UNIVERZITA PAVLA JOZEFA ŠAFÁRIKA V KOŠICIACH
PRÍRODOVEDECKÁ FAKULTA

REWEIGHTING OF SPECTRAL AND BINAURAL CUES IN SPATIAL HEARING

2021 Bc. Ondrej SPIŠÁK

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Názov: Reweighting of spectral and binaural cues in spatial hearing

Názov SK: Zmena váženia spektrálnych a binaurálnych kľúčov v priestorovom sluchu

Cieľ:
- Examine the possibility of reweighting of spectral components of sounds and binaural cues by visually guided training in real environment.
- Describe of change in weighting of spectral and binaural cues by linear regression model.
- Analyze the impact of awareness about spectral composition of sounds to reweighting of binaural cues in informed listeners.
- Examine the generalization of reweighting of the high-frequency and low-frequency components of sound to weighting of untrained mid-frequency components.
- Analyze the temporal profile of re-weighting during training sessions of experiment.

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Abstrakt v štátnom jazyku

Ľudia lokalizujú zdroje zvuku v mnohých každodenných situáciách. Na lokalizáciu zvuku v horizontálnej rovine používame binaurálne kľúče interaurálneho časového rozdielu (ITD) a interaurálneho rozdielu v hlasitosti (ILD). ITD vyjadruje rozdiel v čase s akým príde zvuk do jedného a druhého ucha a ILD je rozdiel v hlasitosti s ktorou príde zvuk do jedného a druhého ucha. Binaurálne kľúče sú frekvenčne závislé. Pre nízkofrekvenčné zvuky (LF) je dominantné ITD, zatiaľ čo pre vysokofrekvenčné zvuky (HF) dominuje ILD. V reálnom prostredí s ozvenou sme uskutočnili experiment s tréningovou procedúrou, ktorej cieľom bolo zvýšiť váženie HF alebo LF komponentov širokopásmových stimulov. Následne sme testovali, či sa zmena váženia spektrálnych komponentov generalizuje na váženie netrénovaných strednofrekvenčných zvukov a na váženie ITD/ILD kľúčov vo virtuálnom prostredí. Trénovanie separátnych skupín na zvýšenie váženia HF alebo LF zložky viedlo k spektrálnej zmene váženia v očakávanom smere pre obe skupiny. Len HF tréning sa generalizoval na nový, strednofrekvenčný zvuk. Vo virtuálnom prostredí, obe skupiny zvýšili svoju ILD váhu z pretestu ku posttestu, čím sa nepotvrdila hypotéza, že tréning na LF zložky zvuku zvýši váhu ITD. Záverom je možné konštatovať, že zmena váženia spektrálnych komponentov zvuku je možná avšak jej generalizácia na zmenu váženia ITD/ILD kľúčov nie je zrejmá. Tieto výsledky sú dôležité napríklad pre navrhovanie sluchových pomôcok a kochleárnych implantátov ktoré vyžadujú aby sa ich užívatelia adaptovali na stimuly pozmenené týmito protetickými zariadeniami.

Abstrakt v cudzom jazyku

Humans need to localize sound sources in many everyday situations. To localize sounds in the horizontal plane, we use the binaural cues of interaural time difference (ITD) and interaural level difference (ILD). ITD is the time difference of sound arrival between two ears. ILD is the difference in the level with which the sound is received at the ears. Binaural cues are frequency dependent. For low-frequency (LF) sounds, the ITD dominates, while for high-frequency (HF) sounds, the ILD dominates. We performed a training experiment in a real reverberant environment in which visual cues were used to increase the weighting of either HF or LF components of broadband sound stimuli. Then, we tested whether this spectral reweighting generalizes to untrained mid-frequency sounds, and to the weighting of ITD/ILD cues in virtual environment. Training separate groups to increase their HF or LF weighting led to spectral reweighting in the expected direction for both groups. However, only HF training generalized to new, mid-frequency sounds. In the virtual environment, both groups increased their ILD weight from pre- to posttest, not confirming the hypothesis that training on LFs would increase the ITD weight. In conclusion, reweighting of HF or LF components of sound for localization is possible. However, the generalization to ITD/ILD reweighting is not straightforward. These results are important, e.g., for the design of hearing aids and cochlear implants which require that the listeners adapt to the stimuli altered by the prosthetic devices.

Contents

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List of abbreviations and symbols

ITD **I**nteraural **T**ime **D**ifference – time difference of sound coming to one and other ear

ILD **I**nteraural **L**evel **D**ifference – difference in intensity of sound coming to one and other ear

HF **H**igh **F**requency

LF **L**ow **F**requency

HFI **H**igh **F**requency **I**nformed – experimental group, where subjects were informed about spectral composition of stimuli

RE **R**eal **E**nvironment – in context of our thesis it is environment where was conducted first part of experiment

VE **V**irtual **E**nvironment - in context of our thesis it is environment where was conducted second part of experiment

Vocabulary

Anechoic means without reverberation

Binaural means related to both ears

Non-target is control sound

Posttest is last part of experiment

Pretest is first part of experiment

Trial is one measurement

Introduction

One of the most important parts of human perception is hearing. Its importance lies mostly in language processing, orienting in space, warning function, etc. and it is commonly believed that hearing is after vision the second most important sense for orientation. Specific aspect of hearing is spatial hearing, which helps us to orient ourselves in space, localize sound sources, and also focus on particular sounds while ignoring others. Although all these features are essential in everyday life, sound processing in humans is still quite understudied.

The main goal of current study is to analyze data from behavioral experiment, which was conducted as part of our bachelor thesis, where we tried to change sound localization in horizontal plane by series of audio-visual trainings in three separate groups of people with normal hearing. Groups had different visual feedbacks to stimuli during trainings to achieve change in sound localization in accordance to provided feedbacks. Trainings were conducted in reverberant room with loudspeakers, and influence of training was then tested in the same room and in soundproof room with headphones and virtual reality headset. We tried to analyze the effect of training to stimuli used during training sessions but also for untrained stimuli to find out whether the change of sound localization generalize to untrained stimuli as well.

We used multiple linear regression model to describe the change in sound localization before and after training and to separate possible distorting effects in localization, mainly in the form of compression. This model was also used to describe temporal changes of sound localization during and between training sessions. For all modeling and other analysis was used MATLAB. To evaluate the results we used the analysis of variance (ANOVA) computed by UNIX-style command-line program CLEAVE.

Understanding of sound processing can helps us in creating better hearing aids which would replicate sound more accurately and would lead to an increase in the quality of life of disabled people. Moreover with this understanding we will be able to create effective training procedures for improvement of spatial hearing. Such an improvement would help, for example, people with damaged cochlea. People using cochlear implants have problems to focus on specific sound from the palette of concurrent sounds, because of device imperfection. Similar problems occur in people with different hearing disabilities which are making their life considerably more difficult. Another area of application of our study is virtual reality. Precise imitation of acoustic condition in virtual environment is unrealizable without precise and deep understanding of sound processing in humans. This study could contribute to better understanding of sound processing and sound localization in humans and lead to an improvement of different virtual reality systems.

Our study is divided into 5 chapters. In the first chapter we describe theoretical background and current state of research in sound localization related to our study. In the second chapter there are stated research hypothesis and goals of this study. In the third chapter we described methods of experiment including participants, experimental setup and procedure, data analysis and modeling. Fourth chapter deals with the results of experiment in detail. Fifth chapter draws conclusions and summarizes the achieved results.

1 Theoretical background

1.1 Spatial hearing and binaural cues

Spatial perception of sound source locations in the horizontal plane is possible due to the position of ears on head, making the sound come to one ear earlier than to another and with different intensity of sound. It is beyond doubt that the ability to determine sound source without seeing it, is important mainly from evolutionary point of view since it is giving us an advantage in terms of surviving. Localization of sounds is more straightforward in horizontal plane because of ears position, in vertical plane is localization more difficult, mainly because same differences in intensity and arrival time in ears correspondent to multiple positions. This ambiguity leads to confusion when we perceive sound from above or below us. However, in most situations of life we perceive sounds, or have to localize sound source in horizontal plane, roughly at the level of our head and this includes processing of language which is one of the most important feature of hearing. In noisy environments especially it is very important ability to determine sound source and distinguish one particular sound from other sounds.

Sound localization in horizontal plane is mostly determined by two binaural parameters, interaural time difference (ITD) which reflects time difference of sound coming to one and other ear and interaural level difference (ILD) reflecting difference in intensity of sound coming to ears. Whereas ITD is a frequency independent but dominates for low-frequency sounds while boundary between sounds is approximately 1.3 kHz [17], ILD is a frequency dependent and rises alongside rising frequency. By combining these two cues we can achieve perception of sound from different places in horizontal plane. To make ITD a useful cue it is important to keep binaural coherence of sound at high level. With rising reverberation is ITD less useful and it is not used for localization [12].

1.2 Weighting of binaural cues

The importance of each cue for sound to be perceived as coming from certain location in plane can be expressed as trading ratio [8] between binaural cues or as weight of cue.

Common approach in determining trading ratio is to set one cue constant and adjust the other cue until auditory image seems to come from the front of the listener. Previous studies [3], [15], [16] show that trading ratio differs according to the cue being adjusted. According to Lang et al. [8], subjects tend to weight more cue which they are adjusting during experiment. In the first part of the Lang et al. experiment, subjects were sitting in the dark anechoic room with headphones and their task was to adjust position of one cue until the stimuli were coming from the center, while the other cue was held constant. In the second part, stimuli consisted of the same ITD and ILD values obtained in previous part of experiment and also from the stimuli where value of to-be-adjusted cue from first part of experiment was set to zero. The subject's task in the second part of the experiment was to determine the position of stimuli relative to their head. Answers to these trials were shifted towards cue that was adjusted in the first part. This effect was explained as the result of paying more attention to cue that was adjusted.

Alternative explanation is given in Moore et al. [11] where different trading ratios are obtained depending on which cue was adjusted, explained in terms of reduced influence of the non-adjusted cue because this cue is exposed repeatedly and sensitivity of listener to this cue decreases.

1.3 Spectral components of sound

ITD and ILD can be easily computed and simulated via headphones by delaying sound and altering loudness in one channel. This approach gives the experimenter a possibility to simulate sound location anywhere in the horizontal plane of listener. In real environment the manipulation with ITD and ILD is much more difficult. There are several studies regarding weighting of binaural cues using loudspeakers or recordings of sound from loudspeakers [12],[9] to determine the trading ratio. The main issue is insufficient possibility of manipulation with ITD and ILD. We can create different ITDs and ILDs by positioning loudspeakers, but it gives us only estimate of these values, because of different HRTFs in each participant. Another issue is the creation of unnatural combinations of binaural cues used in training procedure to reweight ITD or ILD, elimination of surrounding sounds and reverberation which can alter sound incoming to the ears.

Macpherson et al. [9] study shows, in accordance with duplex theory [13], that listeners are giving high weight to ITD and low weight to ILD for low-pass stimuli, and high weight to ILD and often low weight for ITD for high-pass stimuli. Frequency region of low-pass stimuli were set at 0.5-2kHz and for high-pass stimuli at 4-16kHz. With wideband stimuli, in range from 0.5kHz to 16kHz, the ITD weight was higher or equal to given ILD weight.

Hartman et al. [11] looked at the relationship between binaural coherence, what is the similarity of waveforms coming to ears, and effectiveness of ITD cue in sound localization. In three different environments, with different level of coherence were prepared sound recordings using “KEMAR” manikin. These recordings were then presented to listeners via headphones with altered value of ITD created by delaying one of the channels. The biggest contribution to sound localization had ITD when the frequency of sound was around 700Hz. ITD influence was highest when waveforms were similar. This happens in the free field where the reverberation is minimal. With rising reverberation the ITD is becoming less relatable.

1.4 Reweighting

It has recently been shown that reweighting of binaural parameters is possible in virtual environment [1], but it is not always successful [4].

There are several other recent studies focused on reweighting of binaural cues. In Kumpik et al. 2019 [6], experiment was examined whether it is possible to alter weighting of auditory localization cues by visually consistent and inconsistent stimuli. Weights of ITD and ILD were estimated from the slopes of a two-factor multiple regression of response angle on given ITD and ILD. There were two groups which differed in training procedure. In the first one presented visual cue was congruent with auditory stimuli and in the second one it was not. Participants were sitting in the chamber with headphones on, and their task was to focus on visual cue while ignoring auditory stimuli. There were 4 different types of trials for both groups, in the first type both ITD and ILD were congruent with each other, in the second one ILD was fixed and ITD was set random up to 20° from ILD, in the third one ITD was fixed and ILD was chosen randomly, and in the fourth one ITD and ILD was congruent with each other but they were shifted to the right or to the left from the midline by 10°. When visual cues were uninformative subjects showed reduction in auditory bias and when auditory binaural cues were congruent, weighting of ILD increased in both groups. The ILD weight also increased when visual cue was informative and aligned with ILD while ITD was set random. However, increase of ILD weighting can be observed partly due to its higher weighting in pretest.

In Kumpik et al. 2010 [7] study was conducted experiment focused on possibility of reweighting spatial cues used for sound localization in horizontal plane in participants with one plugged ear. Results show bigger importance of spectral cues when one ear is plugged and thus binaural cues are not useful. This reweighting is gradual and localization improves with training as result of greater use of spectral cues.

In Ferber et al. [1], study, the authors tried to reweight binaural cues by visually guided training in virtual environment. Two experimental groups consisting of 10 people each, complete seven days long training focused on changing the weight of ILD or ITD, depending on experimental group. Subject was in an anechoic room with headphones and Oculus rift on. In pretest the task was to move head toward position of heard sound, confirm the position by pressing a response button and return head to central position. Each stimulus had a specific combination of ITD and ILD values, each corresponding to a certain azimuth from range -70.2° to 70.2°. This procedure was used to obtain the initial weighting of ITD and ILD. Pretest was followed by 7-days long training. The task during training was similar than in pretest but in this case participants also got visual feedback either on position of ILD or ITD, depending on which group they were in. After their response they had to turn head towards visual feedback and confirm that position as well, than they turn head to 0° azimuth. At the end of experiment was conducted posttest, which was identic to pretest, to measure change in weighting. Results show significant change in weighting from pretest to posttest corresponding to visual feedback provided during training in both groups. While a group with visual feedback on the position of ITD increased weight of ITD cue a group with visual feedback on the position of ILD increased weight of ILD cue.

In our study we used the same pretest/posttest procedure as in Ferber et al. but we also added pretest and posttest procedure in a real reverberant room. Training procedure was completely in real reverberant room with stimuli coming from loudspeakers. This approach allows us to study the possibility of reweighting in real environment and its impact on reweighting of binaural cues in virtual environment.

2 Hypothesis and goals

Our main goal is to examine whether visual guided training in a real environment (RE) can be used for reweighting of high-frequency (HF) and low-frequency (LF) components of sound and whether this change of weighting will generalize to change of weighting for untrained mid-frequency components and to binaural reweighting. Also, we will examine the progress of reweighting by the analysis of temporal profile of training.

It was shown in Kumpik et al. 2010 [7], that improvement of sound localization can be based on reinforcing of spectral cues by behavioral training, thus reweighting of spectral components of sound is possible and achievable by appropriate training. Weighting of spectral components of sounds, used for localization in horizontal plane change depending on reverberation characteristics of environment. In an anechoic environment the lower frequencies are dominant while with rising reverberation high-frequencies are more reliable. This is in accordance with Hartman et al. [12] study where usefulness of ITD cue, which dominates for lower frequencies, was highly reduced with rising reverberation. In Hartman et al. study were sounds recorded in different rooms, and then played via headphones to participants. However, in our study we used loudspeakers to directly play stimuli to participants to examine the possibility of reweighting of HF or LF components of sound rather than ILD and ITD. We also want to examine whether reweighting of spectral components is exclusive only for sounds used during training or whether it will generalize to mid-frequency sounds which were not presented during training.

It is not clear whether weighting of binaural cues can be also changed in virtual environment (VE) by training in RE, with stimuli playing from loudspeakers. We know that ITD is a dominant cue for low frequency sounds and ILD for sounds with higher frequency, thus question is whether the change in weighting of high and low spectral components of sound will generalize in the change of ITD/ILD weighting. Specifically, we are trying to examine that if the training in a group focused on increasing weight of LF component will be successful, whether this change will be present in weighting of ITD component as well. Similarly, whether successful change in weighting of HF component, in a group trained on HF frequency, will generalize in similar change of ILD weight. We will try to describe this change by multiple linear regression model used for both, real and virtual environment.

Another question is whether the awareness of spectral composition of sounds and focusing on certain frequency influences reweighting of spectral components and binaural cues. It is often difficult task to discriminate frequency composition of sounds but it might be possible that explicit learning could strengthen the effect of reweighting.

Hypotheses we are trying to attest:

1. Visually guided training in real environment will increase high-frequency weight or low-frequency weight in accordance to training group.
2. The reweighting of high-frequency and low-frequency spectral components will generalize to reweighting of untrained mid-frequency components.
3. The reweighting of spectral components in real environment will generalize to reweighting of ITD and ILD in virtual environment.
4. Awareness about spectral composition of sounds does have a significant effect on reweighting.

