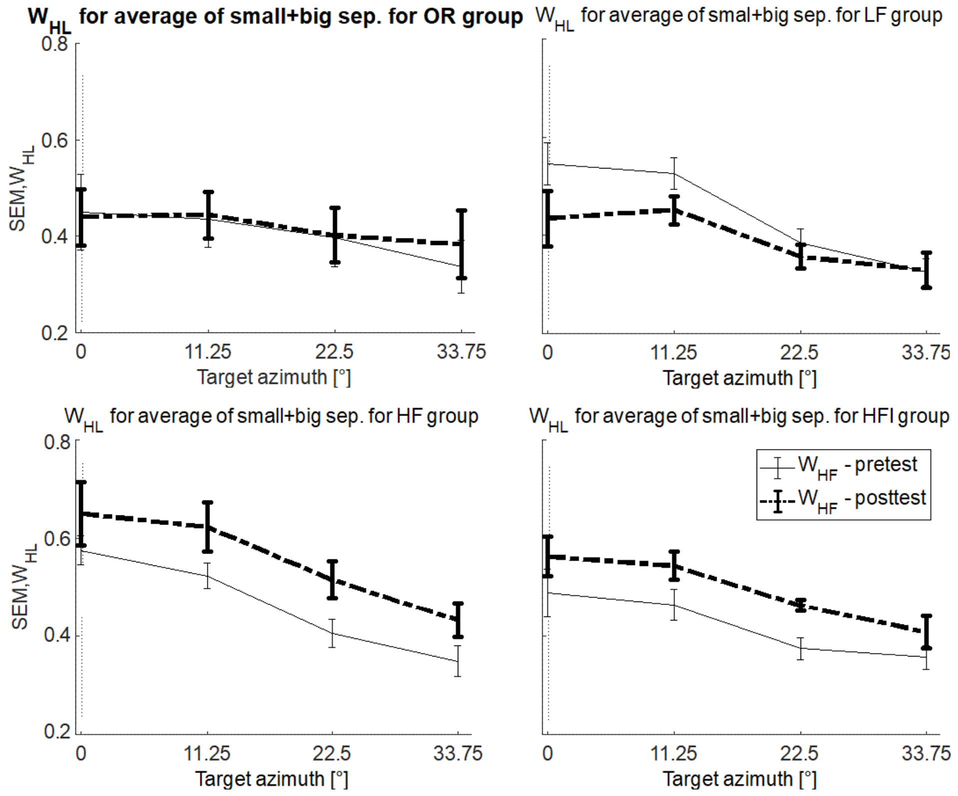

Figure 10: w_{HL} as a function of target azimuth for mean of small and big separations for all groups. Thin line represents pretest and thick dashed line represents posttest. Data are left-right collapsed. Errorbars are standard error of the mean (SEM).

To draw a better view on weights we plotted them as barplots after averaging across azimuth (Figure 12).

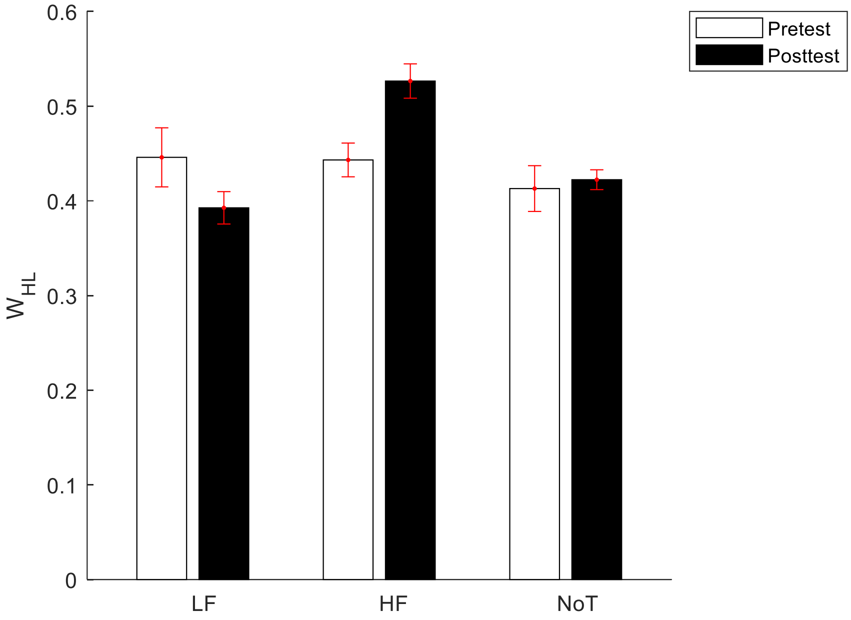

Figure 11: Barplots for w_{HL} for all groups in pretest and posttest, averaged across locations with errorbars as standard error of mean.

5.1.2 Results in RE for *k* parameter for big and small separations

With regression analysis model it is possible to compute parameters such as k_{LF} and k_{HF}. We expect no changes in k_{LF} and k_{HF} component for OR group. In the Figure 10 are k_{LF} and h_{LF} parameters separately for the pretest and posttest computed as across-subjects average of k_{LF} and k_{HF}.

Partial ANOVA for k_{LF} for OR group with factors azimuth (0°, 11.25°, 22:5°, 33.75°) and time (pretest,posttest) have shown no significant effect of azimuth (F(3,18)=3.05, p>0.05) and time (F(1,6)=0.85, p>0.05). Furthermore, the interaction time X azimuth (F (3,18) =1.84, p>0.05) was not significant. ANOVA for k_{HF} for OR group with factors azimuth (0°, 11.25°, 22:5°, 33.75°) and time (pretest,posttest) have shown no significant effect of azimuth (F(3,18)=0.33, p>0.05) and time (F(1,6)=0.23, p>0.05). Furthermore, no significant interaction time X azimuth (F (3,18) =1.48, p>0.05). From pretest to posttest, we cannot see a significant changes in both parameters as was expected.

Mixed ANOVA for k_{LF} for training and no training groups with factors azimuth (0°, 11.25°, 22:5°, 33.75°), time (pretest,posttest), group (HF,LF,NOT) gave significant effect of azimuth (F(3,117)=42.49, p<0.01), time (F(1,39)=10.87, p<0.01), group

(F(2,39)=4.38, p<0.05) and significant effect of interactions azimuth X time (F(3,117)=4.13, p<0.01), time X group (F(2,39)=10.53, p<0.01), but not for azimuth X group (F(6,117)=1.87, p>0.05) and azimuth X time X group (F(6,117)=1.53, p>0.05).

Mixed ANOVA for k_{HF} for training and no training groups with factors azimuth (0°, 11.25°, 22:5°, 33.75°), time (pretest,posttest), group (HF,LF,NOT) gave significant effect of azimuth (F(3,117)=15.00, p<0.01), but not for time (F(1,39)=2.58, p>0.05), group (F(2,39)=3.17, p>0.05), and significant effect of interactions time X group (F(2,39)=10.53, p<0.05), but not for azimuth X time (F(3,117)=1.27, p>0.05), azimuth X group (F(6,117)=1.50, p>0.05) and azimuth X time X group (F(6,117)=1.86, p>0.05).

To sum up results from ANOVA for *k* parameter, we can say that in groups without training no significant change of *k* parameters happened, on the contrary, results from training groups showed significant change in *k* parameters, that supports our hypothesis that without training no changes occur.

