Binaural masking threshold of HRTF based reproduction in hear-through headphone environment

Taeho Kim
Aalto Universtiy
Department of Signal Processing and Acoustics

`taeho.kim@aalto.fi`

Abstract

The detectability of sound signals in a noisy environment from hear-through headphones is examined by measuring masking level differences between different localisation cues of masked signals. Masking thresholds of HRTF filtered signals from different horizontal/vertical directions were examined when a broadband pink noise and a low-passed pink noise are used as maskers. They were compared with the masking thresholds of signals from the "inside-the-head" lateralised locations that correspond to the directions of HRTF filtered signals. At horizontal directions, signals filtered with both individual and generic HRTFs showed masking level differences (MLDs) between 1-6dB for the broadband noise. However, signals with generic HRTF filtering showed a noticeable decrease in MLDs compared to those from individual HRTFs when the low-pass noise was used for the masker. At vertical directions, signals with individual HRTFs showed significantly higher MLDs than those with generic HRTFs for both broadband and low-pass maskers. The effect of the low-pass masker on MLD was less prominent than for signals in horizontal directions.

1 Introduction

The hear-through headphone technology delivers a surrounding acoustic environment to a listener. The outer-ambience sounds are transmitted through the headphone using the microphones integrated in it, then simultaneously presented with the sounds normally reproduced to the headphone. The idea of this technology can motivate enormous possibilities that allow diverse applications such as augmented reality audio and active noise cancelling. Current research works for the hear-through headphone technology mainly focus on acquiring the *acoustic transparency* technique that refers to the method of reshaping the received outer-ambience sounds as similar to the sounds in an open ear condition [13, 17, 20]. Another technical issue in this technology is the auditory effects arising from the combination of two different sound streams. However, those effects have not been sufficiently studied until the present. Since two sound streams are simultaneously mixed in the reproduction process, auditory masking is an unavoidable consequence in this listening environment. In order to examine the masking effect, it is necessary to investigate various potential combinations of masked *signal* and noise *masker* in such applications utilising a hear-through headphone technology. This paper will examine masking effects of signals in various auditory locations with diotically presented masker noises.

In most cases, a sound signal is presented as a normal two-channel stereophonic reproduction in a headphone. Since this stereophonic sound is commonly created assuming a loudspeaker reproduction, the location of a sound signal is normally determined by the amplitude panning method, and positioned at certain point between two speakers. However, when this stereophonic reproduction is presented in a headphone, sound signals are located between two ears, somewhere inside the head. This inside-the-head localisation of a sound source is referred to as *lateralisation.*

On the other hand, different methods to localise a sound signal are employed in such applications as virtual reality audio and augmented reality audio. The augmented reality audio is one of the captivating applications enabled by the hear-through headphone technology. In this application, a sound signal can be located in a virtual auditory space (VAS). By combining a virtual auditory space to an acoustic environment surrounding a listener, the auditory space is extended creating an *augmented reality* audio environment [13]. This augmented auditory space can be attained by the following process. Firstly, a real audio environment is filtered and equalised in the frequency domain to obtain acoustic transparency. This *pseudo* acoustic environment is then blended with a virtual auditory space reproduced by the auralization of given sound sources. In other words, sound sources can be located in a virtual auditory space using binaural auralization, which is accomplished by applying spatial auditory filters such as *head related transfer function* (HRTF) [13, 17] or *binaural room impulse response* (BRIR) [15].

HRTF refers to the transfer function of sound from the sound source to the ear canal entrance [1]. Those transfer functions vary depending on the location of a sound source and the morphology of the listener's head, shoulder and body. Therefore, HRTF is a direction-dependent, individually-variant acoustic transfer function. At each different location of a sound source, the corresponding HRTFs from the ears indicate localisation cues of the source location such as *interaural time difference* (ITD), *interaural level difference* (ILD) and spectral cues. Unlike the fact that the binaural hearing of a normal stereophonic reproduction locates perceived sound sources inside the head (lateralisation), utilisation of HRTF filters allows sound sources to be localised outside the head due to the comprehensive localisation cues derived from it. The method which enables this outside-the-head localisation is referred to as acoustic *externalisation.* HRTF filtering allows, namely, acoustic externalisation of sound sources. However, it is practically challenging to employ HRTF to every listener since HRTFs vary considerably from individuals. Therefore, instead of measuring HRTF for each listener, a single standard HRTF [10] is often used for binaural reproduction in many virtual audio applications as well as research works despite its weakness in the accurate localisation.