3 Methods

3.1 Participants

Overall, we collected data on 41 participants. Three participants were excluded, because they started experiment but did not finish it and other two were excluded because they had higher hearing threshold. Whole experiment was successfully finished by 36 participants of which 22 were women and 14 men. All these participants had normal hearing tested by audiometer with threshold set to 20dB. They were randomly assigned to one of the 3 groups. There were 13 subjects in HF group, 12 subjects in LF group and 11 subjects in HFI group. All subjects signed an informed consent and the experiment was approved by the ethical committee of UPJŠ.

3.2 Experimental design

Experiment was performed in two environments, in virtual anechoic environment (VE) and in real environment (RE). In RE, pretest, training and posttest were performed, while in VE, pre-training, pretest and posttest were performed. On the first day of experiment was done pre-training in VE, to get subjects used to environment and setup, then pretest in VE and pretest in RE. On the second day training in RE started. It was 3 days long and differed according to experimental group, and on the last training day subjects also completed posttest, which was identical with pretest, first in RE and then in VE. In HF group subjects were trained to reinforce weighting of high-frequency (HF) components of sound, while subjects in LF group were trained to increase weighting of low-frequency (LF) components. In both groups, subjects were naïve about experimental design or origin of the presented sounds or their relation to the presented visual feedback. Pre-training, pretest and posttest were identical in both groups. Their task during testing was to localize the sound and respond in the middle if they perceived it at multiple locations, while in training their task was to imagine the sound as coming from the feedback location even if they initially heard it elsewhere. In HFI group, subjects were also trained to increase weight of HF component but were informed about structure of the sound and were instructed to focus and respond to sound with higher frequency already in the pretest.

3.3 Apparatus and stimuli

3.3.1 Setup and stimuli in real environment

RE was a quiet dark reverberant sound-treated experimental room with dimensions of 5.5 x 4.7 x 2.7 m. 11 loudspeakers were placed in a semicircle around the subject with spacing 11.25° between them, in range from -56.25° to 56.25° (Figure 1). The speaker array was covered by acoustically transparent cloth to prevent the subjects from knowing the locations or the number of speakers (Figure 2). For all trials of experiment was the position of subject on the chair with headrest in the middle of the room.

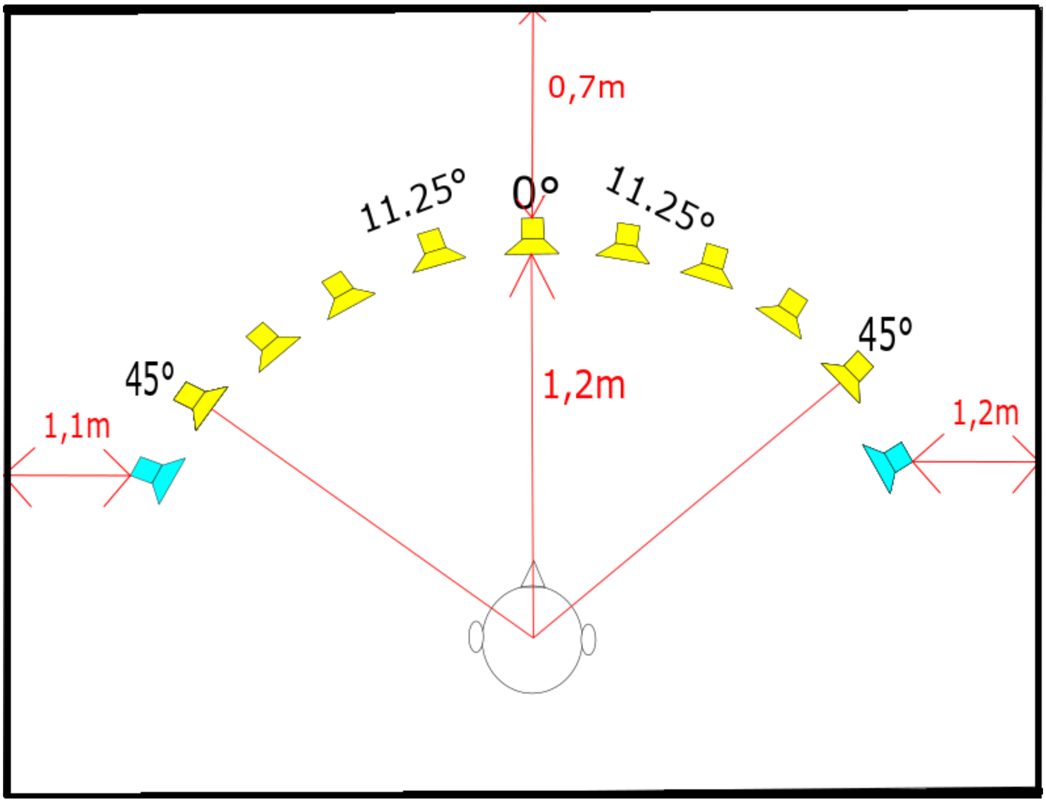

Figure 1: Sketch of RE with loudspeakers. Yellow color represents possible position of target loudspeaker and blue color represents position only of non-target loudspeakers. The room has dimensions 5.5 x 4.7 x 2.7 m

Figure 2:Room for RE part of the experiment. Chair with the headset is in the middle, loudspeakers are behind black cloth, with white stripe of the paper, for presenting visual stimuli, on the top.

There were 5 types of sound which differed in frequency. Stimuli with frequency 0.35kHz and 0.7kHz are low-frequency sounds, 2.8kHz is mid-frequency, 5.6kHz and 11.2kHz are high-frequency sounds. Nine loudspeakers in the middle were used both as target and non-target, while 2 at the edges were non-target only. All stimuli were pre-generated and consisted of 0.5-octave noise bands with duration 0.3s. At the start and end of each stimuli was ramp to make them sound more naturally. We had 3 types of stimuli. In “2-channel” trials were played stimuli consisting of one high frequency and one low frequency component, which could be played from same loudspeaker or from 2 different loudspeakers which were one or two positions apart from each other (Tab.1).

In “4-channel” trials, sound consists of two high-frequency components and two low-frequency components, while both high frequency sounds or both low frequency sounds were played from the same loudspeaker (consistent pair) and other pair played from two different positions which could be apart from consistent pair zero, one or two positions in the same direction (Tab.2).

The 2-channel and 4-channel trials are divided into 2 categories: big and small separations. In big separations are 2-chanel trials where are loudspeakers two position apart and 4-channel trials where are two sounds playing from same loudspeaker (consistent pair) and other two are playing from two different loudspeakers as consistent pair. In small separations are 2-channel trials where are loudspeakers one position apart and 4-channel trials where from same loudspeaker is playing consistent pair with one other sound. (Tab.2, Tab.3)

In “2-channel with mid-frequency” trials, sound consist of mid-frequency component and one either high frequency or low frequency component which was one position apart from the mid-frequency component (Tab.3). Sounds with mid-frequency were used only for testing, but not for training. On the top of loudspeakers was continuous white stripe of paper on which all visual feedback was displayed. The subject had a tracker device on the head, and the current orientation of the subject’s head was shown by a blue dot projected on the screen. The central position at the 0° azimuth was represented by the red cross. Subjects had small hand-held keyboard in hand for confirming their answer on stimulus and for centering the position of head.

Tab. 1: Example of 2-channel trials. Number in table express position of loudspeaker which played in specific trial.

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

Tab. 2: Example of 4-channel trials. Number in table express position of loudspeaker which played in specific trial.

Frequency / Trial	5.6 kHz	11.2 kHz	0.35 kHz	0.7 kHz	2.8kHz	Type of separation
1.	4	5	5	5	-	Small
2.	3	2	4	4	-	Big
3.	4	4	6	5	-	Big
4.	4	4	5	6	-	Big
5.	8	8	8	9	-	Small

Tab. 3: Example of 2-channel with mid-frequency trials. Number in table express position of loudspeaker which played in specific trial.

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

3.3.2 Setup and stimuli in virtual Environment

Design of VE part was the same as in Ferber et al. [1]. ITD/ILD combination were corresponding to one from 40 possible positions in horizontal plane in range from -70.2° to 70.2° with spacing 3.6°. Positions from -45° to 45° were also target positions, the rest were non-target only (Figure 3). For the whole VE part of the experiment subject sat in front of the computer, with headphones on, in double-walled soundproof booth with Oculus Development Kit 2 headset, which displayed virtual room made of black-white stripes (Figure 4). Orientation of the head was monitored by the sensor on the top of the monitor. The current position of head was represented by a yellow triangle. Only left-right movements of the head were relevant, other were ignored. 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.

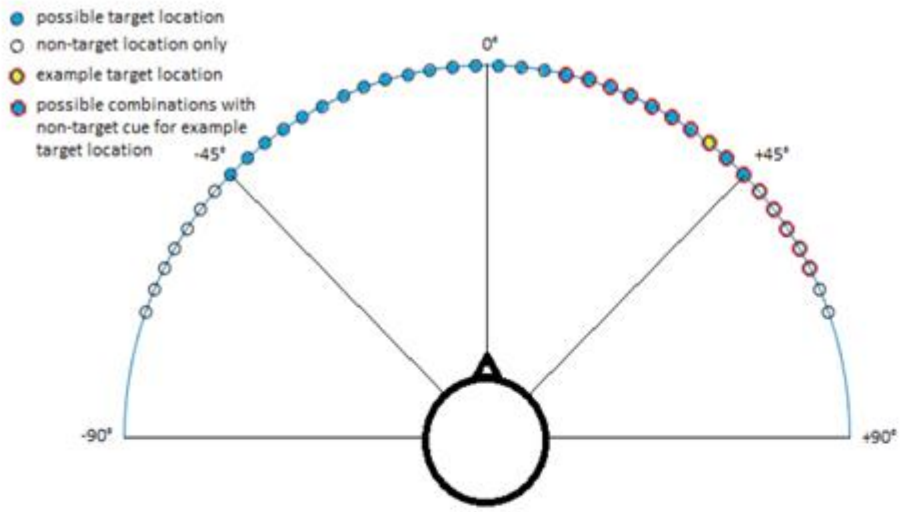

Figure 3: Design of VE part of the experiment from study [2].

Figure 4: Subject in VE during testing.

3.4 Experimental procedure

3.4.1 VE and RE pretests

First, a pre-training and pretest was done in a virtual environment. Each trial of the pretest started by the subject orienting his/her head straight ahead with Oculus headset and headphones on. After pressing a button on the keyboard, the trial continued by a stimulus presentation. The task of the subject was to indicate the perceived position of the received sound in horizontal plane by turning his/her head towards it and pressing the enter key on the keyboard. Then subject returned head back to the starting position at 0°, with same elevation as he/she started, and another trial followed. A total number of trials was 446 and after each 150 trials the subject could have taken a short rest.

The VE pretest was preceded by a short pre-training, which was similar to pretest but visual feedback, showing position of incoming sound, was provided and subject needed to confirm position of the feedback by turning his/her head towards it. In pre-training there were only 80 trials and its main purpose was to get used to the virtual environment.

The VE pretest was followed by pretest in RE. In the beginning of each trial the subject faced 0° azimuth, after pressing the enter button on the keyboard, the sound was played and his/her task was to turn a head towards the position of sound and confirm this position by pressing the enter button on the keyboard. After that the subject returned head back to 0° azimuth and another trial followed. 396 trials were played in total with 3 optional short breaks.

3.4.2 Training

Training was performed in RE and consisted of 3 sessions, each performed on a separate day. First training was on the next day after pretest for all subjects. Trainings were conducted on three consecutive days, only one subject from LF group had three-day gap between second and third training. Procedure was similar to the one in pretest. On each trial the subjects faced the 0° azimuth and after they pressed “enter” the sound played once, subjects were instructed to turn a head to the perceived position of sound source and confirm this position by pressing “enter”. After confirming the position, the visual feedback in the shape of green triangle was provided at the position of high frequency component for the HF and HFI groups and at the position of low frequency component for the LF group, and simultaneously the repeated sound was played from the same position as in trial. Subject‘s task was to turn a head to the position of the visual feedback, confirm this position by pressing “enter”, return back to 0° azimuth and next trial followed (Figure 5). In training were same 2-channel and 4-channel trials as in pretest/posttest but their number was doubled. Number of trials in each training session was 456, a subject could take short break after every 57 trials, so there was total of 8 breaks. Each session took approximately 1 hour.

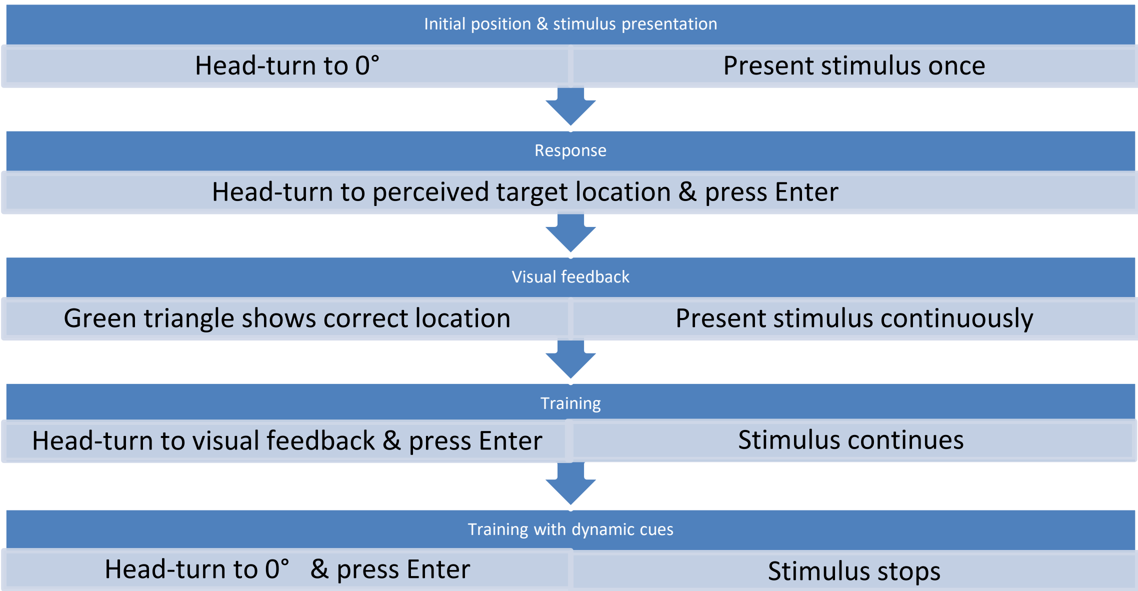

Figure 5: Training in RE

3.4.3 Posttest

On the last training day, the training session was immediately followed by a posttest, which was almost identical to pretest with two differences. First difference was that posttest was done firstly in RE and after that in VE. The second one was that in VE part there was no pre-training.

3.5 Analysis in RE

For modeling was used multiple linear regression model and analysis were done for each azimuth separately. This type of analysis gives us weights without compression. Compression is an effect where subjects at lateral positions have a tendency to localize sound source closer to the central position. If we simply compute difference between position of HF and LF component, the result would be affected by the compression. By using linear regression, we can filter compression into an additional parameter.

Formula (1) shows a multiple regression model for 2-channel and 4-channel data and formula (2) shows computation of relative weight of high-frequency to low-frequency component.

$$R(\alpha,\ \Delta_{LF},\ \Delta_{HF}) = k_{LF}(\alpha) * \Delta_{LF} + k_{HF}(\alpha) * \Delta_{HF} + Q(\alpha) \qquad (1)$$

$$w_{HL} = \frac{atan\left(\frac{k_{LF}(\alpha)}{k_{HF}(\alpha)}\right)}{90} \qquad (2)$$

R is a subject's response azimuth, recorded by headtracker in a trial with LF and HF components at positions α + Δ_{LF} and α + Δ_{HF}, respectively (α is between -56.25° and 56.25° with 11.25° steps). k_{LF}, k_{HF} and Q are estimated parameters of a regression model, where k_{LF} and k_{HF} are regression slopes (determining the weights of the frequency components) and Q is the overall bias for azimuth α, where compression is filtered. w_{HL} is estimated weight of HF vs. LF components, where 1 means that subjects orient only according to HF component and 0 that subjects orient only according to LF component. For all further analysis in RE using model (1) we will be considering only w_{HL} and change in weights of spectral components for all groups will be expressed in this weight. All errorbars are standard error of the mean (3).

$$SEM = \frac{\delta}{\sqrt{n}} \qquad (3)$$

Where δ is a standard deviation and n is a sample size.

Modeling was done separately on big separations and small separations to achieve same leverage for both types of separations, since model would give more leverage to big separations. We are showing analysis for average of big and small separations, but also separately for big separations and small separations.

All the raw data (Figure 6) for targets away from the midline (i.e., not at 0°) were collapsed from left to right side and averaged before fitting over y-axis. For example, response to the trial where the HF part of the stimuli was playing from azimuth -22.5° and LF part from 11.25° relative to HF position was averaged with the response to the trial where HF part of the stimuli was at the position 22.5° and LF part was at the position -11.25° relative to HF position. This approach gives us smoother raw data and makes model more accurate, assuming that the perception is left-right symmetric. Azimuths for which we had data after collapsing were 0°,11.25°,22.5°,33.75°,45° and 56.25°. However, since 56.25° was not target azimuth for any stimuli and 45° was not target azimuth for 4-channel stimuli we did not include them into analysis. All analyses in RE were then done only on 4 azimuths: 0°,11.25°,22.5° and 33.75°. For the evaluation of results, we used the analysis of variances (ANOVA).