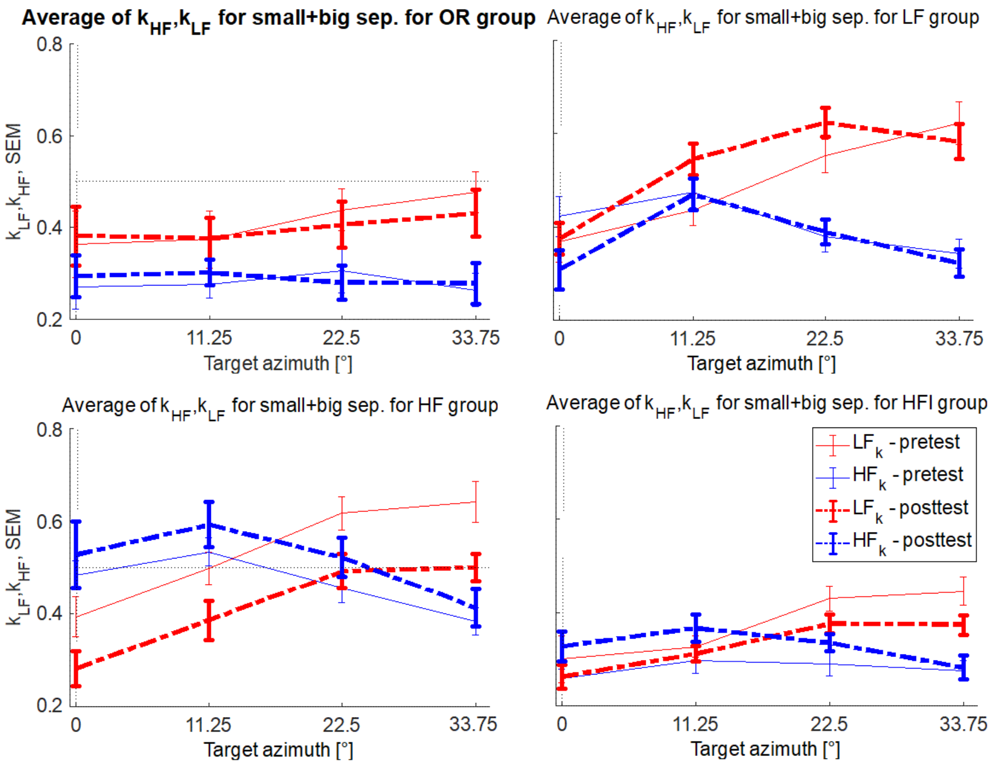

Figure 12: Mean of k_{LF} and k_{HF} for small and big separations. Continuous thin line are data from pretest and thick dashed line is posttest as a funciton of target azimuth for OR group. Data are left-right collapsed and errorbars are standard error of the mean (SEM).

5.1.3 Results in RE for *Q* parameter for big and small separations

After expelling compression from weights, linear regression model concentrated it into *Q* parameter. Changes in *Q* parameter are in Figure 13. From pretest to posttest, we can see no change in *Q* values.

We ran partial ANOVA for *Q* parameter for OR group with factors azimuth (0°, 11.25°, 22:5°, 33.75°) and time (pretest, posttest), that have shown significant effect of azimuth (F(3,18)=386.79, p<0.01) but not time (F(1,6)=0.56, p>0.05). Furthermore, the interaction time X azimuth showed no significance (F(3,18)= 0.72, p>0.05).

Mixed ANOVA for *Q* parameter for training and no training groups with factors azimuth (0°, 11.25°, 22:5°, 33.75°), time (pretest, posttest) and group (HF, LF, NoT) gave significant effect of azimuth (F(3,108)=2869.23, p<0.01), but not for time (F(2,36)=0.76, p>0.05), group (F(2,36)=0.52, p>0.05), nor for interactions time X group (F(2,36)=0.99, p>0.05), azimuth X time (F(3,108)=1.44, p>0.05), azimuth X group (F(6,108)=0.75, p>0.05) and azimuth X time X group (F(6,108)=0.42, p>0.05).

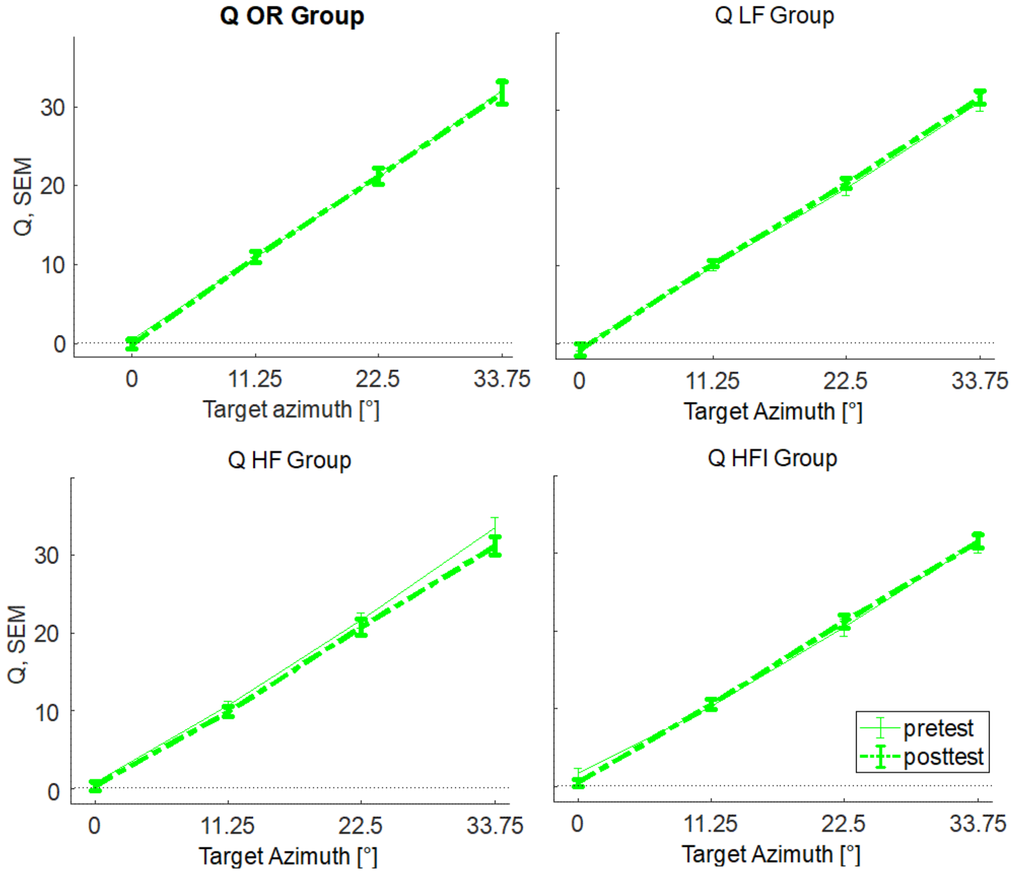

Figure 13: *Q* parameter for all groups as a funciton of target azimuth.