In addition to the directional localisation of sound sources, further spatial properties are required for more realistic auralization of sound sources, such as source distance and room reverberation. In order to achieve natural auditory spaciousness in a closed space, binaural room impulse response (BRIR) can be applied to sound sources. Since BRIR is also an individually variant function similar to HRTF, artificial modelling of BRIR is often employed instead of measuring it for every listener. BRIR can be modelled by employing parameters of the temporal structure of room impulse response, thus enabling efficient implementation to the virtual auditory space [15].

A perceived sound signal can either be positioned in a lateralised location or an externalised location. When multiple sound signals are present, they can be positioned in different locations with each other or in the same location. The degree of auditory masking varies with different locations of a signal and a masker [2, 3, 8, 9, 4]. In general, when two or more sounds are heard together, audibility of one sound is weakened by the presence of other sound(s). Accordingly, the threshold of audible level becomes higher when a sound signal is masked by another sound (masker). This threshold of hearing in the presence of a masker is referred to as the *masking threshold.* In certain binaural conditions for a signal and a masker, the masking threshold of the signal becomes lower than the monaural condition. In other words, when a listener simultaneously hears a signal and a masker with two ears, the signal is more detectable when one of the sounds is presented differently to each of the ears than when all the sounds are monaurally given to both ears.

Figure 1 shows four signal-masker conditions and the influence of binaural condition to the masking threshold. The signal-masker condition is generally described using the symbol S as the signal and N as the noise (masker). Therefore, condition (a) in the figure indicates $\mathrm{S_0N_0}$ which is the in-phase condition and (b) shows $\mathrm{S_\pi N_0}$ which is the out-of-phase condition where the signal is inverted at each ear by 180^0. The ability to detect the signal becomes better in $\mathrm{S_\pi N_0}$ than $\mathrm{S_0N_0}$. (c) and (d) show conditions $\mathrm{S}_m\mathrm{N}_m$ and $\mathrm{S}_m\mathrm{N}_0$, respectively, where the suffix m refers to the *monaural* presentation that a signal is presented to one ear only. The signal at $\mathrm{S}_m\mathrm{N}_0$ is, surprisingly, more detectable than $\mathrm{S}_m\mathrm{N}_m$ where both the signal and masker are presented to one ear. These phenomena shows that different masking thresholds can be observed at different signal-masker conditions.

The difference between the masking thresholds in different signal-masker conditions is called the *masking level difference* (MLD) [18]. In the cases of Figure 1, the MLD of $\mathrm{S_\pi N_0}$ (case b) is the difference of masking thresholds between the 'reference'

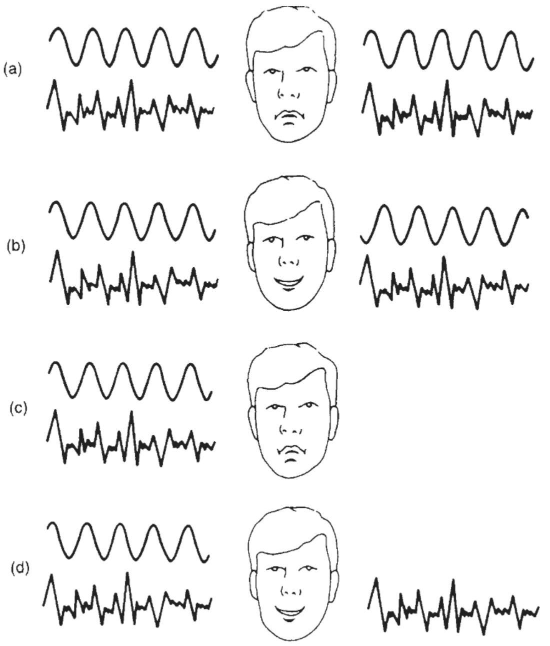


Figure 1: *The influence of different signal-masker conditions to the masking threshold. The smiling face indicates the improved detectability of the signal in the presence of the masker. Adopted from [18].*