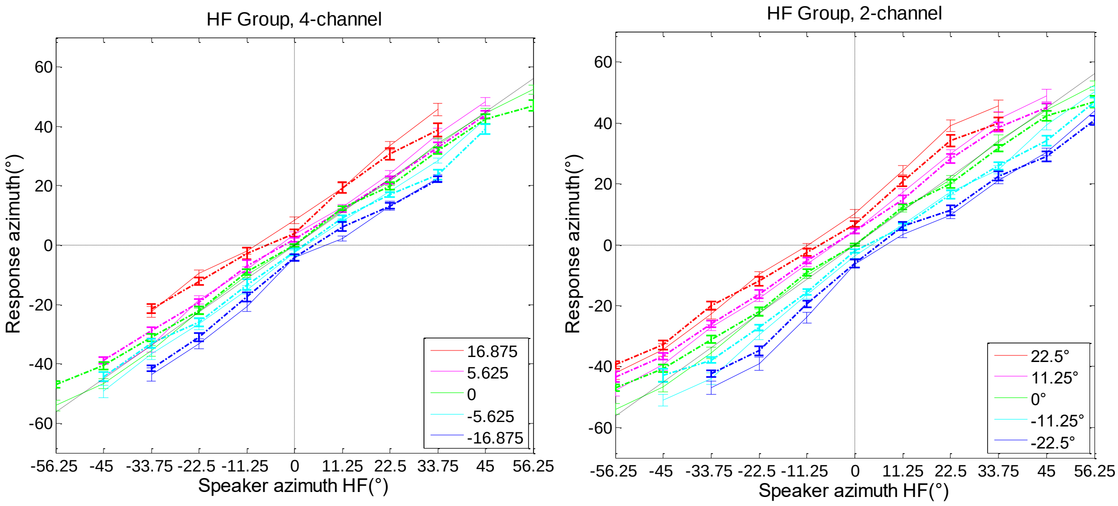

Figure 6: Example of response azimuth for HF group for 4-channel and 2 -channel data from RE as a function of position of HF loudspeaker. Continues line is pretest and dashed line is the posttest. Each line represents trials with different spacing of loudspeakers. Spacing is in the legend.

In trials with mid-frequency we had only one type of separations, since the loudspeakers were one position apart in each trial and therefore we computed bias to high frequency part of the stimuli from difference of response azimuth in pretest and response azimuth in posttest.

For each group and each azimuth of loudspeaker we computed median of change of weight from pretest to posttest and distract obtained value from same weight change for each subject. In Figure 7 is shown boxplot of computed values. Boxplot is using interquartile range analysis where are data divided into quartiles (Q1,Q2,Q3,Q4) and data points exceed Q3 + 1.5*(Q3 – Q1) are considered outliers. We can see outlier in HF group, who was excluded from further analysis. Final number of subjects included in weights analysis for RE was 12 for HF group, 12 for LF group and 11 for HFI group.

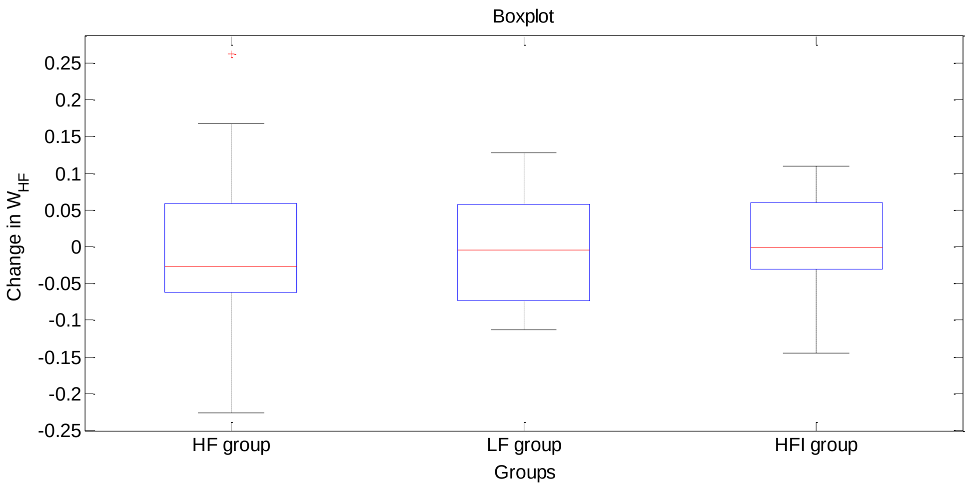

Figure 7: Boxplot of distance of pretest-posttest difference in weight of high-component from the median of pretest-posttest difference weights for all groups, we can see outlier in HF group (red cross).

3.6 Analysis in VE

In VE we used the same linear regression model as in RE:

$$R(\alpha, \Delta_{ITD}, \Delta_{ILD}) = k_{ITD}(\alpha) * \Delta_{ITD} + k_{ILD}(\alpha) * \Delta_{ILD} + Q(\alpha) \qquad (4)$$

$$w_{LT} = \frac{atan\left(\frac{k_{ILD}(\alpha)}{k_{ITD}(\alpha)}\right)}{90} \qquad (5)$$

R is a subject‘s response azimuth, recorded by oculus, in a trial with ITD and ILD components at positions $\alpha + \Delta_{ITD}$ and $\alpha + \Delta_{ILD}$, respectively (α is between -56.25° and 56.25° with 11.25° steps). k_{ITD}, k_{ILD} and Q are approximated parameters of a regression model, where k_{ITD} and k_{ILD} are regression slopes (determining the weights of the ITD and ILD, respectively) and Q is the overall bias for azimuth α, where compression is filtered. w_{LT} is estimated weight of ILD to ITD components. For all further analyses in VE using model (4) we will be considering only w_{LT}, where 1 means that subjects orient only according to ILD and 0 that subjects orient only according to ITD, and change in weights for all groups will be expressed in this weight, which corresponds to w_{HL} in RE. All errorbars are standard error of the mean (6).

$$SEM = \frac{\delta}{\sqrt{n}} \qquad (6)$$

Where δ is a standard deviation and n is a sample size.

For more statistical power and for reducing the noise, we collapsed the data over y-axis as in RE, assuming that perception is left-right symmetric. After collapsing we had data on 13 azimuths, from 1.8° to 45° with 3.6° step. For evaluation of results we used the analysis of variances (ANOVA).

For HFI group were analysis made only on 9 subjects, because for 2 subjects were data disrupted due to technical issues.

4 Results

4.1 Real environment

4.1.1 Results in real environment for mean of big and small separations

We hypothesized that relative weight of HF component to LF component from pretest to posttest will increase for HF and HFI group and decrease for LF group as the result of training procedure. Since HFI group was informed about spectral composition of stimuli, and instructed to follow them, we expect that increase in weighting will be stronger for HFI group than for HF group.

In the figures 8,9,10 is W_{HL} as a function of target azimuth, computed from averaged parameters k_{LF} and k_{HF} for LF, HF and HFI group respectively. Mixed ANOVA with factors location (0°, 11.25°, 22.5°,33.75°) , time (pretest, posttest) and group (HF, LF, HFI) showed significant effect of location ($F(3,96) = 54.49$, $p<0.01$) and time($F(1,32) = 6.44$, $p<0.05$) and significant interaction time X group ($F(2,32) = 10.30$, $p<0.01$). Partial ANOVA with only HFI and HF group as a factor showed significant effect of location($F(3,63) = 47.38$, $p<0.01$) and time($F(1,21) = 16.77$,$p<0.01$) but no significant interaction. Partial ANOVA for HFI group showed significant effect of location($F(3,30) = 12.12$, $p<0.01$) and time($F(1,10) = 13.87$, $p<0.01$), for HF group showed significant effect of location($F(3,33) = 37.57$, $p<0.01$) and time($F(1,11) = 8.97$,$p<0.05$) and for LF group significant effect of location($F(3,33) = 13.31$, $p<0.01$) and time($F(1,11) = 5.86$, $p<0.05$).

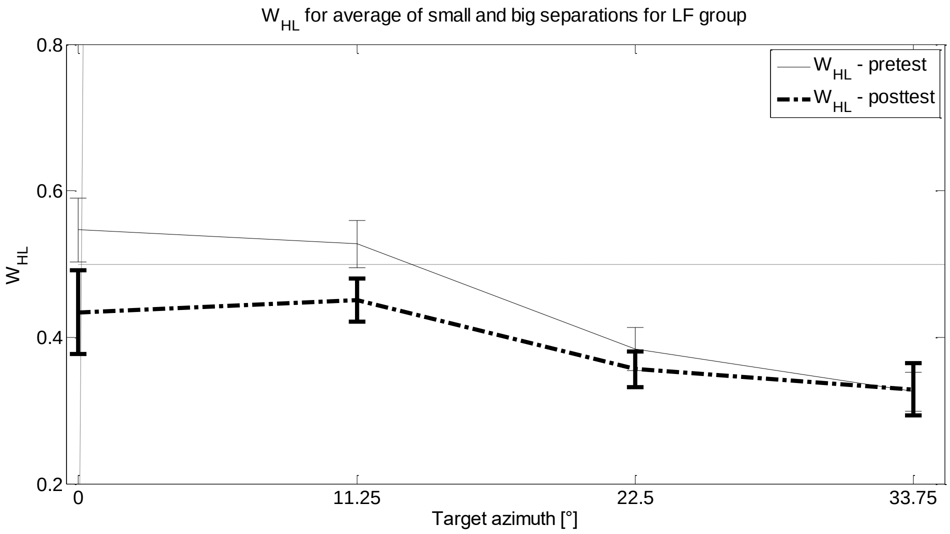

Figure 8: W_{HL} in pretest (thin line) and postest (thick line) as a function of target azimuth for mean of small and big separations for LF group. Data are left-right collapsed. Errorbars are standard error of the mean.

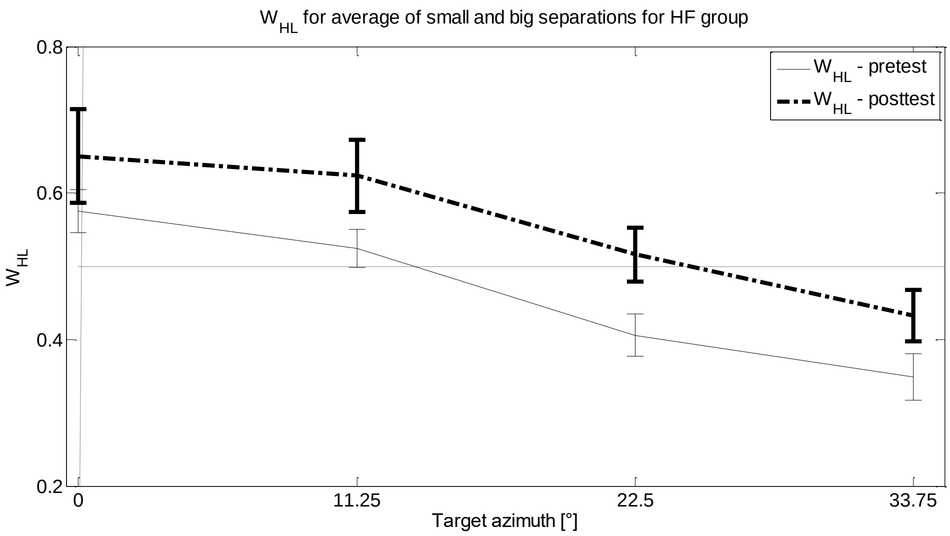

Figure 9: W_{HL} in pretest (thin line) and postest (thick line) as a function of target azimuth for mean of small and big separations for HF group. Data are left-right collapsed. Errorbars are standard error of the mean.

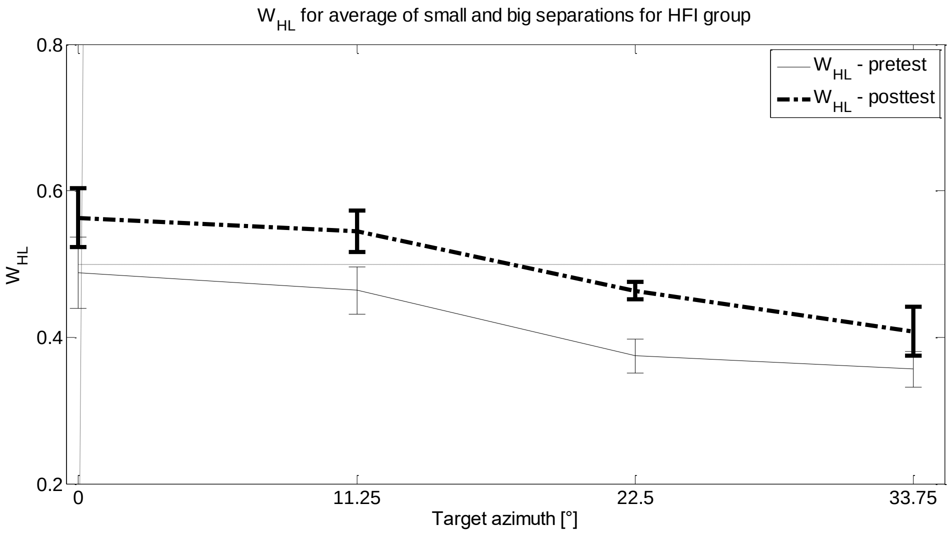

Figure 10: W_{HL} in pretest (thin line) and postest (thick line) as a function of target azimuth for mean of small and big separations for HFI group. Data are left-right collapsed. Errorbars are standard error of the mean.

Significant interaction time X group shows that the change in weighting depends on the group which differs in training. We observe a change in weighting in direction as we stated in hypothesis, increase for HF and HFI group and decrease for LF group (see Figure 11). For all groups there was a difference in weights from pretest to posttest significant, meaning that subjects reinforced a trained spectral component. Hypothesis that there will be a significant difference between HF and HFI group in terms of the reweighting was not confirmed.

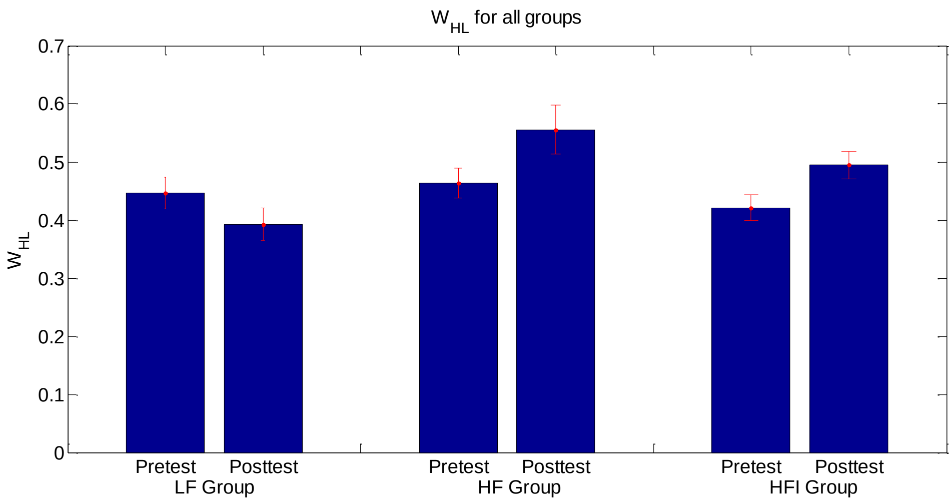

Figure 11: Barplots of W_{HL} for all groups in pretest and posttest, averaged across locations. Errorbars are standards error of mean.

W_{HL} in our model was computed from k_{LF} and k_{HF} parameters. We expect decrease of k_{LF} component for HF and HFI group and increase for LF group. k_{HF} parameter is expected to increase in HF and HFI group and decrease in LF group. Which change will contribute more to reweighting is not clear.

In the figures 12,13,14 are k_{LF} and k_{HF} parameters computed as average of k_{LF} and k_{HF} from small and big separations for LF, HF and HFI group respectively. Mixed ANOVA for k_{LF} parameter with factors location (0°, 11.25°, 22.5°, 33.75°), time (pretest, posttest) and group (LF,HF,HFI) showed significant effect of location($F(3,96) = 41.37$, $p<0.01$), time($F(1,32) = 11.75$, $p<0.01$) and group ($F(2,32) = 14.30$, $p<0.01$) and significant interaction time X group ($F(2,32) = 13.43$, $p<0.01$) and location X time ($F(3,96) = 3.48$, $p<0.05$). Partial ANOVA with only HFI and HF group, showed significant effect of location($F(3,63) = 28.02$, $p<0.01$), time($F(1,21) = 25.92$, $p<0.01$) and group ($F(1,21) = 16.25$, $p<0.01$) and significant interaction time X group ($F(1,21) = 5.36$, $p<0.05$). Partial ANOVA for HFI group showed significant effect of location($F(3,30) = 10.44$, $p<0.01$), for HF group significant effect of location ($F(3,33) = 17.83$, $p<0.01$) and time($F(1,11) = 26.18$, $p<0.01$) and for LF group significant effect of location ($F(3,33) = 14.11$, $p<0.01$) and significant interaction location X time ($F(3,33) = 4.12$, $p<0.05$).