5.1.4 Results in RE for mid-frequency

To examine whether the change in localization also occurs when stimuli consist of high or low frequency component and one mid- frequency component, Spišák (2021) used them in trials in pretest and posttest but not in the training in RE. Generalization for mid-frequency component was successful only for HF group and not for HFI and LF group. What we expected was that we won't see a change in weighting of spectral components. For pretest, w_{HL}= 0.45 and for posttest w_{HL}=0.41. What might act like a significant change in weights from pretest to posttest, ANOVA with factor time (pretest,posttest) gave no significant effect of time (F(1,6)=2.72, p>0.05). Meaning that generalization to mid-frequency component without training did not happen.

5.2 Virtual environment

We hypothesized that the increased ILD weight in Spišák was due to the RE posttest immediately preceding the VE posttest. Thus, we hypothesized that ILD weight increase will be observed for the OR group but not for O group.

Same as in the real environment, green line represents that there is no compression (or very little). The offset of the other colors that both HF and LF components were used by the subjects. Figure 6 shows responses of each subject as azimuth of HF speaker towards LF speaker position. To get stronger data without compression figures 15,16,17 shows how it is done. However, to reduce the noise in raw data we firstly took 3 adjacent azimuths and averaged them as triplets, building stronger dataset (Figure 14).

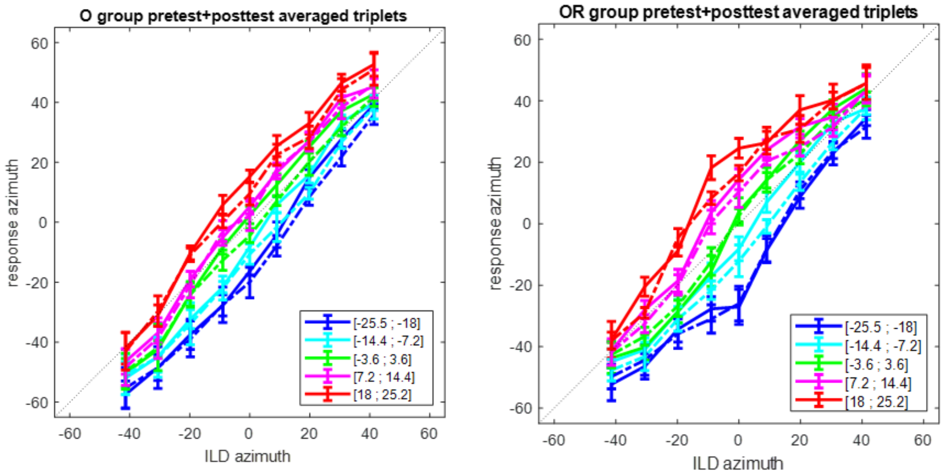

Figure 14: Raw data of response azimuth for both groups in VE as a function of position of ILD component. Continuous line is pretest and dashed line is posttest. Each line represents trials with different spacing of loudspeakers mentioned in legend.

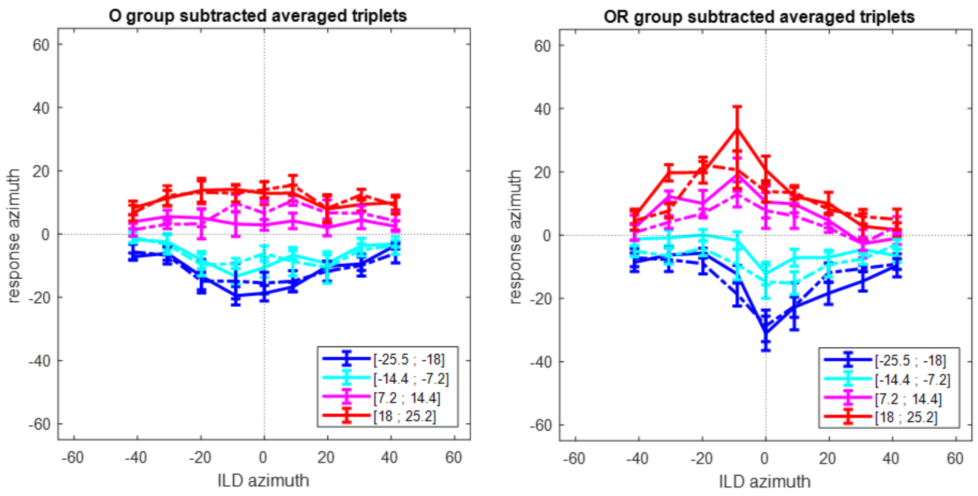

Figure 15: Raw data- bias towards ITD azimuth as a function of ILD azimuth.

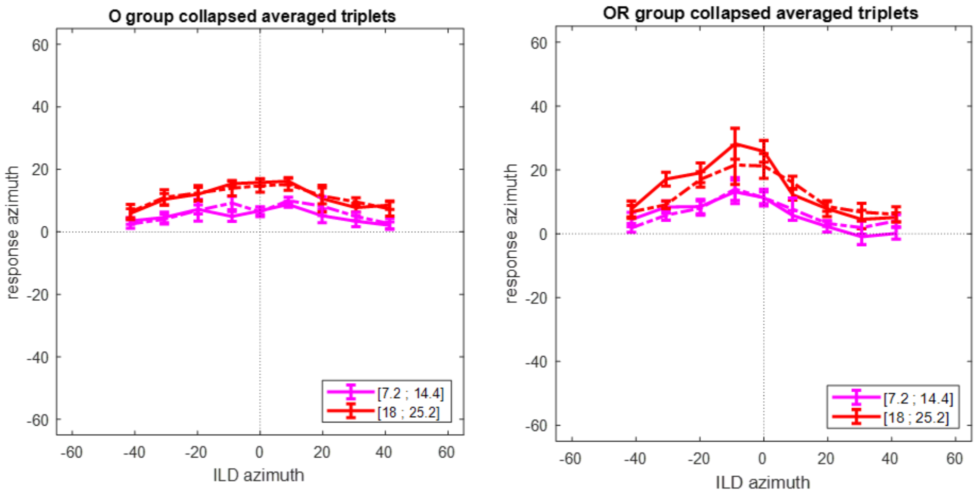

Figure 16: Raw data- bias towards ITD azimuth as a function of ILD azimuth.

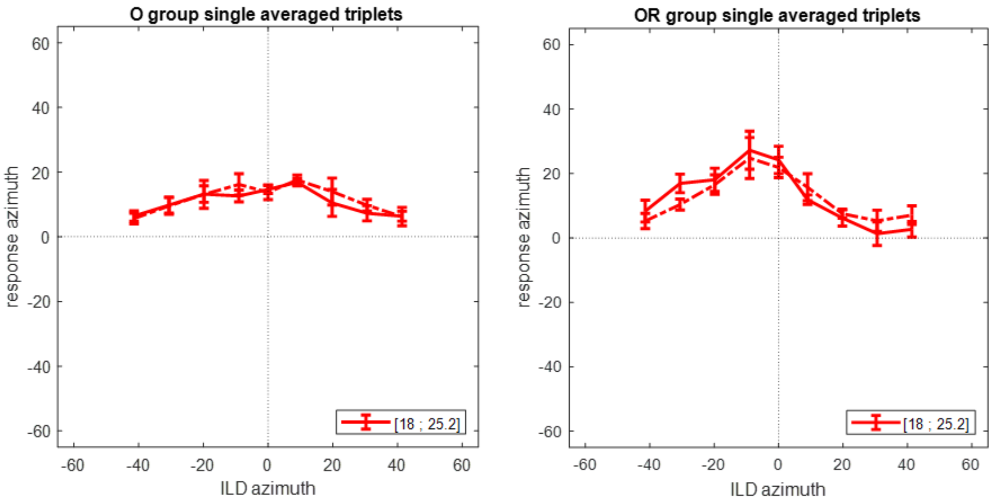

Figure 17: Raw data- bias towards ITD azimuth as a function of ILD azimuth.