condition S_0N_0 (case a) and the given condition. MLD in binaural hearing, namely *binaural masking level difference* (BMLD) or *binaural masking release*, has been extensively studied until the present [2, 3, 5, 6, 8, 9, 21, 22]. For broadband noise for the masker and pure tones for signals, the BMLD of $S_\pi N_0$ was measured up to 15dB at a low-frequency signal (500Hz), and decreased to 2-3dB at high-frequency signals above 1500Hz [5]. Even when a noise is presented out-of-phase with the diotic signal, i.e. in S_0N_π condition, BMLD was observed as 13dB at a low-frequency signal [18]. Hence, by inverting the phase of either the signal or the masker, the ability to detect the signal was observed as remarkably improved, especially for low-frequency signals.

BMLDs have not been observed only at pure tones for the signals, but for clicks, bursts, complex sounds and speech sounds as well [2, 3, 8, 9, 19]. The effect of different masking noises for BMLD has also been investigated such as diverse noise bandwidths and speech sounds. A certain frequency range around the centre frequency of the signal was observed to be the most effective noise bandwidth to obtain BMLD for the given signal, whose frequency range is assumed as the *binaural critical bandwidth* [12, 11, 23, 21, 22]. The influence of interaural disparity on BMLD has been examined as well. For either broadband noise or speech for the masker, masking release was achieved when the signal and masker differs in ITD [9]. The binaural effect on masking release was more significant when ITD and ILD were combined in the signal [2, 8]. Instead of employing ITD or ILD to signals, Carhart et. al. (1968) [3] applied ITD (0.8ms) only to various types of maskers, and obtained MLDs of around 5dB. However, out-of-phase masker condition (180° phase difference) always gave the highest MLDs in all masker types in the experiment. Heijden and Trahiotis (1998) [22] investigated masking thresholds for different maskers with interaural coherence from -1 (out-of-phase) to 1 (in-phase), and obtained the lowest masking threshold when the signal and the masker are 180° out-of-phase with each other, just as the test result from Carhart et. al [3].

A difference in interaural disparity can be interpreted as a different position in the auditory space. Thus, according to these studies, it can be presumed that the ability to detect the signal is improved when the auditory positions of the signal and the masker have less spatial coherence with each other concerning their location and spatial density. Carlile and Wardman (1996) [4] examined the masking thresholds when the signal and the masker are located in different auditory spaces. While playing a 4kHz signal in a lateralised location, the broadband masker was presented in a virtual auditory space. The test result showed a noticeable improvement in the detection of the masked signal compared to the case which both the signal and the masker are located in lateralised locations. This experiment suggests that, accordingly, the separation of the signal and the masker in different auditory space can improve the detection of the masked signal.

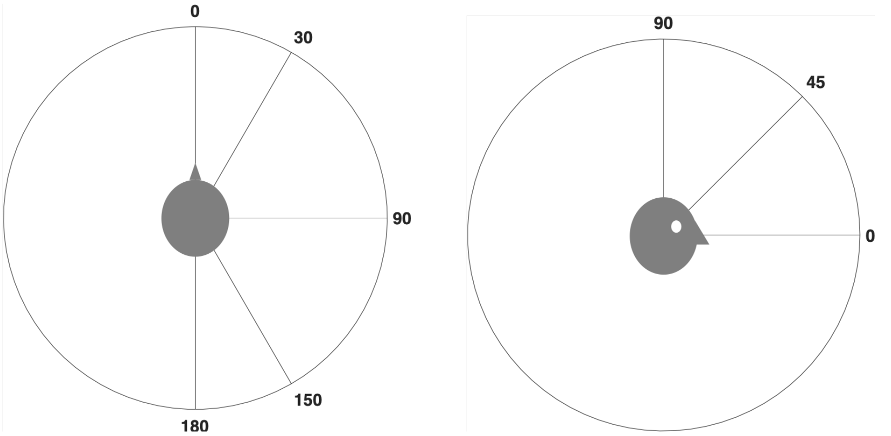
This paper will investigate masking thresholds of signals from different horizontal/vertical directions in the virtual auditory space when a diotic broadband noise is used as the masker. They will then be compared with masking thresholds of signals from the "inside-the-head" lateralised locations which correspond to the directions of signals in the virtual auditory space, thus obtaining MLD for each signal direction. In other words, this experiment will examine the detectability of HRTF-filtered externalised sounds compared to that of lateralised sounds applied with a typical amplitude panning, in the presence of ambient noise that could be fed to the headphone by utilising the hear-through technology.