Mixed ANOVA for k_{HF} parameter with same factors as for k_{LF} showed significant effect of group ($F(2,32) = 14.80$, $p<0.01$), location ($F(3,96) = 16.02$, $p<0.01$) and significant interaction time X group ($F(2,32) = 3.83$,$p<0.05$). Partial ANOVA with only HFI and HF group as a factor showed significant effect of group ($F(1,21) = 29.85$, $p<0.01$), location($F(3,63) = 9.08$, $p<0.01$) and time ($F(1, 21) = 6.31$, $p<0.05$). Partial ANOVA for HFI group showed significant effect of time($F(1,10) = 8.49$, $p<0.05$), for HF group significant effect of location ($F(3,33) = 7.07$, $p<0.01$) and for LF group significant effect of location($F(3,33) = 7.73$, $p<0.01$).

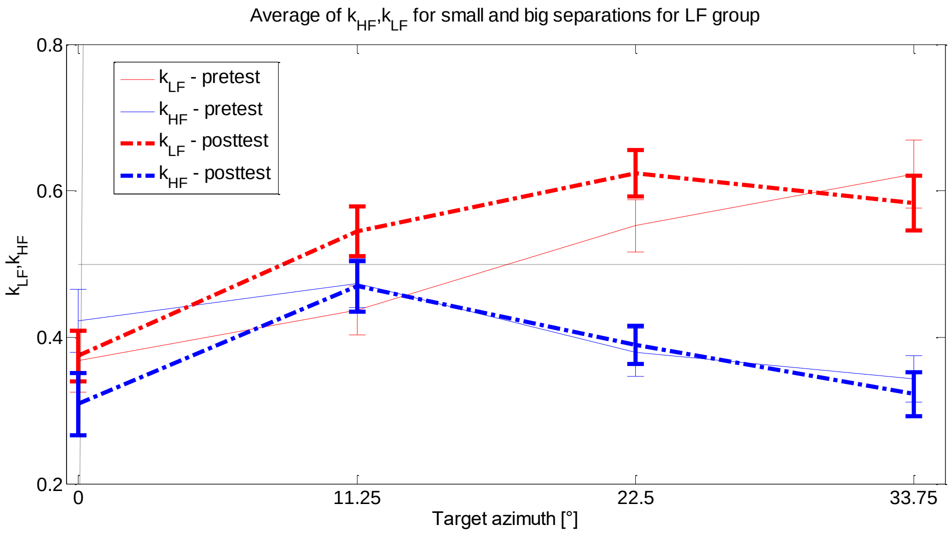

Figure 12: Mean of k_{LF} and k_{HF} for small separations and big separations in pretest (thin line) and postest (thick line) as a function of target azimuth for LF group. Data are left-right collapsed. Errorbars are standard error of the mean.

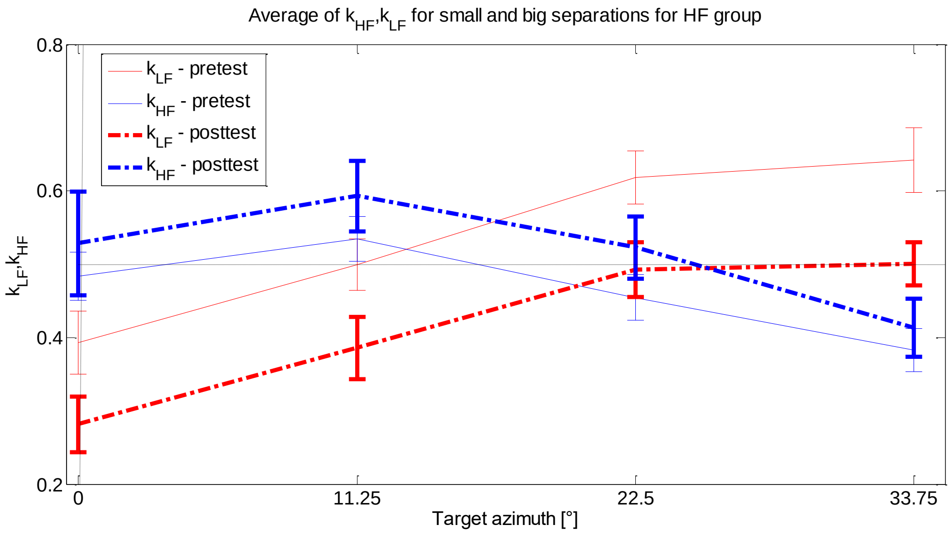

Figure 13: Mean of k_{HF} and k_{LF} for small separations and big separations in pretest (thin line) and postest (thick line) as a function of target azimuth for HF group. Data are left-right collapsed. Errorbars are standard error of the mean.

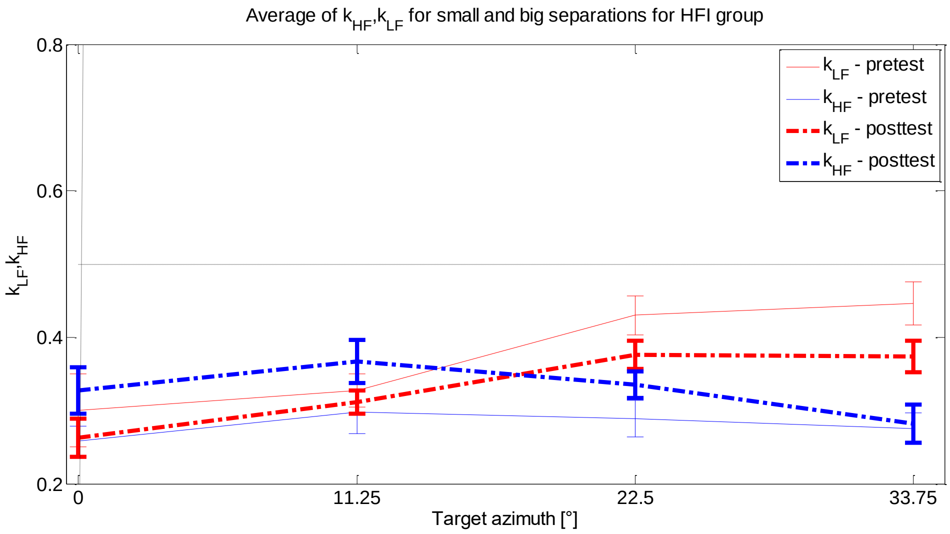

Figure 14: Mean of k_{LF} and k_{HF} for small separations and big separations in pretest (thin line) and postest (thick line) as a function of target azimuth for HFI group. Data are left-right collapsed. Errorbars are standard error of the mean.

As expected in HF and HFI group k_{LF} parameter decreased and k_{HF} parameter increased for all locations, while in LF group k_{LF} parameter increased on all azimuth except most lateral one, but k_{HF} parameter decreased only for central azimuth. For change of weighting was thus more prominent decrease of k_{LF} parameter.

4.1.2 Results in real environment for big separations

To achieve same leverage for both, big and small separations, we applied regression model on big and small separations separately. In this chapter we are going to examine how weight of big separations changed from pretest to posttest in all three groups.

Figures 15,16,17 display W_{HL} as a function of target azimuth for LF group, HF group and HFI group, respectively. We ran ANOVAs with factors location (0°, 11.25°, 22.5°,33.75°), time (pretest, posttest) and group (HF, LF, HFI). Mixed ANOVA with all groups as a factor showed significant effect of location ($F(3,96) = 34.51$, $p<0.01$) and time ($F(1,32) = 15.89$,$p<0.01$) and significant interaction time X group ($F(2,32) = 8.78$, $p<0.01$). Partial ANOVA with only HF and HFI group showed significant effect of location($F(3,63) = 25.19$, $p<0.01$) and time ($F(1,21) = 29.11$,$p<0.01$). Partial ANOVA for HFI group showed significant effect of time($F(1,10) = 23.08$, $p<0.01$) and location ($F(3, 30) = 8.41$, $p<0.01$), for HF group showed significant effect of time($F(1,11) = 12.29$, $p<0.01$) and location ($F(3, 33) = 19.37$, $p<0.01$) and for LF group showed significant effect of location($F(3,33) = 10.58$, $p<0.01$).

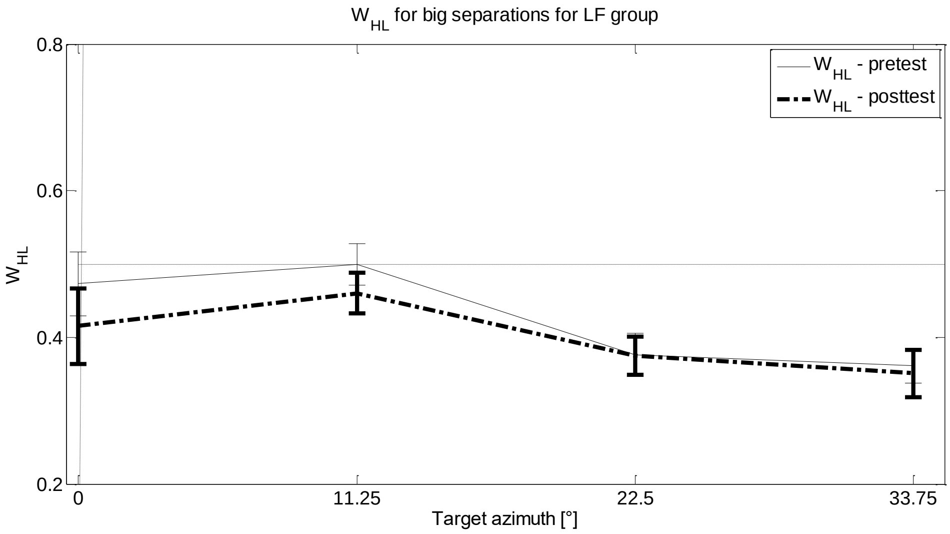

Figure 15: W_{HL} in pretest (thin line) and postest (thick line) as a function of target azimuth for big separations for LF group. Data are left-right collapsed. Errorbars are standard error of the mean.

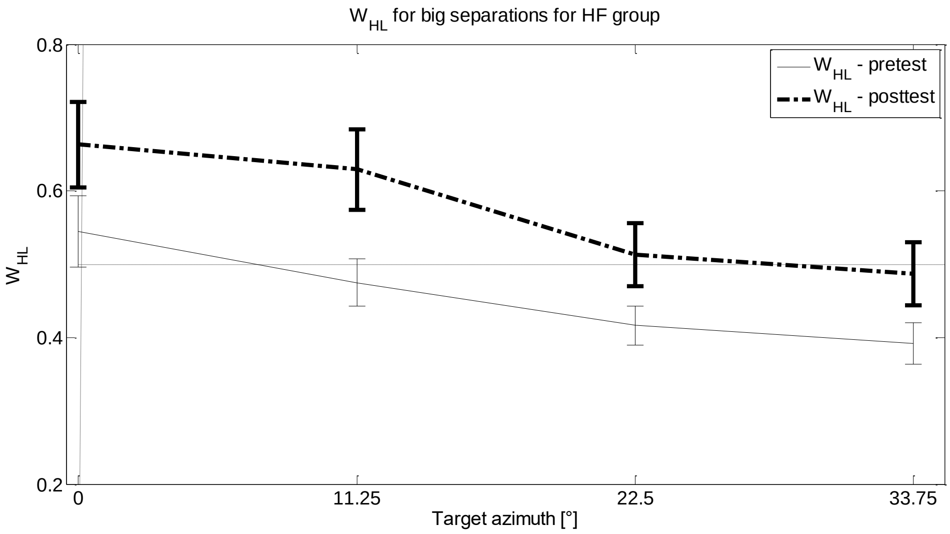

Figure 16: W_{HL} in pretest (thin line) and postest (thick line) as a function of target azimuth for big separations for HF group. Data are left-right collapsed. Errorbars are standard error of the mean.

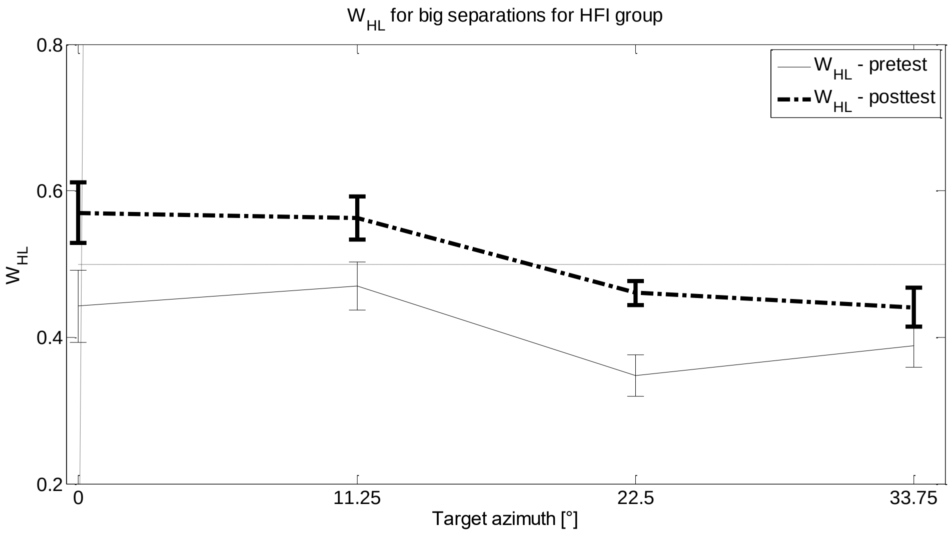

Figure 17: W_{HL} in pretest (thin line) and postest (thick line) as a function of target azimuth for big separations for HFI group. Data are left-right collapsed. Errorbars are standard error of the mean.

All three groups changed relative weight of HF component to LF component in expected direction. However only for HF and HFI group was this change significant, and there was no significant difference between HF and HFI group. This suggest that for big separations is reweighting of high frequencies easier.

In the figures 18,19, and 20 is shown change in parameters k_{LF} and k_{HF} from pretest to posttest for big separations for LF group, HF group and HFI group, respectively. We ran ANOVAs for k_{LF} and k_{HF} parameters with factors time (pretest, posttest), location (0°, 11.25°, 22.5°, 33.75°), and group (LF, HF, HFI). For k_{LF} mixed ANOVA showed significant effect of location ($F(3, 96) = 51.28$, $p<0.01$) and time ($F(1,32) = 14.03$, $p<0.01$) and significant interaction time X group ($F(2,32) = 8.24$, $p<0.01$). Partial ANOVA with only HF and HFI group showed significant effect of location ($F(3, 63) = 35.48$, $p<0.01$) and time ($F(1,21) = 21.89$, $p<0.01$), but no significant interaction. Partial ANOVA for HFI group shows only significant effect of location ($F(3, 30) = 11.61$, $p<0.01$), for HF group significant effect of location ($F(3,33) = 25.88$, $p<0.01$) and time ($F(1,11) = 20.51$, $p<0.01$) and for LF group significant effect of location ($F(3,33) = 15.87$, $p<0.01$).

For k_{HF} parameter mixed ANOVA showed significant effect of location ($F(3, 96) = 10.30$, $p<0.01$), time ($F(1,32) = 9.99$, $p<0.01$), group ($F(2, 32) = 4.01$, $p<0.05$) and significant interaction time X group ($F(2,32) = 3.75$, $p<0.05$). Partial ANOVA with only HF and HFI group showed significant effect of time ($F(1, 21) = 14.27$, $p<0.01$) and location ($F(3,63) = 4.77$, $p<0.05$), and significant interaction location X time (F(3,63) =

3.76, $p<0.05$) but not interaction time X group. Partial ANOVA for HFI group yielded significant effect of time($F(1,10) = 16.52$, $p<0.01$), no significant effect for HF group and for LF group significant effect of location($F(3,33) = 6.62$, $p<0.05$).

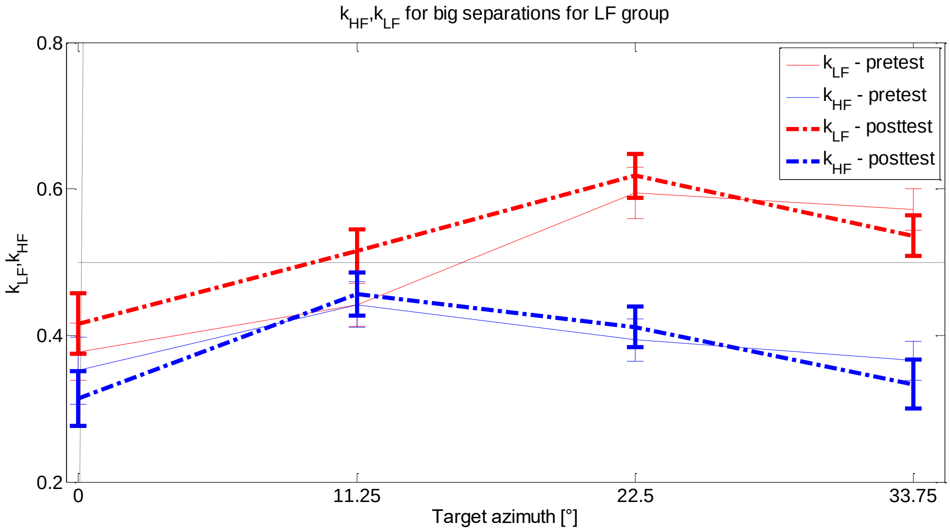

Figure 18: Parameters k_{LF} and k_{HF} in pretest (thin line) and postest (thick line) as a function of target azimuth for big separations for LF group. Data are left-right collapsed. Errorbars are standard error of the mean.