5.2.1 Results in VE for w_{LT}

In the figure 19 is w_{LT} as a function of target azimuth of each subject.

Partial ANOVA for w_{LT} for OR group with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest) showed significant effect of azimuth ($F(12,72)= 4.34$, $p<0.01$) and no significant effect of time ($F(1,6)= 0.01$, $p>0.05$). For interaction azimuth X time there is no significant effect ($F(12,72)=0.60$, $p>0.05$). And for O group with same factors showed no significant effect of azimuth ($F(12,72)= 0.94$, $p>0.05$), time ($F(1,6)= 0.30$, $p>0.05$), and also interaction azimuth X time there is no significant effect ($F(12,72)=0.63$, $p>0.05$).

Mixed ANOVA for w_{LT} for O and OR group with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest), group (O,OR) showed significant effect of azimuth ($F(12,144)=4.19$, $p<0.01$) but no significant effect of time ($F(1,12)=0.28$, $p>0.05$), group ($F(1,12)=3.35$, $p>0.05$) and also no significant interactions azimuth X time ($F(12,144)=0.30$, $p>0.05$), azimuth X group ($F(12,144)=1.17$, $p>0.05$), time X group ($F(1,12)=0.19$, $p>0.05$) and also azimuth X time X group ($F(12,144)=0.91$, $p>0.05$).

Mixed ANOVA for w_{LT} for training and no training groups with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest), group (LF,HF,NoT) showed significant effect of azimuth ($F(12,528)=7.10$, $p<0.01$), time ($F(1,44)=13.89$, $p<0.01$). No significant effect of group ($F(2,44)=0.07$, $p>0.05$) and also no significant effect of interactions azimuth X time ($F(12,528)=1,23$, $p>0.05$), azimuth X group ($F(24,528)=1.44$, $p>0.05$), time X group ($F(12,144)=0.91$, $p>0.05$) and azimuth X time X group ($F(24,528)=0.78$, $p>0.05$).

Mixed ANOVA for w_{LT} for combined training groups (HF+LF) and no training groups with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest), group (LFHF,NoT) showed significant effect of azimuth ($F(12,540)=7.20$, $p<0.01$), time ($F(1,45)=13.99$, $p<0.01$) but no significant effect of group ($F(1,45)=0.00$, $p>0.05$). ANOVA showed significant effect of interactions azimuth X group ($F(12,540)=2.59$, $p<0.01$) and near significant effect of time x group ($F(1,45)=3.13$, $p=0.0835$), everything else was not significant.

For training groups the change of weighting did not happened the same way as in RE. They observed the increase of ILD weight independent of the training group, the change was significant in the same direction for all groups. For our no training groups change in pretest to posttest was not significant and change in reweighting was not dependent on group, meaning that RE posttest done before VE posttest has no effect. That is the opposite we hypothesized.

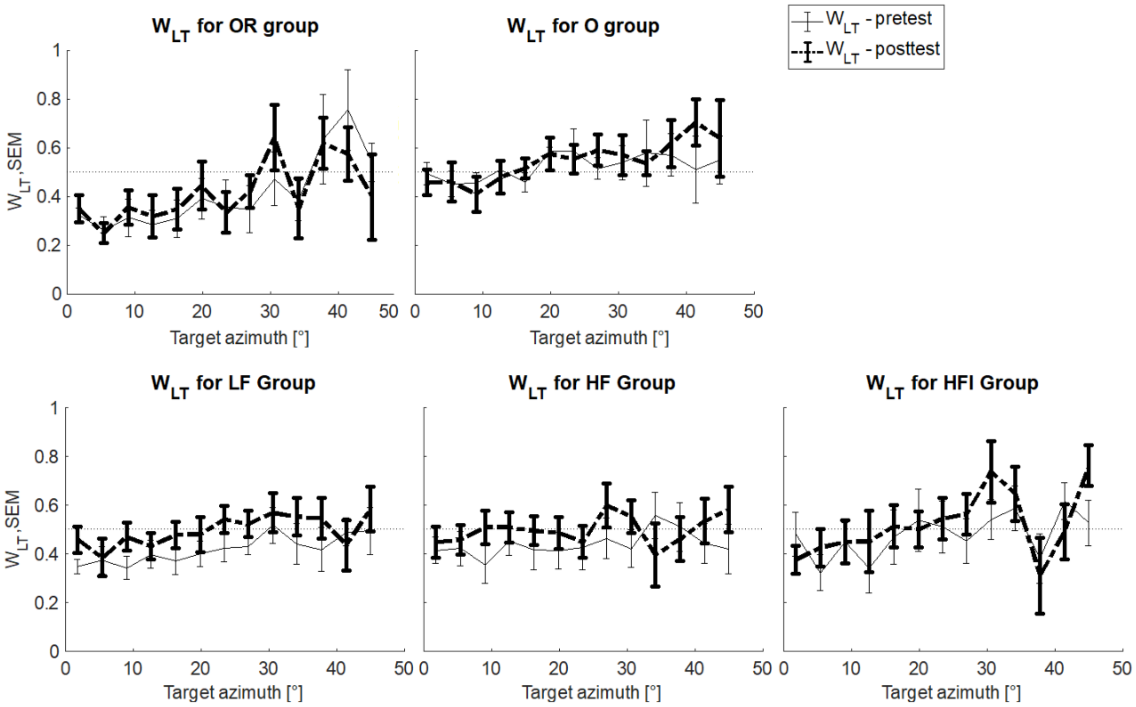

Figure 18: *W_{LT}* as a function of target azimuth for each subject in all groups. Thin line is pretest and thick line is posttest. Data are left-right collapsed and errorbars are standard error of the mean.

To draw a better view on weights we plotted our groups O and OR as barplots (Figure 20). And again, for all groups LF and HF+HFI as HF and O+OR as NoT (Figure 21). On the figure 22 we can see our no training group in contrast to trained groups.

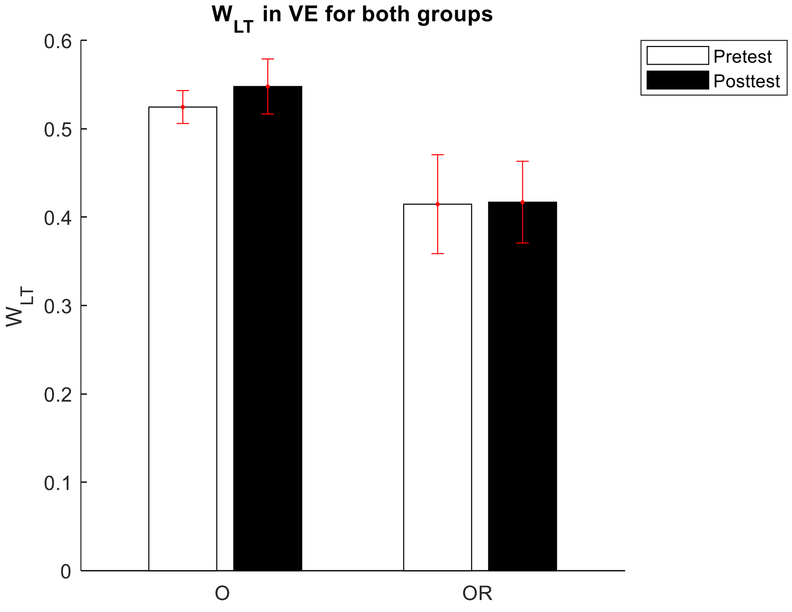

Figure 19: Barplot for w_{LT} for O and OR group in pretest and posttest, averaged across locations with errorbars as standard error of mean.