2 Method

The experiment aims to examine masking thresholds of sound sources applied with HRTFs of different directions in the presence of a broadband noise diotically reproduced in a binaural listening environment. Masking thresholds of sound sources applied with a typical amplitude panning technique will also be examined and compared with the threshold data from HRTF filtered sounds to obtain MLDs between them.

2.1 Stimuli and setups

A broadband white Gaussian noise burst of 100ms length is used as the signal (the maskee). It is presented in the temporal center point of a 300ms pink noise, which is used as the noise (the masker). The 10ms-length cosine ramp is applied to the onset and offset of the signal while 20ms-length ramp is applied to the onset and offset of the noise. For each trial, the location of the signal varied as the signal is applied with HRTF or ILD of different direction. Five horizontal directions and two vertical directions were applied to HRTF filtering: 0°, 30°, 90°, 150° and 180° azimuth in the horizontal plane (clockwise from the front-centre position), and 45° and 90° elevation in the median plane (see Figure 2). For inside-the-head lateralised directions applied for different ILDs, 0°, 30° and 90° azimuth were employed to the lateral panning method, which is described in Figure 3.



(a) *HRTF directions in the horizontal plane.* (b) *HRTF directions in the median plane.*

Figure 2: *The signal directions applied for HRTF filtering*

Supposing the points L and R in Figure 3 as the ears, the angle α can be expected as the lateral panning direction. The lateralised location can thus be the point in the horizontal cross-line right below the panned position. In order to apply the amplitude panning method to the binaural presentation, the angle β derived from the lateralised location can be applied to the amplitude panning to accomplish the lateral panning.

The HRTF data employed to the masked signal were either individual HRTFs from the subjects or a generic HRTF database measured from KEMAR dummy head microphone [10]. The masking noise was presented as either a broadband pink noise or a low-pass pink noise filtered at 2kHz. The 2kHz low-passed noise was used to mask only the localisation attributes of the signal which mainly cause the ITD. The loudness level of every signal was normalised to -10dB LUFS by integrated loudness measurement based on EBU-R 128 Standard [7].

2.2 Participants

Eight subjects with normal hearing aged between 24 and 44 years participated in the listening test. Four subjects were tested with individual HRTF data from themselves whereas four other subjects were tested with generic KEMAR HRTF. All the

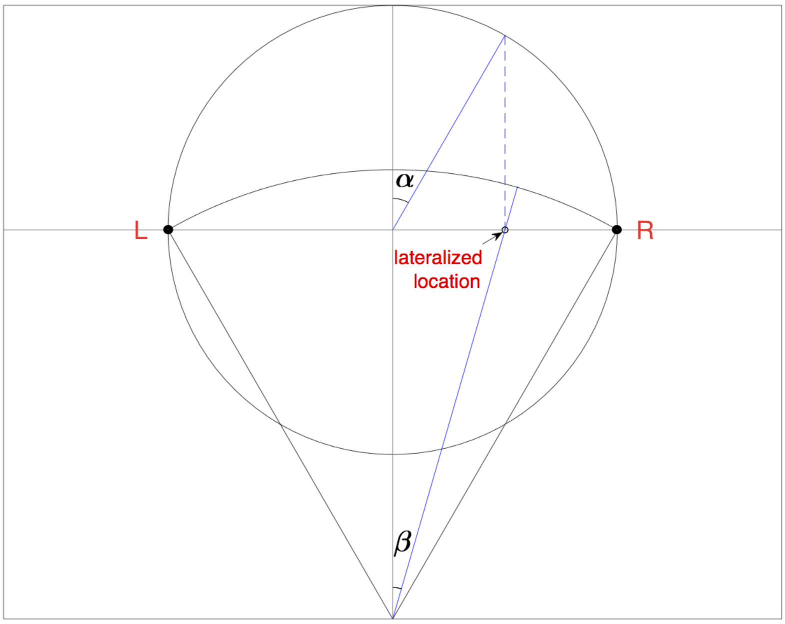


Figure 3: *The application of binaural panning by utilising the amplitude panning method*

participants were staff members or students from *The Acoustics Lab, Aalto University*.