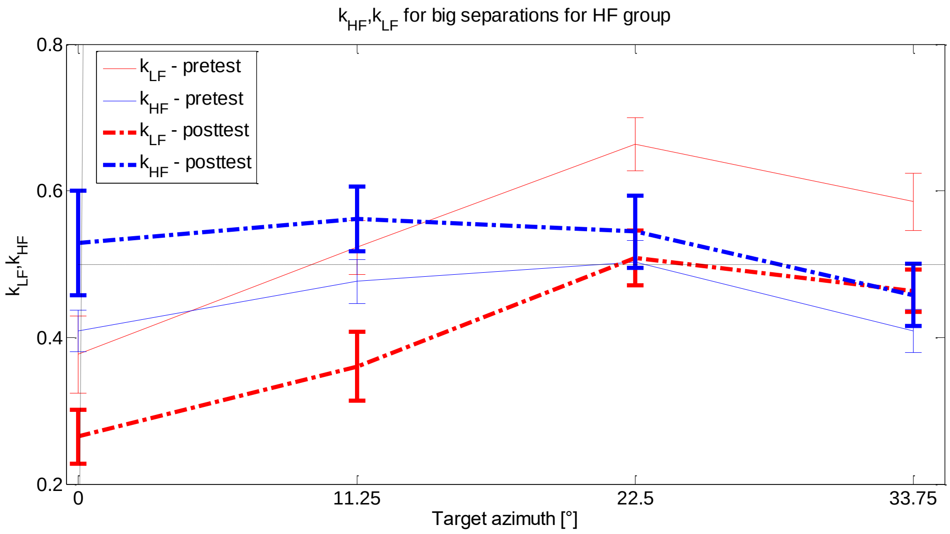

Figure 19 : Parameters k_{LF} and k_{HF} in pretest (thin line) and postest (thick line) as a function of target azimuth for big separations for HF group. Data are left-right collapsed. Errorbars are standard error of the mean.

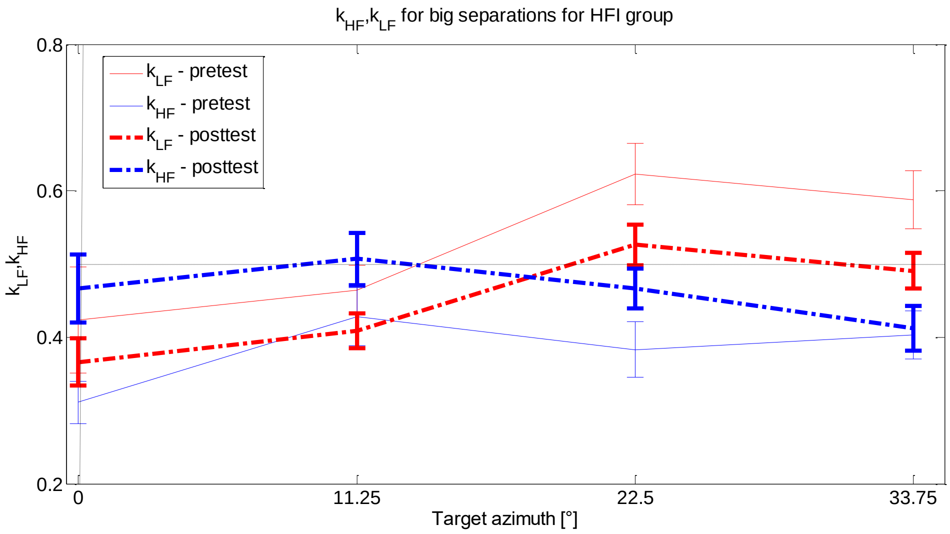

Figure 20: Parameters k_{LF} and k_{HF} in pretest (thin line) and postest (thick line) as a function of target azimuth for big separations for HFI group. Data are left-right collapsed. Errorbars are standard error of the mean.

Similar as it was for mean of big and small separations, for big separations also both parameters k_{LF} and k_{HF} changed in expected direction and the change of k_{LF} parameter was more prominent. As expected, we observe rise of k_{LF} from pretest to posttest on 3 central azimuths in LF group and decline on all 4 azimuths in HF and HFI group.

4.1.3 Results in real environment for small separations

For small separations we also expect increase of relative weight of HF component to LF component for HF and HFI group and decrease for LF group.

In the figures 21,22,23 we can see W_{HL} for small separations as function of target azimuth for LF, HF and HFI group, respectively. Mixed ANOVA with factors location (0°, 11.25°, 22.5°, 33.75°), time (pretest, posttest) and group (LF,HF,HFI) showed significant effect of location ($F(3,96) = 43.94$, $p<0.01$) and significant interaction time X group ($F(2,32) = 5.04$, $p<0.05$). Partial ANOVA with only HF and HFI group showed significant effect of location ($F(3,63)$, $p<0.01$) and time ($F(1,21) = 4.43$, $p<0.05$) but no significant interaction. Partial ANOVA for HFI group showed significant effect of location ($F(3,30) = 10.60$, $p<0.01$), for HF group we observe significant effect of location ($F(3,33) = 33.70$, $p<0.01$) and for LF group ANOVA yield significant effect of location($F(3,33) = 10.47$, $p<0.01$) and time($F(1,11) = 5.90$, $p<0.05$).

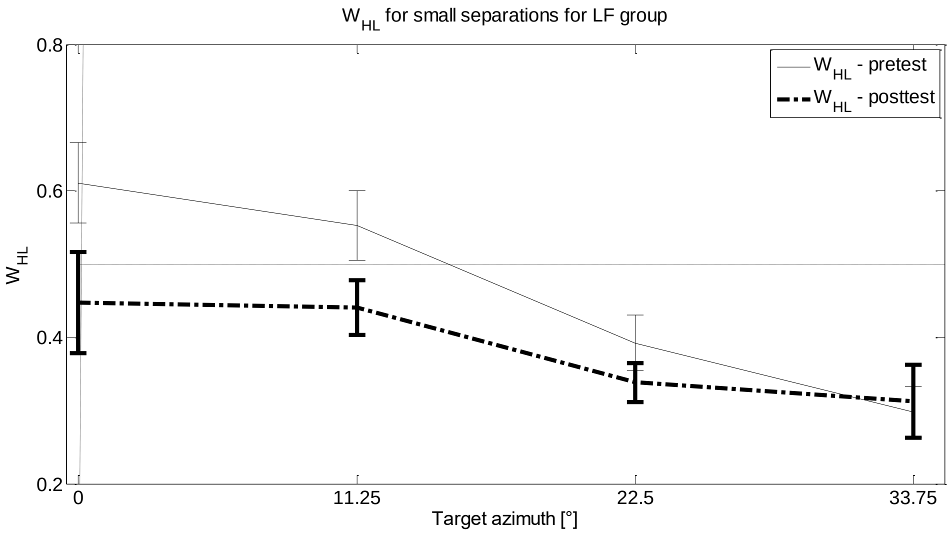

Figure 21: W_{HL} in pretest (thin line) and postest (thick line) as a function of target azimuth for small separations for LF group. Data are left-right collapsed. Errorbars are standard error of the mean.

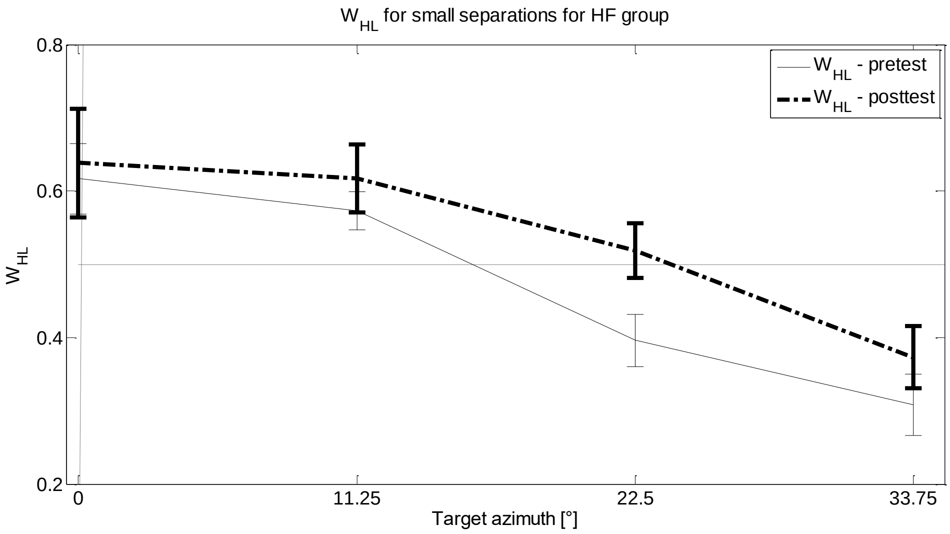

Figure 22: W_{HL} in pretest (thin line) and postest (thick line) as a function of target azimuth for small separations for HF group. Data are left-right collapsed. Errorbars are standard error of the mean.

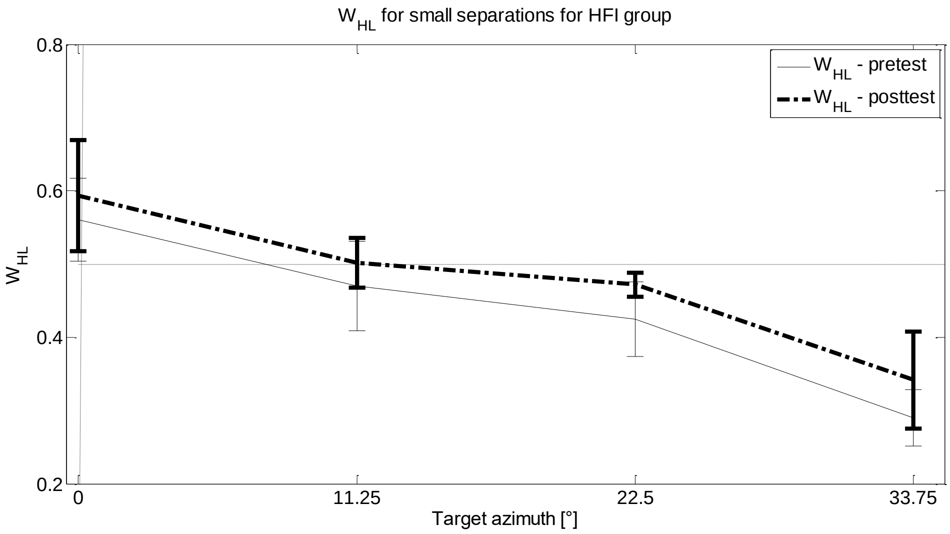

Figure 23: W_{HL} in pretest (thin line) and postest (thick line) as a function of target azimuth for small separations for HFI group. Data are left-right collapsed. Errorbars are standard error of the mean.

We observe a change in weighting in expected direction for all groups however, only change in LF group was significant. No significant difference was observed between HF and HFI group.

In the figures 24,25,26 we can see analysis of k_{LF} and k_{HF} parameters for small separations for LF group, HF group and HFI group, respectively. We ran same ANOVAs as for big separations, with same factors (0°, 11.25°, 22.5°, 33.75°), time (pretest, posttest) and group (LF,HF,HFI). Mixed ANOVA for k_{LF} parameter showed significant effect of group ($F(2,32) = 55.45$, $p<0.01$) and location ($F(3,96)$, $p<0.01$) and significant interaction time X group ($F(2,32) = 9.88$, $p<0.01$) and location X time ($F(3,96) = 4.19$, $p<0.05$). Partial ANOVA with only HF and HFI group showed significant effect of group ($F(1,21) = 94.85$, $p<0.01$), location($F(3,63) = 15.45$, $p<0.01$) and time($F(1,21) = 12.16$, $p<0.01$). We also got significant interaction time X group ($F(1,21) = 6.98$, $p<0.05$), which was due to overall low weighting of parameters in HFI group. Partial ANOVA for HFI group showed significant effect of location ($F(3,30)$, $p<0.05$), for HF group significant effect of location ($F(3,33) = 10.00$, $p<0.01$) and time ($F(1,11) = 11.47$, $p<0.01$) and for LF group significant effect of location ($F(3,33) = 11.33$, $p<0.01$) and significant interaction location X time ($F(3,33) = 3.43$, $p<0.05$).

For k_{HF} parameter mixed ANOVA on LF, HF and HFI group showed significant effect of group ($F(2,32) = 43.01$, $p<0.01$) and location ($F(3,96) = 16.74$, $p<0.01$) and significant interaction of location X group ($F(6,96) = 2.74$, $p<0.05$) and location X time

(F(3,96) = 3.31 , p<0.05). Partial ANOVA with only two groups HF and HFI showed significant effect of group (F(1,21) = 92.83, p<0.01) and location (F(3,63) = 11.10, p<0.01) and significant interaction location X group (F(3,63) = 5.28 , p<0.01). Partial ANOVA for HFI group showed no main effect, for HF group we got significant effect of location (F(3,33) = 9.67, p<0.01) and for LF group also significant effect of location (F(3,33) = 6.19, p<0.01).

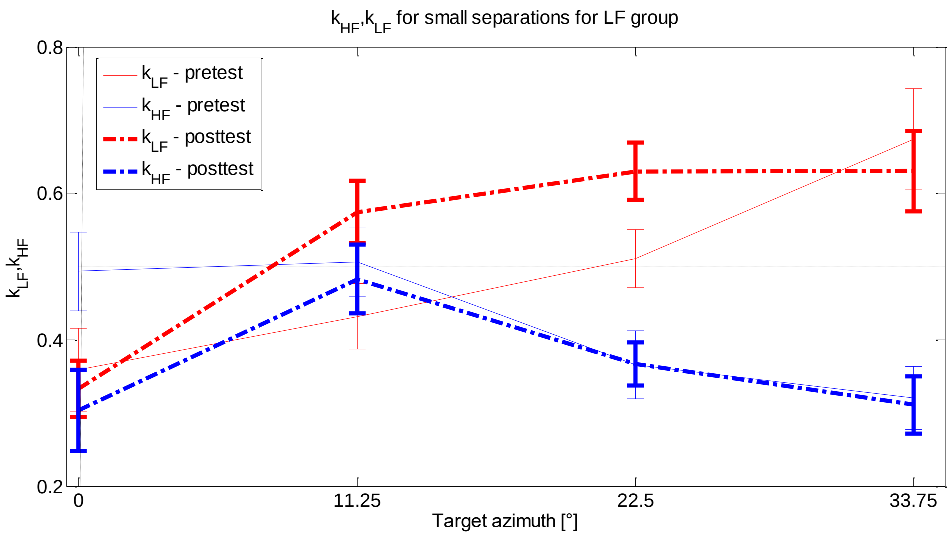

Figure 24 : Parameters k_{LF} and k_{HF} in pretest (thin line) and postest (thick line) as a function of target azimuth for small separations for LF group. Data are left-right collapsed. Errorbars are standard error of the mean.

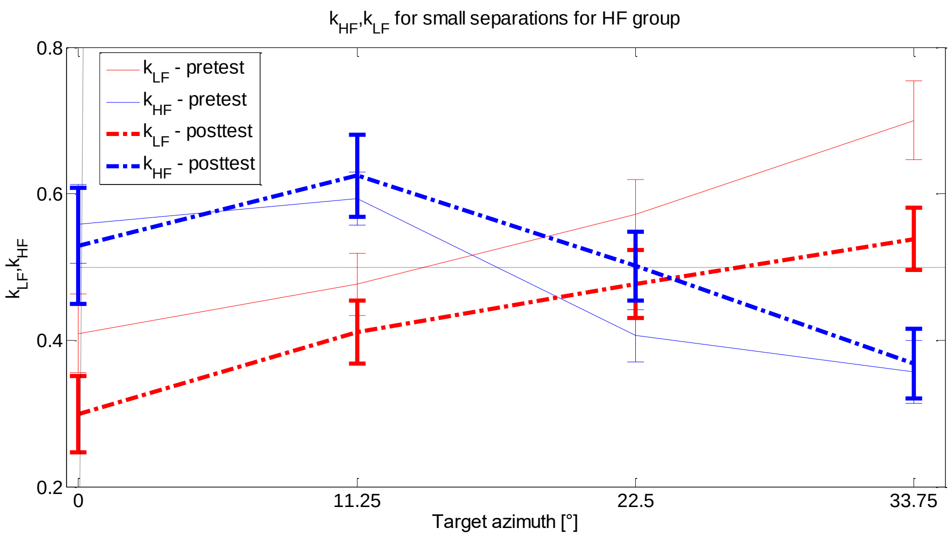

Figure 25: Parameters k_{LF} and k_{HF} in pretest (thin line) and postest (thick line) as a function of target azimuth for small separations for HF group. Data are left-right collapsed. Errorbars are standard error of the mean.