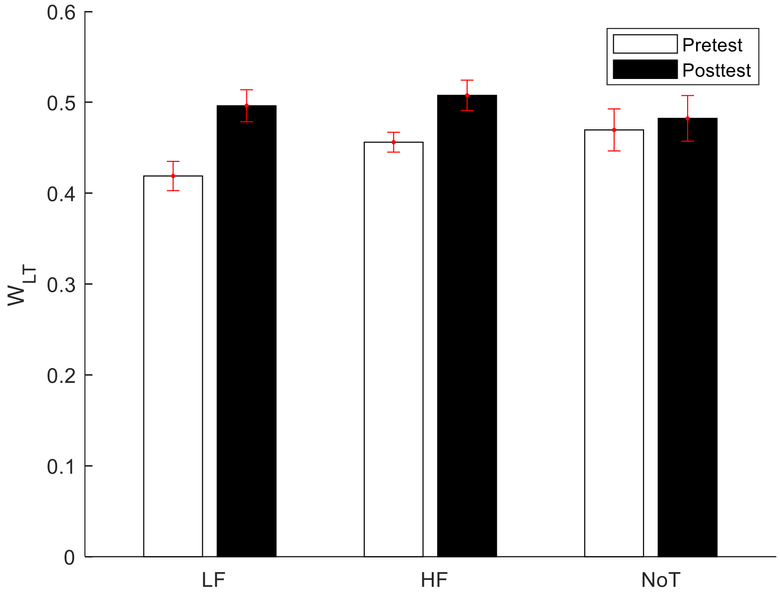

Figure 20: Barplot for w_{LT} for LF and HF (HF and HFI) group from Spišák's experiment and NoT group (O and OR group together) from our experiment in pretest and posttest, averaged across locations with errorbars as standard error of mean.

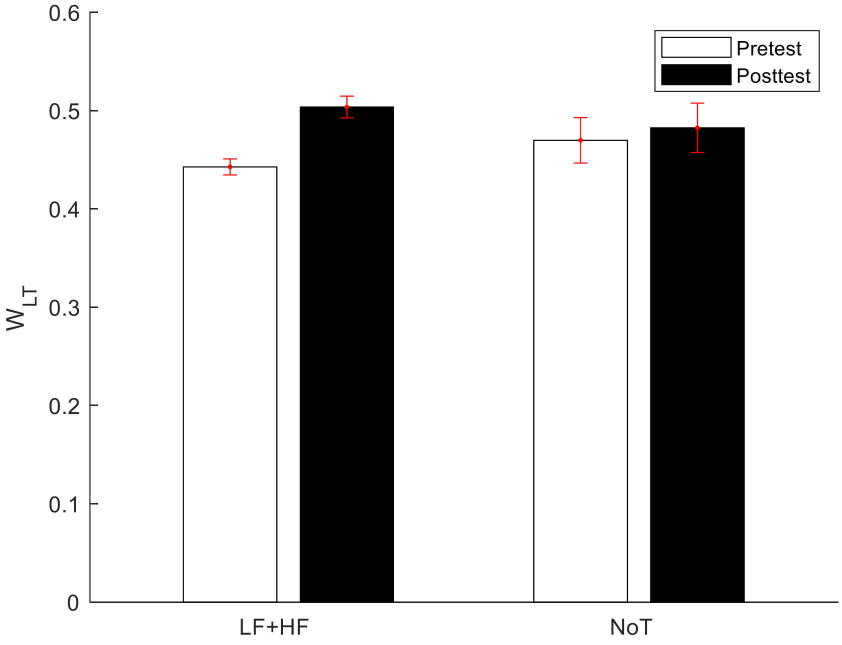

Figure 21: Barplot for w_{LT} for LF+HF+HFI group from Spišák's experiment and NoT group (O and OR group together) from our experiment in pretest and posttest, averaged across locations with errorbars as standard error of mean.

5.2.2 Results in VE for *k* parameter

As in real environment, after using linear regression model we can compute parameters k_{ILD}, k_{ITD} for O group and for OR group (Figure 18). For both groups we did not see a significant change in k parameters from pretest to posttest.

Partial ANOVA for k_{ITD} for OR group with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest) showed significant effect of azimuth (F(12,72)= 18.94, $p<0.01$), no significant effect of time (F(1,6)= 0.12, $p>0.05$) and not significant interaction azimuth X time (F(12,72)= 0.60, $p>0.05$). Partial ANOVA for k_{ITD} for O group with same factors showed significant effect of azimuth (F(12,72)= 7.61, $p<0.01$), no significant effect of time (F(1,6)= 0.01, $p>0.05$) and not significant interaction azimuth X time (F(12,72)= 0.49, $p>0.05$).

Mixed ANOVA for k_{ITD} for O and OR group with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest), group (O, OR) gives significant effect of azimuth (F(12,144)=15.23, $p<0.01$) and no significant effect of time (F(1,12)=0.03, $p>0.05$), group (F(1,12)=0.00, $p>0.05$), interactions azimuth X time (F(12,144)=0.99, $p>0.05$), azimuth X group (F(12,144)=0.00, $p>0.05$), time X group (F(1,12)=0.00, $p>0.05$) and azimuth X time X group (F(12,144)=0.00, $p>0.05$).

Mixed ANOVA for k_{ITD} with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest), group (HF, LF, NoT) gives significant effect of azimuth (F(12,528)=47.62, $p<0.01$), time (F(1,44)=4.06, $p<0.01$), and no significant effect of group (F(2,44)=0.51, $p>0.05$), gave us significant effect of interaction azimuth X time (F(12,528)=2.09, $p<0.05$), but not for azimuth X group (F(12,528)=0.88, $p>0.05$), time X group (F(2,44)=1.30, $p>0.05$) and no significant interaction of azimuth X time X group (F(24,528)=0.99, $p>0.05$).

Partial ANOVA for k_{ILD} for OR group with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest) showed no significant effect of azimuth (F(12,72)= 1.86, $p>0.05$), no significant effect of time (F(1,6)= 0.09, $p>0.05$) and not significant interaction azimuth X time (F(12,72)= 0.32, $p>0.05$). Partial ANOVA for k_{ILD} for O group with same factors showed no significant effect of azimuth (F(12,72)= 1.88, $p>0.05$), no significant effect of time (F(1,6)= 0.00, $p>0.05$) and not significant interaction azimuth X time (F(12,72)= 1.04, $p>0.05$).