2.3 Procedure

Each subject examined the masking threshold for each signal direction using a three-interval forced-choice procedure with adaptive signal-level adjustment method suggested by Levitt(1971) [16]. A two-down one-up rule was employed for this method. Three intervals of noise bursts were presented for each question. Among those intervals, one randomly selected interval contained the signal which were simultaneously presented at the temporal midpoint of the noise interval. Subjects were asked that which of three noise interval contains the signal. Two consecutive correct answers decreased the signal level by the step size Δf whereas one wrong answer increased the signal level. The step size Δf was adjusted (reduced) based on the number of up-down reversals of the signal level. The test consisted of two sessions and each session was applied with each of two different masker noises. Ten trials corresponding to ten signal directions comprised a session, thus a total of twenty signal-masker combinations were provided to each subject. Participants were allowed to rest at anytime during the test. The duration took for each subject was about 3-4 min for each trial and 40-45 min for each session. Listening tests were carried out with a well-isolated circum-aural headphone in a silent listening room.

3 Results

Figure 4 and 5 show the mean masking thresholds for the subjects tested with generic HRTF and individual HRTFs, respectively. Blue bars in the figures indicate target masking thresholds applied with HRTF and red bars show ILD employed masking thresholds as references. Each group of bar graphs represents each signal-masker combination regarding the auditory plane where the signals were located, as shown in the subtitle of each bar graph. In every location, the HRTF filtered signal provided lower masking threshold than the ILD employed signal in every signal-masker combination.

The masking level differences of all subjects are shown in Figure 7 and 8 (see Appendices). MLDs of four subjects tested with the generic HRTF are shown in Figure 7, where all the subjects provided noticeable decrease in MLDs from the low-pass masker compared to the broadband masker in horizontal directions. For signals in vertical directions, the effect of the generic HRTF was relatively weak for both the broadband masker and the low-pass masker. Figure 8 shows MLDs of four subjects with individual HRTFs. MLDs for vertical directions were relatively higher than those from the generic HRTF for both the broadband masker and the low-pass masker. However, the effect of the low-pass masker was not observed to be significant compared to the broadband masker for both horizontal and vertical signal directions.

Figure 6 shows the comparison between MLDs from the generic HRTF and individual HRTFs. For each signal-masker combination, the mean MLDs from the generic and individual HRTFs are compared with each other. For the combination of broadband masker - horizontal directions, neither the MLDs from generic HRTF nor individual HRTFs was found to be significantly higher than the other except at the front position (0°). However, all the other combinations showed higher MLDs in individual HRTFs compared to the generic HRTF at all the signal directions.

A statistical test was also carried out to obtain the statistical differences between MLDs from the generic HRTF and individual HRTFs in each direction. Table 1 shows the p-values obtained from the *permutation test*. The values shown as bold characters indicate the statistically significant difference at the significance level of $\alpha = 0.05$.

Table 1: The p-values showing the difference between mean results from the generic HRTF and individual HRTFs. The bold characters indicate the statistically significant difference at $\alpha = 0.05$ in the permutation test.

	Horizontal direction					Vertical direction		
Masker	0°	30°	90°	150°	180°	0°	45°	90°
Broadband	**.014**	.352	.916	.887	.183	**.014**	.465	**.042**
Low-pass	**.042**	.070	**.014**	**.014**	.211	**.042**	.380	**.014**