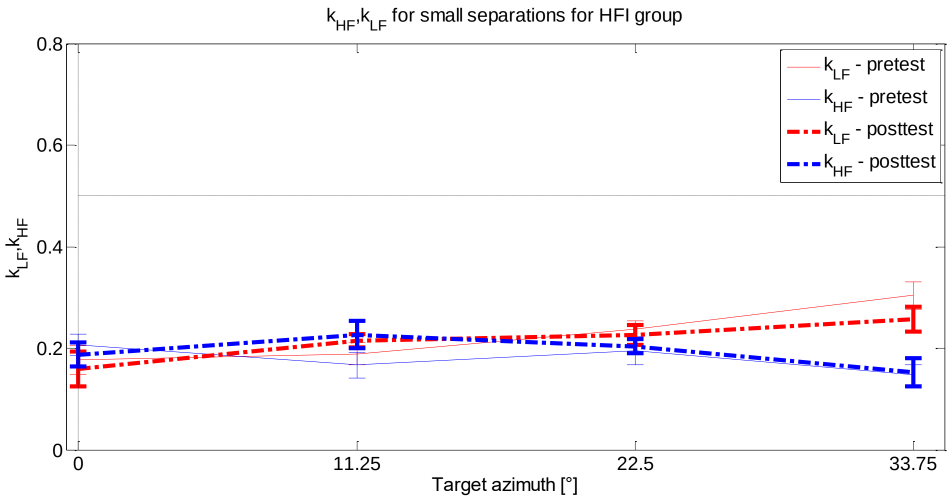

Figure 26: Parameters k_{LF} and k_{HF} in pretest (thin line) and postest (thick line) as a function of target azimuth for small separations for HFI group. Data are left-right collapsed. Errorbars are standard error of the mean.

Change of k_{HF} and k_{LF} parameter for small separations is in accordance with change of parameters in big separations, but here was more significant for LF group.

4.1.4 Training results

A change in weighting was successful for all groups, most probably as an effect of our training. We hypothesize that a change in weighing was gradual and happened between trainings as well as during them. Here we are going to analyze training sessions at each day.

In the figures 27,28,29 we can see development of reweighting for LF, HF and HFI group, respectively. Red points are W_{HL} of pretest and posttest respectively averaged across locations. Magenta points are also relative weights of HF components to LF components from pretest and posttest but computed only on the same number of trials as in training sessions. Blue points are weights in training days divided into halves according to order in which were played trials. First blue point is W_{HL} computed from first half of trials in training session, and second blue point is W_{HL} computed from second half of trials in the same training session. We ran mixed ANOVA on training data with factors day (first, second, third) X half (first,second) X group (LF,HF,HFI) which yield significant interaction day X group ($F(4,62) = 4.91$, $p<0.01$) and significant effect of group ($F(2,31) = 5.69$, $p<0.01$). Mixed ANOVA with factors day (first, second, third) X half (first,second) X group (HF and HFI) showed significant effect of half ($F(1,21) = 7.75$, $p<0.05$) and day ($F(2,42) = 4.42$, $p<0.05$) but no significant effect of group or interaction with group. Partial ANOVA for LF group with factors day (3) and half (2) showed significant effect of day ($F(2,20) = 8.46$, $p<0.01$). Same ANOVA for HF group showed significant effect of half ($F(1,11) = 7.52$, $p<0.05$) and same ANOVA for HFI group did not yield any significant effect.

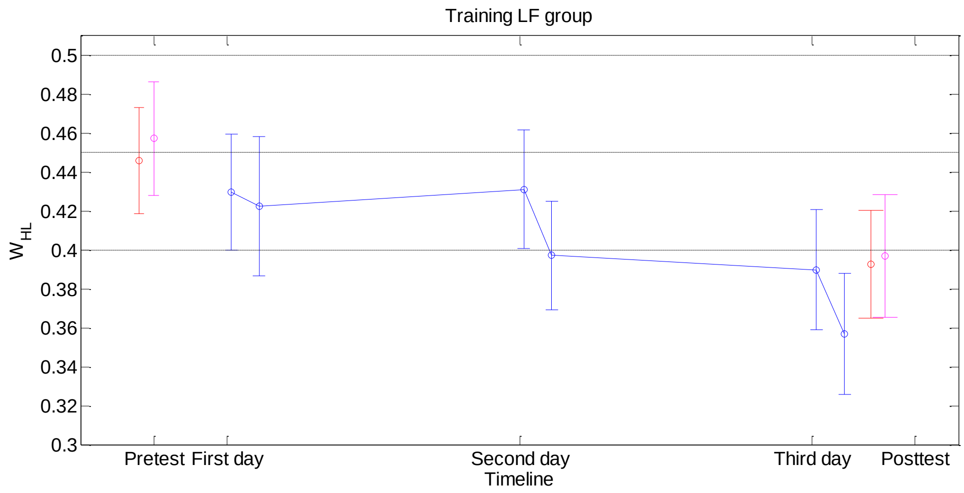

Figure 27: Development of temporal profile of re-weighting during experimental sessions for LF group. Red points are W_{HL} in pretest and posttest. Magenta points are also W_{HL} in pretest and posttest but computed only on same number of trials as were in training sessions. Blue points are W_{HL} during training sessions divided into first and second half. Errorbars are standard error of the mean.

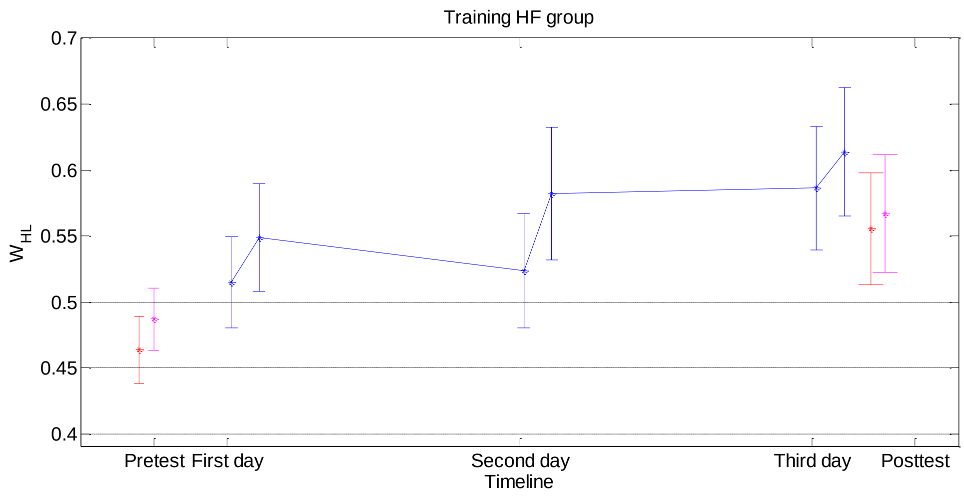

Figure 28: Development of temporal profile of re-weighting during experimental sessions for HF group. Red points are W_{HL} in pretest and posttest. Magenta points are also W_{HL} in pretest and posttest but computed only on same number of trials as were in training sessions. Blue points are W_{HL} during training sessions divided into first and second half. Errorbars are standard error of the mean.

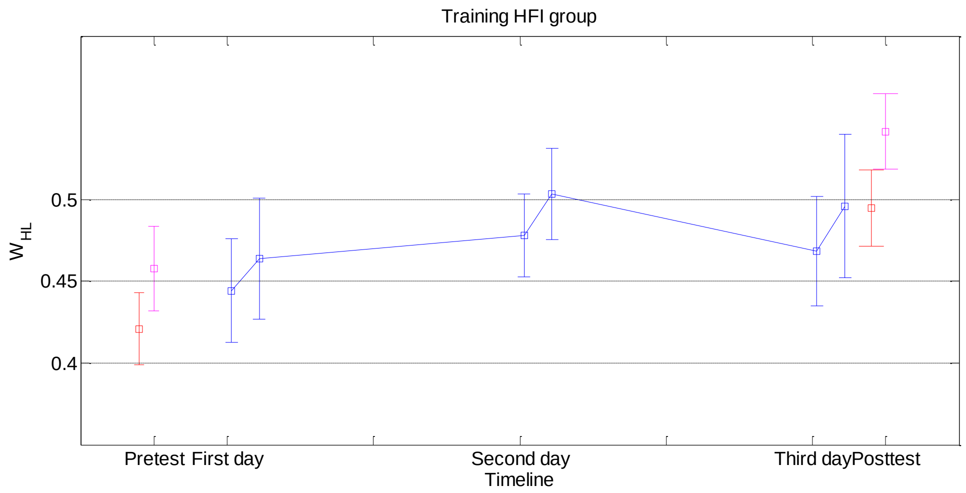

Figure 29: Development of temporal profile of re-weighting during experimental sessions for HFI group. Red points are W_{HL} in pretest and posttest. Magenta points are also W_{HL} in pretest and posttest but computed only on same number of trials as were in training sessions. Blue points are W_{HL} during training sessions divided into first and second half. Errorbars are standard error of the mean.

We can see that in pretest is W_{HL} roughly the same for all groups. For HF group we observe a constant rise of weight during training days, while for HFI group HF weight raised most in first and second training day and then stayed almost same. For LF group we observe a constant decrease of W_{HL} weight as we expected. Gradual change in weights during training sessions and their small change between two following training sessions suggest that observed change in relative HF weight from pretest to posttest is the result of training.

4.1.5 Results for mid-frequency

We observe a change in weighting in trials where stimuli consist of high and low frequency components. Here we examine whether the change in localization also occurs when stimuli consist of either high or low frequency component and mid-frequency component which was not used during training.

In figure 30 we can see the bias of responses to the component with higher frequency in trials where sound consists of mid-frequency and high or low frequency component. These trials were only in pretest and posttest and subjects were not trained on them. Mixed ANOVA with factors group (LF,HF,HFI) X time (pretest, posttest) show a significant interaction time X group ($F(2,32)=3.61$, $p<0.05$). Mixed ANOVA with only HF and HFI group shows also a significant effect time X group ($F(1,21) = 6.48$, $p<0.05$). Partial

ANOVA with factor time (pretest, posttest) yielded significant effect of time only for HF group ($F(1,11) = 12.86$, $p<0.01$) but not for LF or HFI group.

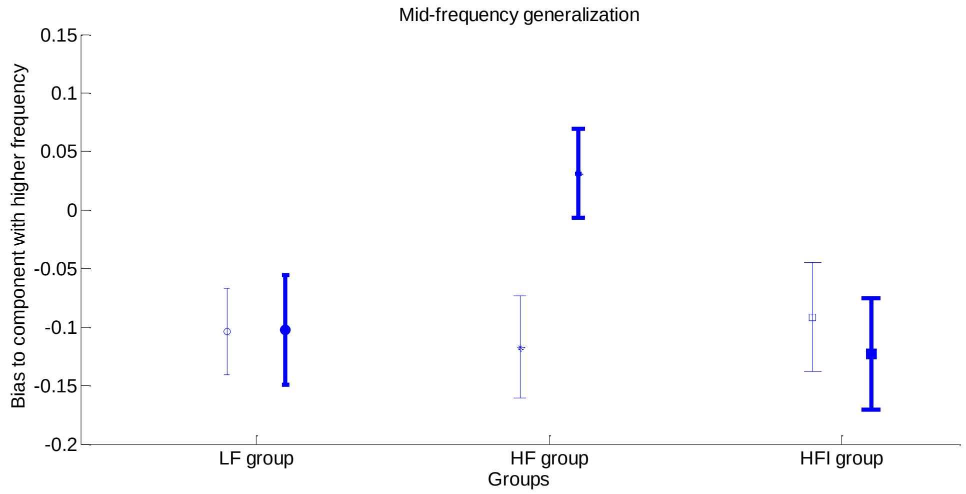

Figure 30: Mean of bias of responses to component with higher frequency from pretest (thin line) and posttest (thick line) for all groups. Errorbars are standard error of the mean.

Generalization to mid-frequency component was successful only for HF group, but not for HFI or LF group. This proves that there is some generalization of the reweighting, but it is fairly weak and only for the stronger version of HF training which was for HF group. HFI training was weaker because the subjects were instructed to follow the HF components already in pretest.

4.1.6 Results in real environment for Q parameter

Our model expelled the effect of compression from weights and concentrated it into parameter Q. Here we examine how parameter Q changed from pretest to posttest for mean of big and small separations.

In the figures 31,32,33 is displayed parameter Q from our regression model for LF ,HF, and HFI group respectively. We excluded from analysis of Q parameter from HF group 3 subjects with the worst performance in pretest because they were distorting pretest data. Mixed ANOVA with factors location (0°, 11.25°, 22.5°, 33.75°), time (pretest, posttest) and group (LF,HF,HFI) showed only significant effect of location ($F(3,87)$, $p<0.01$). Partial ANOVAs with factors location and time showed for LF group significant effect of location ($F(3,33) = 800.87$, $p<0.01$), for HF group significant effect of location ($F(3,24) = 885.51$, $p<0.01$) and for HFI group significant effect of location ($F(3,30) = 766.65$, $p<0.01$).

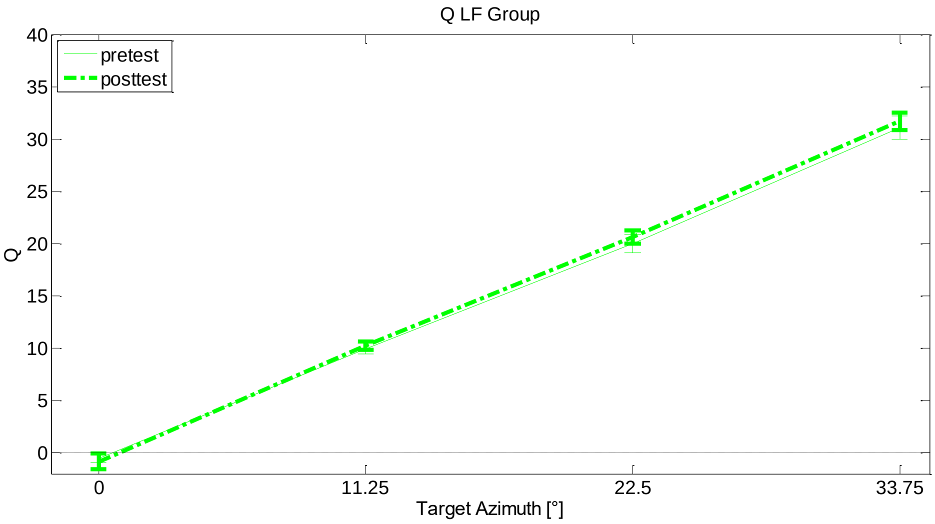

Figure 31: Q parameter as a function of target azimuth for LF group in real environment. Data are left-rigt collapsed. Errorbars are standard error of the mean.

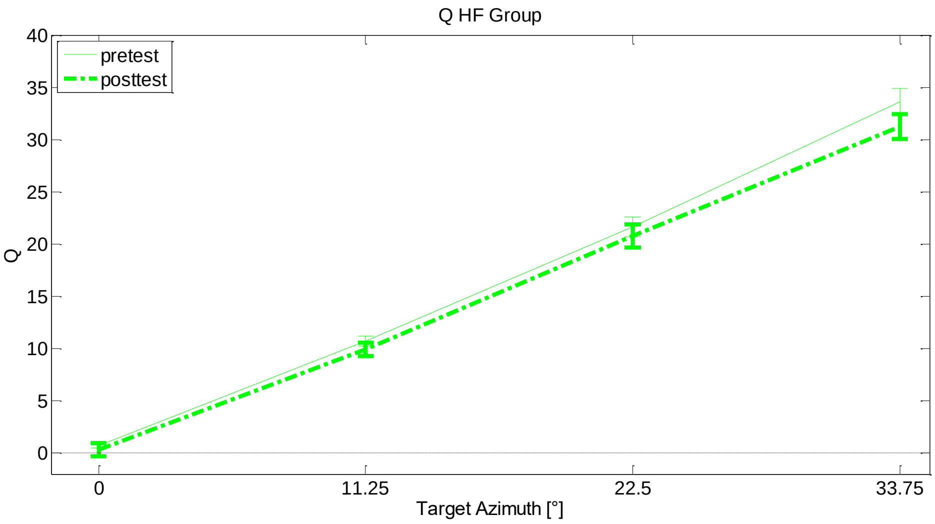

Figure 32: Q parameter as a function of target azimuth for HF group in real environment. Data are left-right collapsed. Errorbars are standard error of the mean.

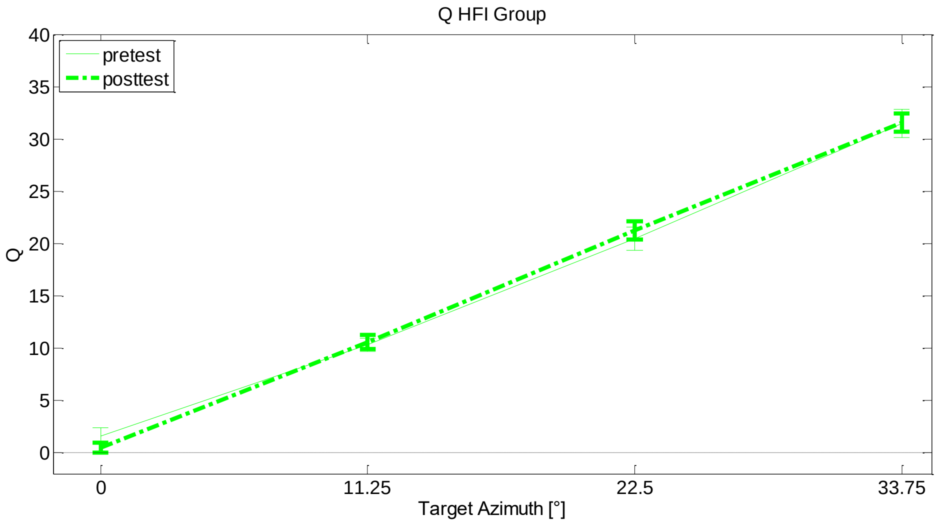

Figure 33: Q parameter as a function of target azimuth for HFI group in real environment. Data are left-right collapsed. Errorbars are standard error of the mean.