Mixed ANOVA for k_{ILD} for O and OR group with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest), group (O, OR) gives significant effect of azimuth (F(10,120)=17.86, p<0.01) and no significant effects of time (F(1,12)=0.00, p>0.05), group (F(1,12)=0.00, p>0.05), interactions azimuth X time (F(10,120)=1.07, p>0.05), azimuth X group (F(10,120)=0.00, p>0.05), time X group (F(1,12)=0.00, p>0.05) and no significant interaction of azimuth X time X group (F(10,120)=0.00, p>0.05).

Mixed ANOVA for k_{ILD} with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest), group (HF, LF, NoT) gives significant effect of azimuth (F(12,528)=10.64, p<0.01), time (F(1,44)=5.56, p<0.05), and no significant effect of group (F(2,44)=0.45, p>0.05), gave us significant effect of interaction azimuth X time (F(12,528)=2.95, p<0.01), but not for azimuth X group (F(12,528)=0.65, p>0.05), time X group (F(2,44)=1.24, p>0.05) and no significant interaction of azimuth X time X group (F(24,528)=1.15, p>0.05).

k_{ITD} and k_{ILD} are changing in groups with training in a way they were trained for, however k_{ITD} was changing more significantly. In our groups change from pretest to posttest is not significant. We can see that change in *k* parameter is not dependent on group.

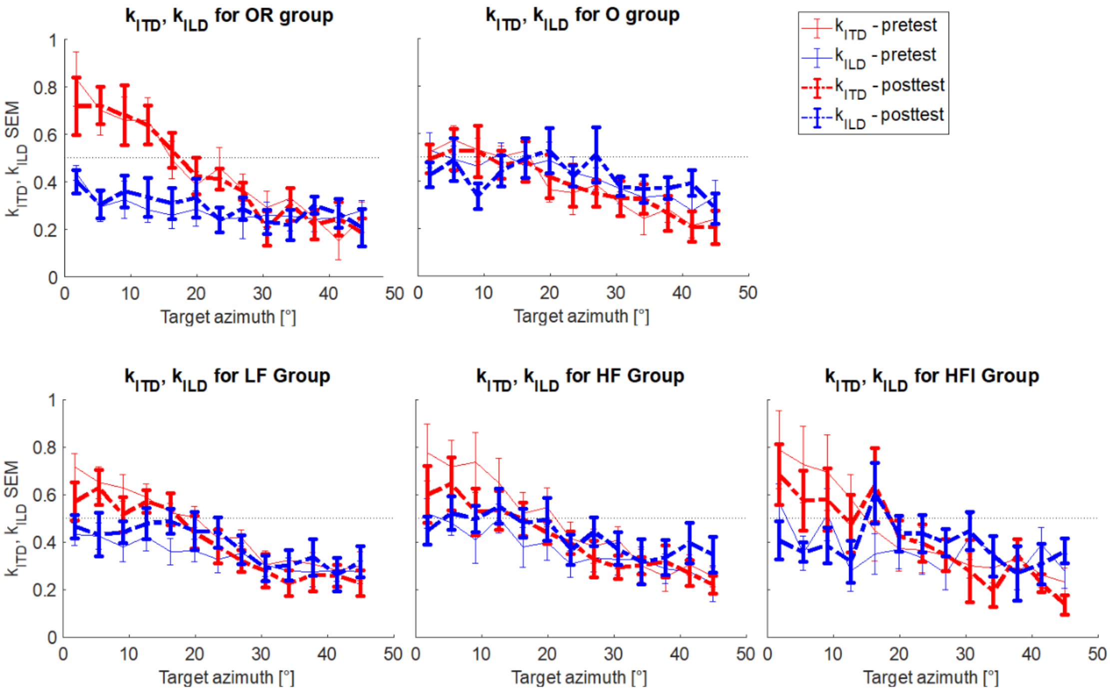

Figure 22: Values of k_{ITD} and k_{ILD}. Continuous thin line are data from pretest and thick dashed line is posttest as a funciton of target azimuth for all groups. Data are left-right collapsed and errorbars are standard error of the mean (SEM).

5.2.3 Results in VE for *Q* parameter

The same thing with compression in RE we did in VE, we expelled the effect of it and concentrated it into parameter *Q*. We expect similar or near the same results as in RE. The change in *Q* parameter from pretest to posttest will not be significant, meaning no compression happens.

Partial ANOVA for *Q* parameter for OR group with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest), giving significant effect of azimuth (F(12,72)= 201.70, $p<0.01$) but not of time (F(1,6)= 0.03, $p > 0.05$) nor of interaction azimuth X time (F(12,72)=0.25, $p>0.05$). For O group partial ANOVA gives same results as for OR group. Significant effect of azimuth (F(12,72)=120.38, $p<0.01$) but not of time (F(1,6)=0.30, $p>0.05$) and interaction azimuth X time (F(12,72)= 0.62, $p>0.05$).

Mixed ANOVA for *Q* parameter for O and OR group with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest) and group (O,OR) shows significant effect of azimuth (F(12,144)= 240.76, $p<0.01$) and not for time (F(1,12)=0.60, $p>0.05$), group (F(1,12)=0.00, $p>0.05$) and also for interactions azimuth X time (F(12,144)=1.24, $p>0.05$), azimuth X group (F(12,144)=0.00, $p>0.05$), time X group (F(1,12)=0.00, $p>0.05$) and azimuth X time X group (F(12,144)= 0.00, $p>0.05$).

Mixed ANOVA for *Q* parameter for training and no training groups with factors azimuth (1.8°to 45°with 3.6°step, 13 azimuths), time (pretest, posttest) and group (HF,LF,NoT) shows significant effect of azimuth (F(12,528)= 731.56, $p<0.01$) and not for time (F(1,44)=2.29, $p>0.05$), group (F(2,44)=0.36, $p>0.05$) and also for interactions azimuth X time (F(12,528)=1.38, $p>0.05$), azimuth X group (F(24,528)=0.21, $p>0.05$), time X group (F(2,44)=0.22, $p>0.05$) and azimuth X time X group (F(24,528)= 0.66, $p>0.05$).

Change of parameter *Q* was according to ANOVA not significant and overall bias stayed unchanged even after reweighting. Results correspond with results from RE for all groups.

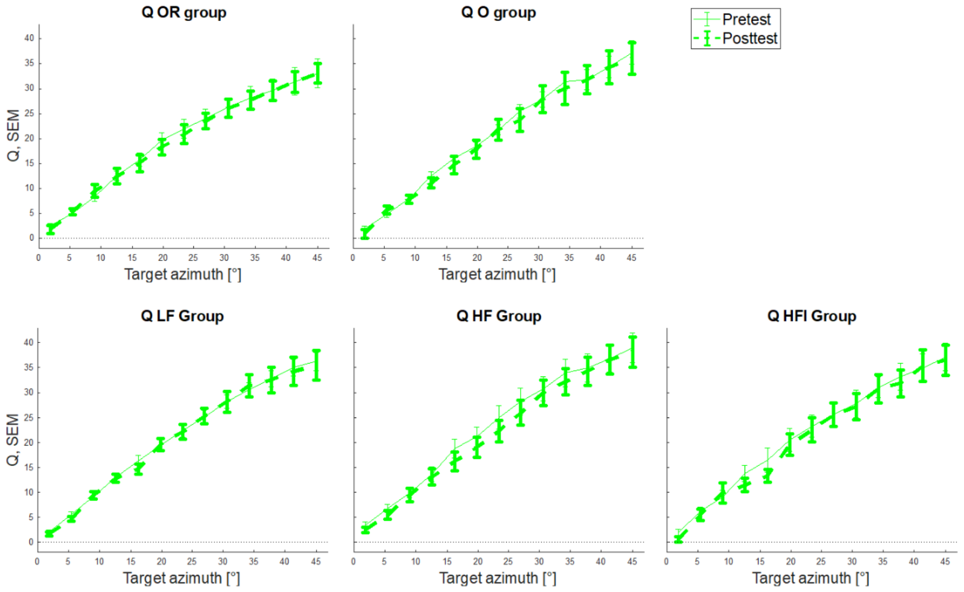

Figure 23: *Q* parameter as a funciton of target azimuth for all groups in VE. Data are left-right collapsed and errorbars are standard error of the mean.