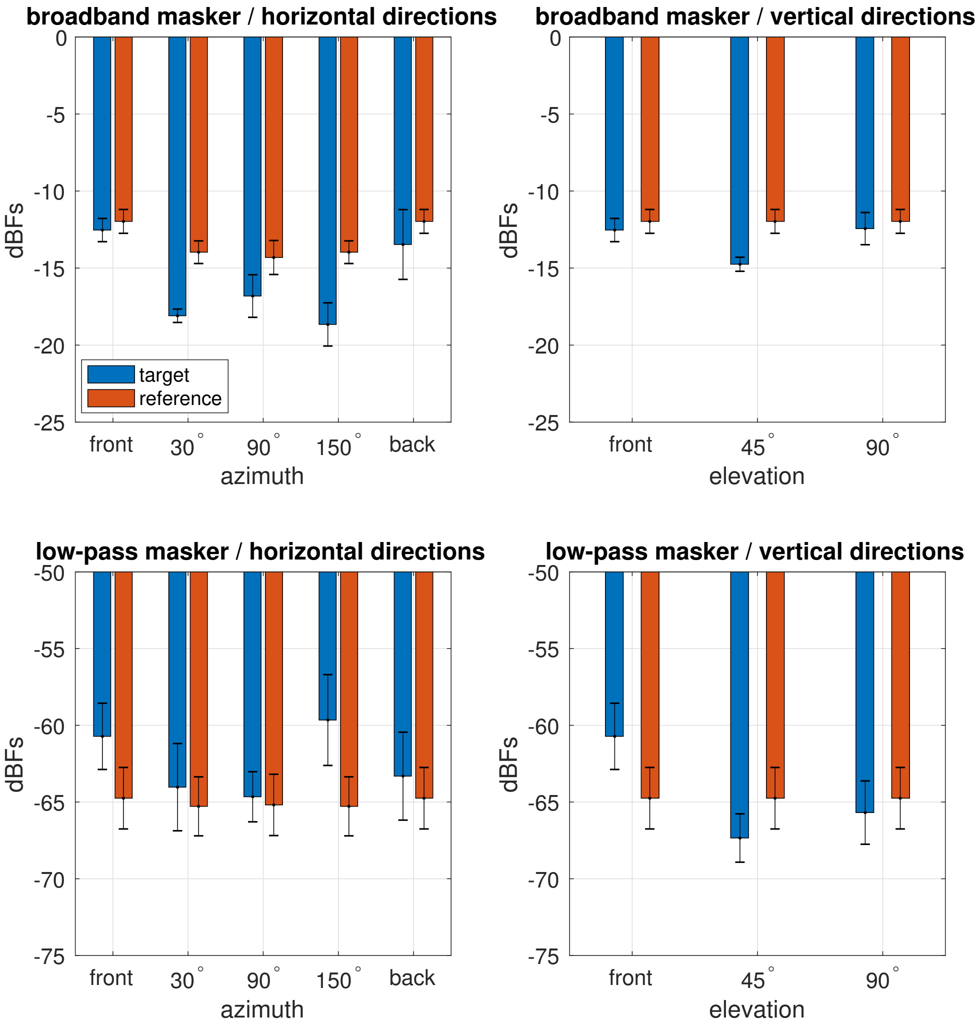


Figure 4: *Masking thresholds for four signal-masker combinations. Signals applied with KEMAR HRTF. The target indicates HRTF filtered signal and the reference indicates ILD ILD employed signals. Error bars indicate standard errors of masking thresholds.*

4 Discussion

Figure 4 and 5 show mean masking thresholds of HRTF filtered signal and the ILD employed signals. HRTF provided lower masking thresholds at every directions in most of signal-masker combinations except the case with low-pass masker in horizontal directions (generic HRTF). The decreased detectablility in this specific case will be discussed later. Another noticeable feature found in Figure 4 is that the signals filtered with generic HRTF masked by broadband masker provided significantly lower masking thresholds, especially at lateral directions (30°, 90° and 150°). In contrast to the relatively low deviation of lateralised signals, those directions at the right