We can see that no significant change happened, and subjects were responding to stimuli with roughly same compression in pretest and posttest, suggesting that training did not have effect on bias. Compression significantly changed only in three subjects in HF group, who were considered outliers because of their results in pretest. This was most probably the effect of misunderstanding of task or these subjects found the localization task too difficult to accomplish. In posttest we do not observe such an effect in these subjects.

4.2 Virtual environment

4.2.1 Results in virtual environment

As we mentioned, ILD is frequently dependent and rise alongside rising frequency, while ITD is frequently independent and dominates for low-frequency stimuli. We hypothesized that relative weight of ILD to ITD from pretest to posttest will increase for HF and HFI group and decrease for LF group as the result of generalization of change in weighting from RE.

In the figures 34,35,36 we can see a relative weight of ILD parameter to ITD parameter computed from parameters k_{ILD} and k_{ITD}. Mixed ANOVA with factors location (1.8° to 45° with 3.6° steps, 13 locations) X time (pretest, posttest) and group (LF,HF,HFI) showed significant effects of time ($F(1,30) = 16.54$, $p<0.01$) and location ($F(12,360) = 5.06$, $p<0.01$) but no significant interaction. Partial ANOVA with only HFI and HF group showed significant effect of time ($F(1,19) = 12.07$, $p<0.01$), location

(F(12,228) = 3.10, p<0.01) and significant interaction location X group (F(12,228) = 2.46, p<0.05). Partial ANOVA for HFI group showed significant effect of location (F(12,96) = 3.46, p<0.01), for HF group significant effect of time (F(1,11) = 8.58, p<0.05) and for LF group significant effect of time (F(1,11) = 5.87, p<0.05) and location (F(12,132) = 2.51, p<0.05).

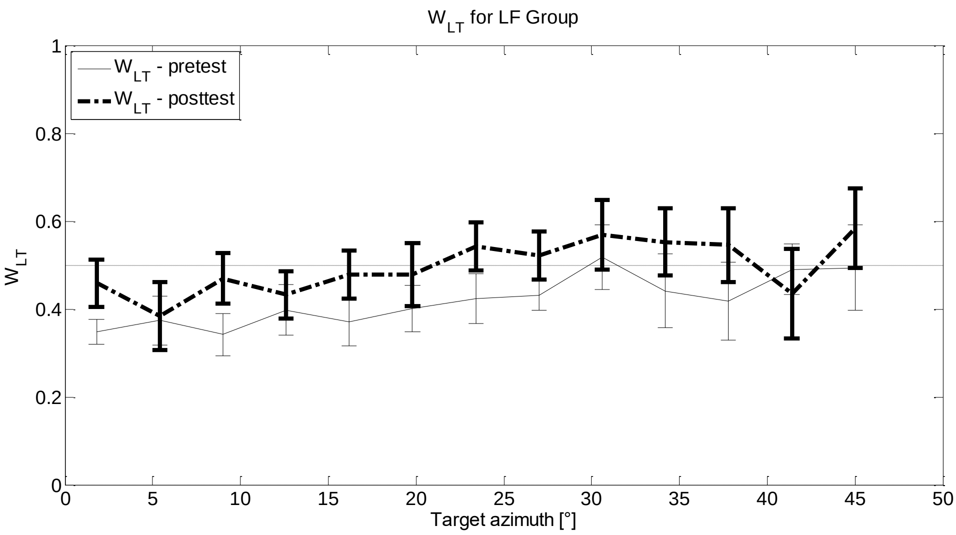

Figure 34: W_{LT} in pretest (thin line) and postest (thick line) as a function of target azimuth separations for LF group. Data are left-right collapsed. Errorbars are standard error of the mean.

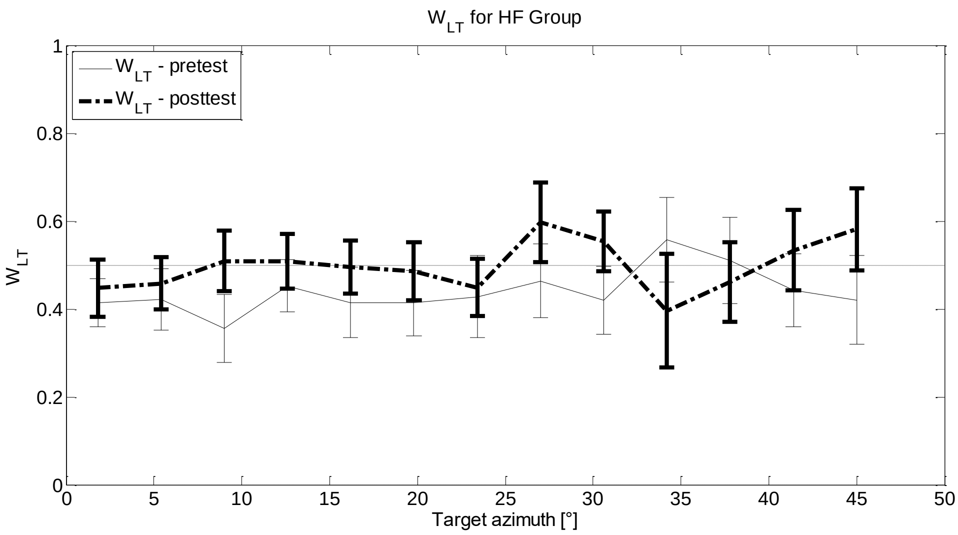

Figure 35: W_{LT} in pretest (thin line) and postest (thick line) as a function of target azimuth separations for HF group. Data are left-right collapsed. Errorbars are standard error of the mean.

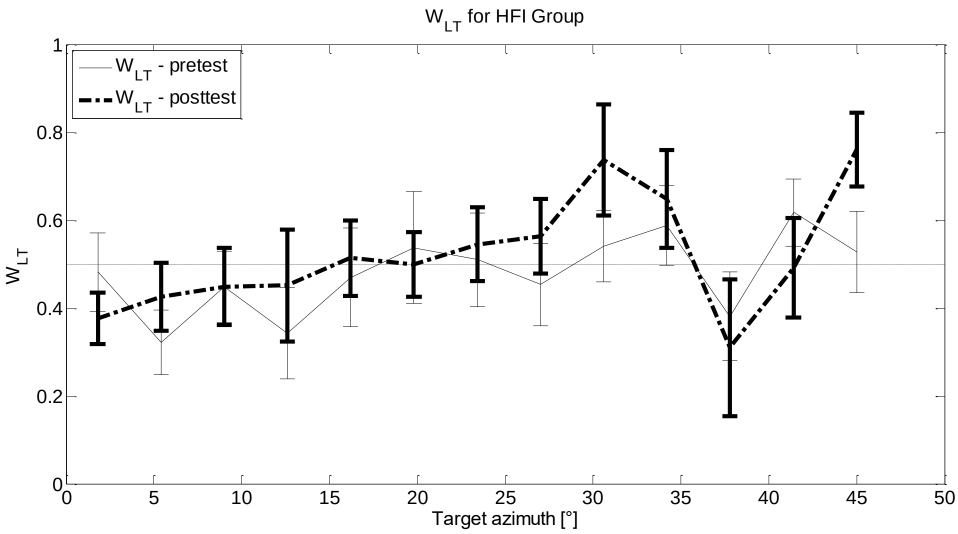

Figure 36: W_{LT} in pretest (thin line) and postest (thick line) as a function of target azimuth separations for HFI group. Data are left-right collapsed. Errorbars are standard error of the mean.

The change of weighting in RE did not generalized to change in ITD/ILD weighting in VE. In VE we observe the increase of ILD weight independent of the training group which was observed also in Kumpik et al. [6] study. This change was significant, and in the same direction, in LF and also in HF group. In HFI group we also observe the increase of W_{LT} but this increase was not significant. In the figure 37 is W_{LT} averaged across all groups.

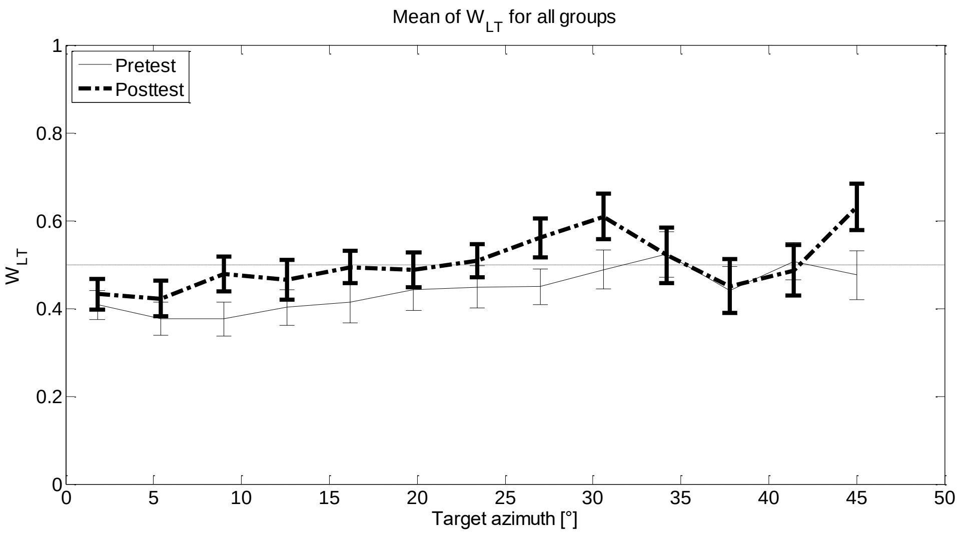

Figure 37: : W_{LT} in pretest (thin line) and postest (thick line) as a function of target azimuth for mean of weights from all groups (LF, HF, HFI). Data are left-right collapsed. Errorbars are standard error of the mean.

In the figures 38,39,40 we can see parameters k_{ITD} and k_{ILD} from regression model from VE part of the experiment.

Mixed ANOVA for k_{ITD} parameter on factors location (1.8° to 45° with 3.6° steps, 13 locations), time(pretest, posttest) and group (LF, HF and HFI) showed significant effect of location($F(12,360) = 32.90$, $p<0.01$), time($F(1,30) = 10.10$, $p<0.01$) and significant interaction location X time($F(12,360) = 2.31$, $p<0.05$). Partial ANOVA with only HFI and HF group as a factor showed significant effect of location($F(12,228) = 18.50$,$p<0.01$) and time($F(1,19) = 5.29$, $p<0.05$).Partial ANOVA for HFI group showed significant effect of location($F(12,96) = 6.85$, $p<0.01$), for HF group significant effect of location ($F(12,132) = 12.76$, $p<0.01$) and time ($F(1,11) = 4.89$, $p<0.05$) and for LF group significant effect of location($F(12,132) = 17.46$, $p<0.01$) and time ($F(1,11) = 5.49$, $p<0.05$).

Mixed ANOVA for k_{ILD} parameter on factors location (1.8° to 45° with 3.6° steps, 13 locations), time(pretest, posttest) and group (LF,HF and HFI) showed significant effect of location ($F(12,360) = 7.69$, $p<0.01$), time ($F(1,30) = 6.50$, $p<0.05$) and significant interaction location X time ($F(12,360) = 2.35$, $p<0.05$). Partial ANOVA with only HFI and HF group showed significant effect of location($F(12,228) = 4.29$, $p<0.01$). Partial ANOVA on HFI group showed no main effect or interaction, for HF group ANOVA showed significant interaction of location ($F(12,132) = 4.51$, $p<0.01$) and for LF group also significant effect of location ($F(12,132) = 4.52$, $p<0.01$).

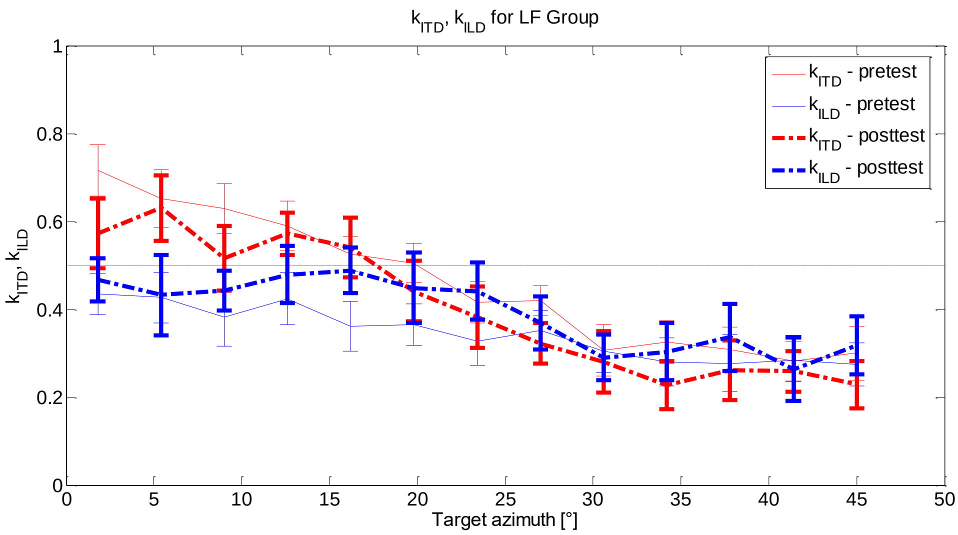

Figure 38: Parameters k_{ITD} and k_{ILD} as a function of azimuth for pretest (thin line) and posttest (thick line) for LF group. Data are left-right collapsed. Errorbars are standard error of the mean.

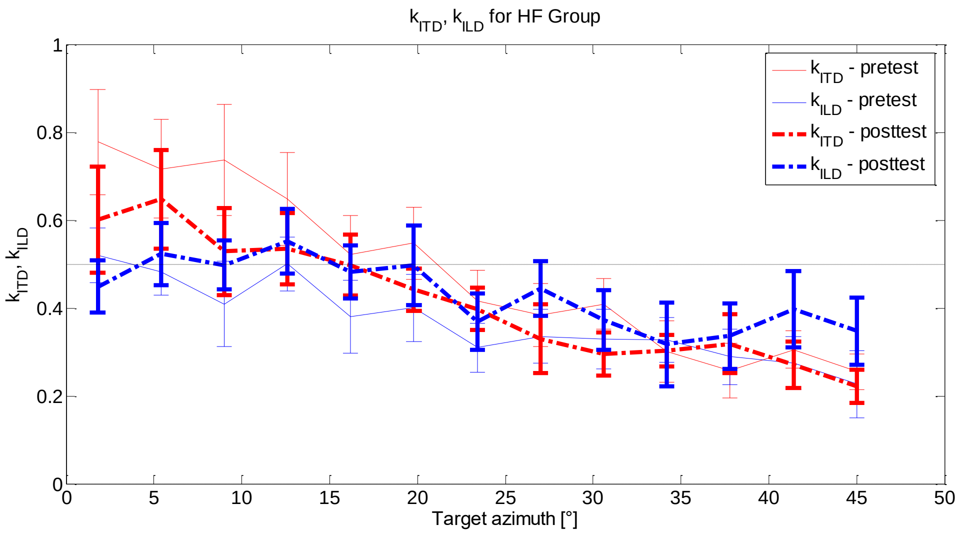

Figure 39: Parameters k_{ITD} and k_{ILD} as a function of azimuth for pretest (thin line) and posttest (thick line) for HF group. Data are left-right collapsed. Errorbars are standard error of the mean.

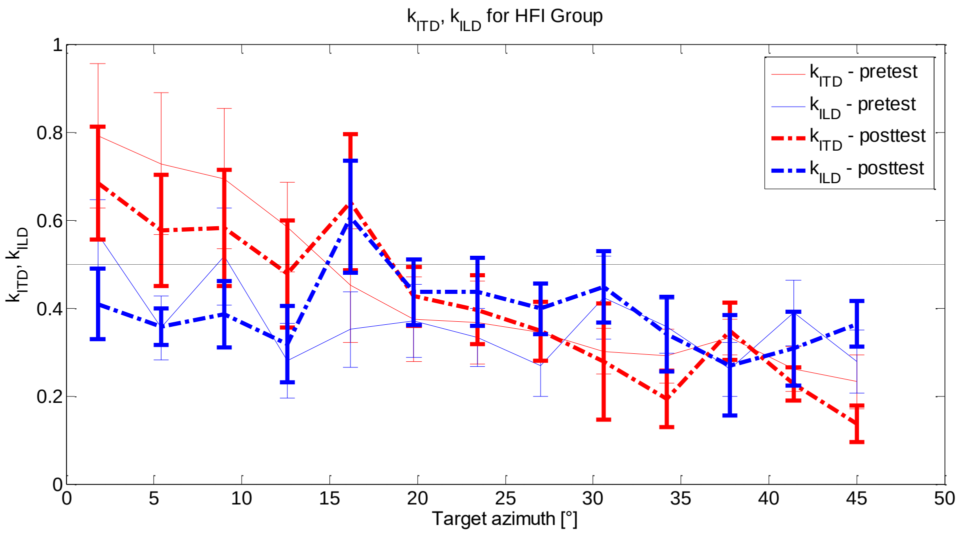

Figure 40: Parameters k_{ITD} and k_{ILD} as a function of azimuth for pretest (thin line) and posttest (thick line) for LF group. Data are left-right collapsed. Errorbars are standard error of the mean.

k_{ITD} and k_{ILD} in VE are changing group-dependent, however k_{ITD} is changing more and is contributing to weight change more significantly. Similar situation happens in RE with k_{HF} and k_{LF}, where k_{LF} change is more significant.