Conclusion

From previous experiments we can see the reweighting of spectral components guided by audiovisual training is possible. Our study tried to show if the training is the only way we can do the reweighting.

Firstly, no significant change from pretest to posttest for Q parameter in both environments shows that compression did not occur and weights were not affected by compression.

In our study, omission of training in RE for OR group caused no changes in weights of spectral components from pretest to posttest. When comparing it to groups that had training (Spišák, 2021), they have changed weighting from pretest to posttest in the way they were trained for. LF group decreased weighting of HF component and HF and HFI groups increased weighting of HF component. This means that training is important for reweighting and this does not support our first hypothesis.

To examine whether the change in localization also occurs when stimuli consist of high or low frequency component and one mid- frequency component, Spišák (2021) used them in trials in pretest and posttest but not in the training in RE. Generalization for mid-frequency component was successful only for HF group and not for HFI and LF group. What we expected was that we won't see a change in weighting of spectral components. We did not observe changes from pretest to posttest. Meaning that generalization to mid-frequency component without training did not happen and that some generalization of the reweighting is, but small and only for the stronger version of HF training.

We expected change of weighting in VE due to posttest in RE that was done before posttest in VE. A confusion might happen because of higher dominance of ILD component in reverberant room (Rakerd, B., & Hartmann, W. M. 2010). Nevertheless, weights from pretest to posttest for OR and O group have not changed, meaning that if no significant effect of time (from pretest to posttest) and group (O or OR) happened, those two groups are the same. It is possible to say that training plays big role in reweighting of binaural components of sound. But simple change in environment does not. To support this statement, we combined those two groups (O and OR) into one, no-training group. In comparison with trained groups that increased relative weight of ILD component, independent to the type of training. Because our OR group did not show such an effect, it is important for further experiments that some part of the training is causing stronger weighting of ILD component.

It is still possible that prolonged performance of spatial auditory task in reverberation is sufficient to increase the ILD weight even if no training is included. In our study, the subjects were only involved in the short RE posttest in the real room, while in the Spišák study they performed an active localization task in 3 additional training session. To fully exclude hypothesis that the increase of ILD weight is not because of change of environment, it would be good to try the same experiments as in our study but after pretest in RE, for three consecutive days subjects will participate in pretest in RE.

Furthermore, experiments show that ITD is in healthy individuals weighted more Manufacturers of hearing aids might get enough insight on how to design cochlear implants for disabled people. From studies on hearing impaired patients, it is known that they do not focus on ITD at all and even after training for high frequencies it has not changed (Klingel, Laback, 2021). This might be because of implants which are falsely coding ITD information. Results from this study contributed to the expansion of knowledge on human spectral and binaural perception in both, real and virtual, environments.

Resumé

Lokalizácia zvuku nie je taká jednoduchá. Každý lokalizovaný zvuk môže byť vnímaný ako prichádzajúci z akejkoľvek vzdialenosti a smeru a je definovaný vo vzťahu k polohe hlavy. Zvuk pochádza z vibrácií zdroja a prenáša sa vzduchom alebo iným druhom média ako zmena tlaku. Na opísanie jednoduchého zvuku musia byť špecifikované tri veci: frekvencia alebo počet opakovaní tvaru vlny za sekundu, jednoduchšie, je to počet vibrácií vytvorených zvukovou vlnou za sekundu; amplitúda alebo miera kolísania tlaku okolo priemeru, inými slovami sa na to môžeme pozerať ako na mieru výšky popisujúcu hlasitosť; a fáza je umiestnenie alebo načasovanie bodu zvukovej vlny vo vzťahu k nejakému pevnému bodu v čase. Pojem „lokalizácia" sa vzťahuje na posúdenie smeru a vzdialenosti zdroja zvuku. Smer zvuku možno opísať jeho azimutom a jeho nadmorskou výškou. Azimut je uhol vytvorený projekciou na vodorovnú rovinu, čo znamená, že zvuky ležiace v strede majú azimut 0°. Elevácia je uhol vytvorený projekciou na mediálnu rovinu, čo znamená, že zvuky ležiace v horizontálnej rovine majú 0° eleváciu. Keď sa nám zobrazí zvuk z akejkoľvek pozície, môžeme ho lokalizovať vďaka dvom možným komponentom zvuku: interaurálnemu časovému rozdielu (ITD) a interaurálnemu rozdielu úrovní (ILD). Spôsob, akým ITD alebo ILD prispieva k lokalizácii zvuku, závisí od frekvenčného obsahu zvuku. Pri nižších frekvenciách sú dominantné ITD. Pre vyššie frekvencie sú dominantné ILD. Jedným z možných spôsobov, ako sledovať, ako ITD/ILD ovplyvňuje lokalizáciu, je meranie váhy. Dá sa to dosiahnuť pomocou pomerov ITD/ILD. Pomery ITD/ILD závisia od toho, ktorý podnet je upravený, tak, že dostáva väčšiu váhu v dôsledku zamerania pozornosti na daný podnet alebo v dôsledku adaptácie. Z predchádzajúcich štúdií vieme, že silnejšie je preváženie podnetov ITD.

Naša štúdia sa zameriava na pochopenie toho, ako ľudia pracujú so zvukom v rôznych prostrediach, a ako ho spracovávajú. Zamerali sme sa na binaurálne lokalizačné signály a binaurálne vnímanie zvuku a hlavným cieľom bolo zhromaždiť a analyzovať údaje z behaviorálneho experimentu, kde bol zvuk prezentovaný subjektom cez slúchadlá vo zvukotesnej miestnosti a v miestnosti cez reproduktory, aby sa preskúmal vplyv trénovania zmeny váženia spektrálnych a binaurálnych zložiek zvuku.

Naše hypotézy:

1. Váhy vysokofrekvenčných a nízkofrekvenčných spektrálnych komponentov v reálnom prostredí sa nezvýšia, pretože sme vynechali tréning jednotlivých komponento.

2. Zmena váženia binaurálnych komponentov ITD a ILD vo virtuálnom prostredí je ovplyvnená predchádzajúcim posttestom v reálnom prostredí.