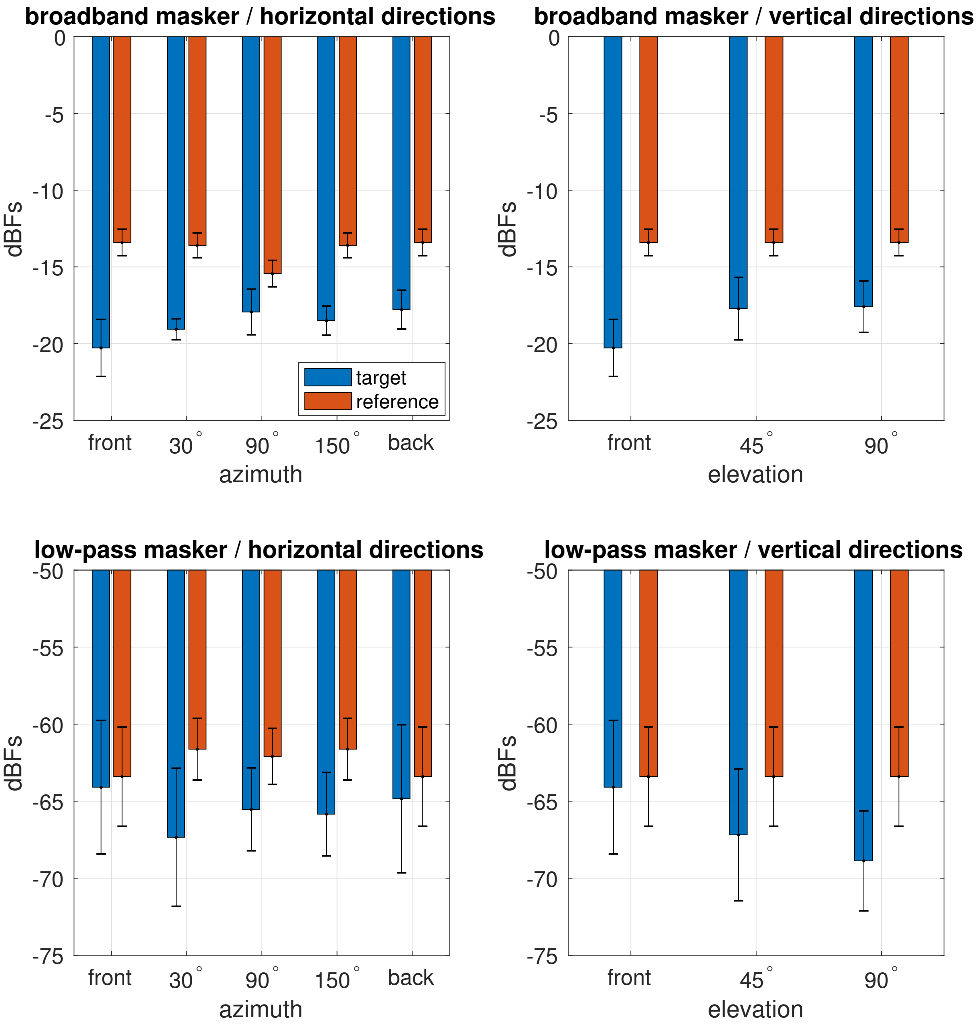


Figure 5: *Masking thresholds for four signal-masker combinations. Signals applied with individual HRTFs. The target indicates HRTF filtered signal and the reference indicates ILD ILD employed signals. Error bars indicate standard errors of masking thresholds.*

side showed about 3-5dB lower masking threshold than front/back directions with generic HRTF. However, no significant trend was found at vertical directions and with the low-pass masker. Consequently, generic HRTF is likely to provide relatively high detectability at lateral directions. Considering masking thresholds with individual HRTFs (see Figure 5), signals at vertical directions showed significantly lower masking thresholds than the target signal. Additionally, individual HRTF provided better detectablility than the generic HRTF.

As mentioned in the previous section, the low-pass filtering of the masker caused significant effect to masking level differences of signals with the generic HRTF.