4.2.2 Results in virtual environment for Q parameter

As in RE in VR we also expelled effect of compression from weights and concentrated it into parameter Q. We expect similar results as in RE, meaning that change of Q parameter from pretest to posttest will not be significant.

In the figures 41,42,43 is displayed parameter Q from our regression model for VR for LF, HF, and HFI group respectively. Mixed ANOVA for with factors location (1.8° to 45° with 3.6° steps, 13 locations), time (pretest, posttest) and group (LF, HF and HFI) showed significant effect of location ($F(12,360) = 472.57$,$p<0.01$). Partial ANOVAs for each group with factors location (13) X time (2) showed for LF group significant effect of location ($F(12,132) = 159.18$, $p<0.01$), for HF group significant effect of location ($F(12,132) = 171.91$, $p<0.01$) and for HFI group significant effect of location ($F(12,96) = 145.12$, $p<0.01$).

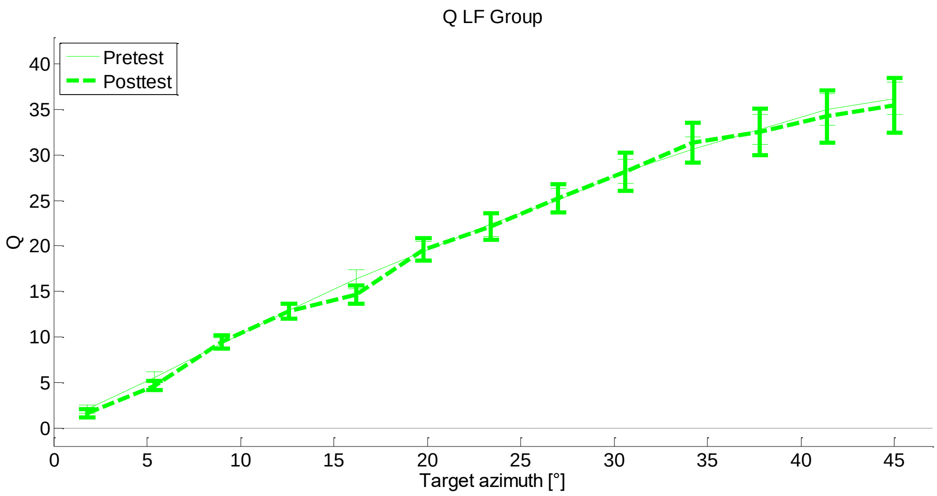

Figure 41: Q parameter as a function of target azimuth for LF group in virtual environment. Data are left-right collapsed. Errorbars are standard error of the mean.

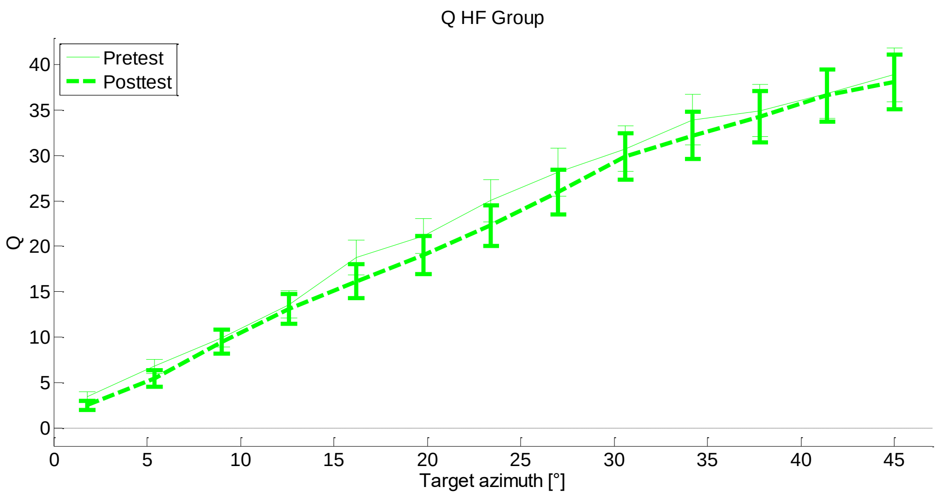

Figure 42: Q parameter as a function of target azimuth for HF group in virtual environment. Data are left-right collapsed. Errorbars are standard error of the mean.

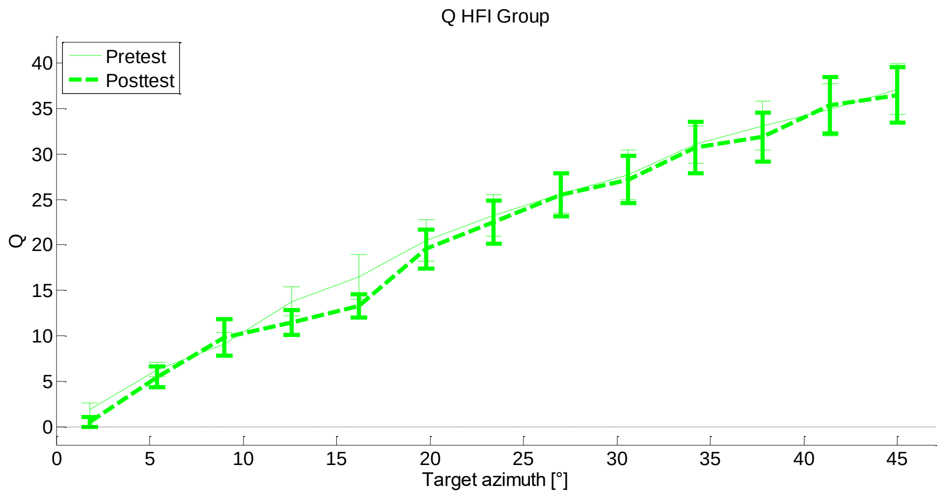

Figure 43: Q parameter as a function of target azimuth for HFI group in virtual environment. Data are left-right collapsed. Errorbars are standard error of the mean.

Change of Q parameter was not significant, meaning that overall bias stayed unchanged even after reweighting. This result corresponds with result from RE.

Conclusions

Reweighting of spectral components of sound by visually guided frequency-specific training in real environment was shown to be possible. All groups significantly changed weighting in accordance to training procedure. While for big separations this change was stronger in HF and HFI group, for small separations it was stronger for LF group. Both parameters k_{LF} and k_{HF} changed in expected direction; however, change of k_{LF} was stronger and contributed to reweighting more prominent.

Change in weight occurs during training sessions rather than between them. However, generalization on mid-frequency occurred only in HF group suggesting higher effectivity of training to high-frequency components and thus ILD.

In VE all groups increased relative weighting of ILD, independent on the type of training, in partial agreement with the mid-frequency results. This effect might be due to a higher weighting of ILD in pretest, or that ILD has a tendency to be changed easier than ITD [6]. Another explanation might be that while in pretest there was the pretraining to get used to VE, in posttest there was no such pretraining and thus task to localize sounds in VE immediately after RE might lead to a confusion, and since ILD is more dominate in reverberant environment [12], it led to its higher weighting. To examine this explanation another experiment would be needed, where VE part would not be immediately followed by RE part and thus subjects would have time to accommodate to a virtual environment.

There was no significant difference between HF and HFI group, meaning that information about spectral composition of sound and instruction to follow this sound was not useful for reweighting. The main reason might be, that it was a difficult task to discriminate higher frequencies from lower ones. This explanation is supported by results in pretest, where responses between HF and HFI group were without significant difference even though HFI group was instructed to focus on higher frequencies.

Multiple linear regression model showed weights cleared of compression. We can see the compression effect in parameter Q and it did not significantly changed in any group from pretest to posttest.

These findings prove usefulness of such trainings for reweighting of spectral cues and might be helpful to improve the quality of life of people using hearing aids, especially cochlear implants users, as well as contribute to further development of sound systems for virtual reality devices.

Resumé

Sluch je u ľudí jedným z hlavných zmyslov, ktorý využívame v každodenných situáciách. Z evolučného hľadiska je dôležitá predovšetkým jeho výstražná funkcia, ale rovnako nám pomáha orientovať sa v priestore a porozumieť reči. Samotné priestorové počutie je možné vďaka polohe uší na hlave. Počutý zvuk nie je rovnaký v oboch ušiach. Rozdiel v čase príchodu zvuku do jedného a druhého ucha a tiež rozdiel v intenzite zvuku nám v rozhodujúcej miere pomáhajú zdroj zvuku lokalizovať. Interaurálny časový rozdiel (ITD) a interaurálny rozdiel v hlasitosti (ILD) sú dve binaurálne kľúče, ktoré najmarkantnejšie prispievajú k lokalizácii v priestore. ITD je frekvenčne nezávislé, no u ľudí je dominantné hlavne pre nízke frekvencie (<2 kHz), zatiaľ čo ILD je frekvenčne závislé a u ľudí dominuje hlavne pre vysoké frekvencie (>2 kHz). Schopnosť lokalizácie zvuku je výrazne obmedzená u ľudí s poškodeným sluchom. Príkladom sú ľudia používajúci kochleárny implantát, ktorý neumožňuje úplne vernú simuláciu priestorového sluchu. Práve vhodnými tréningovými metódami vieme posilniť binaurálne kľúče, dôležité pre lokalizáciu, a tak priestorové počutie zlepšiť. Ďalšou možnosťou aplikácie nášho výskumu priestorového sluchu je virtuálna realita. Na vernú replikáciu zvukových charakteristík virtuálnych miestností je potrebné dôsledné pochopenie spracovania priestorového sluchu.

V našej práci rozoberáme behaviorálny experiment, ktorého cieľom bolo zmeniť váženie spektrálnych zložiek zvuku tréningom v reálnom prostredí. Tréning sa líšil podľa experimentálnej skupiny a mohol byť zameraný na zvýšenie váženia vysokofrekvenčných komponentov (HF) alebo nízkofrekvenčných komponentov zvuku (LF). Naše hypotézy sú:

1. Skupina trénovaná na posilnenie HF komponentov zvuku (HF group) zvýši váženie HF komponentov zvuku, zatiaľ čo skupina trénovaná na posilnenie LF komponentov zvuku (LF group) zvýši váženie LF komponentov zvuku.
2. Zmena váženia HF a LF komponentov zvuku sa zovšeobecní na zmenu váženia strednofrekvenčných komponentov zvuku, ktoré boli použité len počas testovania.
3. Prípadná zmena váženia spektrálnych komponentov zvuku z reálneho prostredia sa zovšeobecní aj na zmenu váženia binaurálnych kľúčov (ILD, ITD) vo virtuálnom prostredí. Pre HF skupinu očakávame zvýšenie váženia ILD a pre LF skupinu zvýšenie váhy ITD.

4. Informácia o spektrálnom zložení zvukov má efekt na zmenu váženia.

Počas experimentu sme mali dve experimentálne prostredia – reálne a virtuálne. V reálnom prostredí (RE) sedel subjekt na stoličke v strede tmavej miestnosti. Pred ním bolo v polkruhu rozmiestnených jedenásť reproduktorov, z ktorých v jednotlivých trialoch prichádzal zvuk, ktorého polohu mal určiť. Zvuk bol zložený z HF a LF zložky, ktoré prichádzali v jednom triale súčasne z viacerých reproduktorov. Vo virtuálnom prostredí (VE) bol subjekt v zvukotesnej miestnosti, mal na ušiach slúchadlá a na očiach Oculus headset. Do slúchadiel mu prichádzal zvuk, zložený z určitej hodnoty ITD a ILD, a jeho úlohou bolo určiť polohu zvuku otočením hlavy k zdroju zvuku.

Experiment mal tri fázy: pretest, tréning a posttest. Najprv bol absolvovaný pretest vo VE a potom v RE. Úlohou subjektu bolo otočiť hlavu smerom k pozícii prichádzajúceho zvuku, potvrdiť pozíciu a otočiť hlavu späť na stred. Vo VE bol ešte pred pretestom spravený krátky pred-tréning, ktorého úlohou bolo zoznámiť participanta s prostredím. Po preteste nasledovali tri tréningy, ktoré sa uskutočnili len v RE spravidla v troch po sebe nasledujúcich dňoch. V posledný tréningový deň sa uskutočnil aj posttest ktorý bol totožný s pretestom, najprv v RE a potom vo VE. Úlohou pretestu bolo určiť pôvodné váženie spektrálnych a binaurálnych kľúčov. V postteste sme vyhodnotili zmenu tohto váženia po tréningu. Pretest a posttest boli rovnaké pre HF aj LF skupinu, ale samotný tréning sa u participantov líšil v závislosti od experimentálnej skupiny. V HF skupine bolo úlohou subjektu počas tréningu odpovedať na trial otočením hlavy ku zdroju zvuku. Následne sa zobrazil vizuálny feedback na pozíciu reproduktora, z ktorého prichádzal HF komponent zvuku. Subjekt otočil hlavu smerom k feedbacku, potvrdil pozíciu a otočil hlavu späť do stredu. Počas potvrdzovania opakovane hral zvuk trialu. V LF skupine bola tréningová procedúra rovnaká, ale feedback sa zobrazoval na pozícií LF komponentu zvuku. HFI skupina mala tréning rovnaký ako HF skupina, ale subjekty boli informované o spektrálnom zložení zvukov, a už v preteste inštruované, aby odpovedali na miesto zvuku s vyššou frekvenciou.

Na analýzu výsledkov z RE sme použili model viacnásobnej lineárnej regresie, ktorý nám určil váhu jednotlivých parametrov zvuku. Z týchto parametrov sme následne vypočítali váhu HF komponentu ku LF komponentu (W_{HL}), v ktorej sme vyjadrovali výsledné váženie. Rovnaký model bol použitý aj na analýzu dát z VE, kde sme vypočítali váhu ILD ku ITD (W_{LT}), čo je ekvivalentom váhy z RE.

U HF a HFI skupiny sme pozorovali signifikantný nárast W_{HL} z pretestu ku posttestu. To znamená, že subjekty v HF a HFI skupine začali po tréningu viac vážiť HF komponenty zvuku. V LF skupine sme videli signifikantný pokles W_{HL} z pretestu ku posttestu, čo značí zvýšenie váženia LF komponentov zvuku. Zmena váženia sa zovšeobecnila pre strednofrekvenčné zvuky len u HF skupiny. Vo VE sme pozorovali nárast W_{LT} z pretestu ku posttestu pre všetky experimentálne skupiny.

Prvá hypotéza o zmene váženia v reálnom prostredí sa potvrdila. Zovšeobecnenie zmeny váženia na strednú, netrénovanú frekvenciu bolo úspešné len pre HF skupinu. To môže byť dôsledkom väčšieho významu HF komponentov zvuku pri lokalizácii v prostredí s reverberáciou. Tretia hypotéza sa nepotvrdila, zmena váženia z RE sa nezovšeobecnila na zmenu váženia vo VE. Všetky skupiny bez ohľadu na tréning zvýšili váženie W_{LT}. To môže byť spôsobené jednak vyšším vážením ILD už v preteste ale tiež aj prítomnosťou predtréningu, ktorý bol pred pretestom, ale už nie pred posttestom. Ďalším faktorom, ktorý mohol ovplyvniť váženie v postteste, bolo poradie posttestov. Najprv bol spravený posttest v RE a až potom vo VE, čo mohlo zvýhodniť váženie ILD. Žiadnu významnú zmenu medzi HF a HFI skupinou sme nezaznamenali, čo ukazuje, že úloha odlíšiť pozíciu jednotlivých frekvenčných zložiek zvuku bola náročná.

Naše výsledky ukazujú, že zmena váženia spektrálnych zložiek zvuku je možná. Aby sme otestovali, prečo sa zmena z RE nezovšeobecnila na zmenu váženia ILD/ITD vo VE, je potrebný ďalší experiment, kde by sa poradie posttestov vymenilo, a teda prvý by bol spravený posttest vo VE a potom v RE. Samotná tréningová procedúra je využiteľná pre ľudí s poškodeným sluchom, predovšetkým pre tých, ktorí používajú kochleárny implantát, keďže môže byť použitá na posilnenie váženia ILD. Rovnako vidíme využitie pri rozvoji systémov pre virtuálnu realitu, keďže naša práca ukazuje rôznu dôležitosť jednotlivých spektrálnych a binaurálnych kľúčov pri lokalizácii zvukov v priestore.

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Attachments

Attachment A: Diploma thesis, source code and figures