Celkový počet 14 účastníkov sme rozdelili do dvoch skupín. Na experimente vo virtuálnom prostredí sa zúčastnilo 7 ľudí nazývaných skupina Oculus (skupina O), ktorý boli ako kontrólna skupina a 7 ľudí s názvom Oculus + reálna miestnosť skupina (skupina OR) sa zúčastnilo experiment vo virtuálnom aj reálnom priestore. Na začiatku prvého experimentálneho stretnutia sa všetkých 14 účastníkov zúčastnilo audiogramu, ktorý nám povedal, či sú vhodní pre samotný experiment. Subjekty skupiny OR začali prvý deň audiogramom, subjekty boli usadené vo zvukotesnej miestnosti so slúchadlami a tlačidlom na zaznamenávanie odpovedí. Boli im prezentované 3 krátke zvuky. Ich úlohou bolo stlačiť tlačidlo vždy, keď začuli zvuky. Po audiograme nasledovali inštrukcie a predtréning vo VE, ktorý pozostával z asi 80 meraní pomocou Oculus Rift, slúchadiel a klávesnice na zaznamenávanie odpovedí. Predtréning bol s vizuálnou spätnou väzbou pre lepšie pochopenie zvukov prichádzajúcich z daného miesta na azimute. Bol im prezentovaný zvuk prichádzajúci z konkrétneho miesta a ich úlohou bolo otočiť hlavu za zvukom v horizontálnej rovine a zaznamenať polohu pomocou klávesnice, následne hlavu otočili späť do východiskovej polohy na 0°. Nasledoval pretest vo VE, ktorý pozostával zo 450 meraní s rovnakým princípom ako predtréning, ale bez vizuálnej spätnej väzby. Za ním nasledoval pretest test v RE, postavený na rovnakom princípe ako pretest vo VE, s výnimkou toho, že zvuk vychádzal z reproduktorov a zaznamenávanie odpovedí bolo pomocou head trackeru umiestneného v strede čela účastníka. Pretest pozostával celkovo z 396 meraní. Nasledujúce dva dni sa nekonal žiaden experiment. Na tretí deň účastníci absolvovali RE posttest a VE posttest, ktoré sú rovnaké ako predtesty a oba boli bez vizuálnej spätnej väzby. Aj všetci účastníci skupiny O začali audiogramom a predtréningom vo VE, po ktorom nasledoval pretest vo VE. Ďalšie dva dni boli voľné a tretí deň bol posttest vo VE, táto skupina sa nezúčastnila nijakej experimentálnej časti v reálnej miestnosti s ozvenami.

Pre všetky analýzy sme použili viacnásobný lineárny regresný model. Tento model nám dáva váhy bez kompresie, kde kompresia je efekt, keď subjekty majú tendenciu lokalizovať zdroj zvuku bližšie k centrálnej polohe v laterálnej rovine. Tento model nám dáva parametre, ktoré nám pomáhajú vypočítať váhu spektrálnych zložiek. V reálnom prostredí odhadovaná váha HF vs. LF komponentov w_{HL} nám hovorí, či sa subjekt orientuje len podľa HF komponentu, kde $w_{HL}=1$ alebo sa subject orientuje len podľa LF komponentu, kedy je w_{HL} =0. Vo virtuálnom prostredí nám odhadovaná váha ILD ku ITD komponentu w_{LT} hovorí, či je sa subjekt orientuje len podľa ILD komponentu, w_{LT}=1 alebo subjekt je orientovaný len podľa ITD komponentu, w_{LT} =0.

V našej štúdii sme vynechali tréning v RE pre skupinu OR, čo nespôsobilo zmeny vo váženiach spektrálnych komponentov pri porovnávaní dát z predtestu k posttest. Keď to porovnáme so skupinami, ktoré mali tréning (Spišák, 2021), tie zmenili váženie od pretestu k posttest spôsobom, na ktorý boli trénovaní. Skupina LF znížila váhu HF zložky a skupiny HF a HFI zvýšili váhu HF zložky. To znamená, že tréning je dôležitý pre zmenu váženia a to podporuje prvú hypotézu.

Aby sa zistilo, či k zmene lokalizácie dochádza aj vtedy, keď stimuly pozostávajú z vysoko alebo nízkofrekvenčnej zložky a jednej stredofrekvenčnej zložky, Spišák (2021) tieto stimuly použil v pokusoch v preteste a postteste, ale nie v tréningu v RE. Generalizácia pre strednofrekvenčnú zložku bola úspešná iba pre skupinu HF a nie pre skupinu HFI a LF. Očakávaná, a teda žiadna, zmena od pretestu k posttestu nenastala. To znamená, že k zovšeobecneniu na strednofrekvenčnú zložku bez tréningu nedošlo a že nejaké zovšeobecnenie preváženia je, ale malé a len pre silnejšiu verziu HF tréningu.

Očakávali sme zmenu váženia vo VE kvôli posttestu v RE, ktorý bol vykonaný pred posttestom vo VE. K zvláštnej zmene váženia môže dôjsť v dôsledku vyššej dominancie zložky ILD v miestnosti s ozvenami (Rakerd, B., & Hartmann, W. M. 2010). Napriek tomu sa váhy od predtestu k posttest pre OR a O skupinu nezmenili, čo znamená, že ak nenastal žiadny významný efekt času (od predtestu po posttest) a skupiny (O alebo OR), tieto dve skupiny sú rovnaké. Dá sa povedať, že tréning zohráva veľkú úlohu pri prevažovaní binaurálnych zložiek zvuku, ale jednoduchá zmena prostredia nie. Aby sme sa upevnili v tvrdení, spojili sme tieto dve skupiny (O a OR) do jednej skupiny bez tréningu. V porovnaní so skupinami s tréningom (Spišák, 2021) došlo k zvýšeniu relatívneho váženia zložky ILD, nezávisle od typu tréningu. Pretože naša skupina OR nepreukázala takýto efekt, znamená to že niektorá časť tréningu spôsobuje silnejšie váženie ILD zložky a pre ďalšie experimenty je dôležité prísť na to, ktorá.

Stále je možné, že predĺžený pobyt v reálnej miestnosti s ozvenami je dostatočný na zvýšenie hmotnosti ILD, aj keď nie je zahrnutý žiadny tréning. V našej štúdii boli subjekty zapojené iba do krátkeho RE posttestu v reálnej miestnosti, zatiaľ čo v štúdii Spišák (2021) subjekty aktívne lokalalizovali zvuky v 3 dodatočných tréningoch. Aby sme úplne vylúčili hypotézu, že zvýšenie hmotnosti ILD nie je spôsobené zmenou prostredia, bolo by dobré vyskúšať rovnaké experimenty ako v našej štúdii, ale po preteste v RE sa počas troch po sebe nasledujúcich dní subjekty zúčastnia pretestu v RE.

Experimenty poukazujú na trend, že ľudia so zdravým sluchom oveľa viac vážia zložku ITD, kým ľudia s načúvacími zariadeniami sa na ňu nezameriavajú takmer vôbec, dokonca ani po trénovaní na zvýšenie jej váženia (Klingel,Laback, 2021). S týmito poznatkami môžu výrobcovia načúvacích prístrojov zmeniť dizajn prístrojov do takej miery, aby sa dokázali aj ľudia so sluchovým postihnutím zamerať na váženie ITD zložky. Výsledky tejto štúdie prispeli k rozšíreniu poznatkov o ľudskom spektrálnom a binaurálnom vnímaní zvuku v reálnom aj virtuálnom prostredí.

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