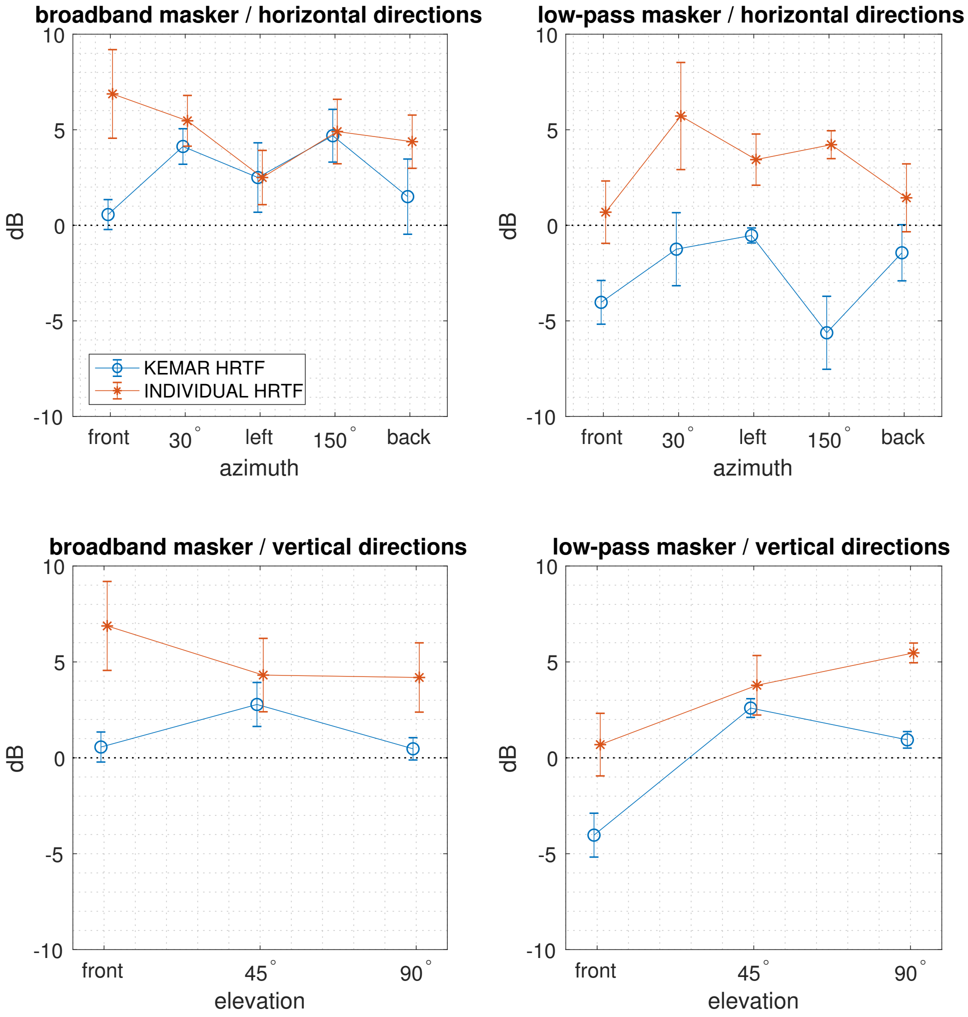


Figure 6: *Mean masking level difference for four signal-masker combinations as a function of signal direction. Error bars indicate standard errors of masking level differences.*

Prominent decrease in MLDs were observed for signals in horizontal directions (see Figure 7 and 6). The low-pass masker was filtered at 2kHz, below which is known as the frequency area where ITD predominates among binaural localisation cues [18]. As HRTF data contains most localisation cues such as ITD, ILD and spectral cues, this low-pass masker is intended to mask ITD properties in the signals and to leave only high-frequency cues. The low frequency components in HRTFs such as ITD are affected from the head, body and shoulder, from which every individual and generic HRTF might show similar patterns. Therefore, the ITD given from the generic HRTF might properly function for different individuals. However, when ITD is weakened by low-pass masking, the remaining high frequency localisation cues from generic HRTF do not sufficiently match with each different individual, thus causing weak localisation. When the auditory position of a masked signal is less salient, the detectablility can also be weakened as well. In this sense, the strong effect of generic HRTF on lateral directions can also be explained because those directions are mainly influenced by ITD. On the other hand, signals in the vertical directions provided relatively low MLDs. Since localisation in the median plane is known as influenced by high frequency *pinna* cues above 4kHz [14], generic HRTF has less effect on the detectablility of vertical sources regardless of masker types.

Besides the MLDs from the signals with the generic HRTF, MLDs from individual HRTFs showed considerably different results (see Figure 8 and 6). MLDs in the vertical directions are relatively higher than those from the generic HRTF because high frequency component above 4kHz is valid in individual HRTFs. The low-pass masking had little effect on MLDs at every signal-masker combinations, which can be explained that the remaining high frequency cues above 2kHz, such as ILD and spectral cues are still effective for individual HRTF. Similarly, the ability to localise signals in vertical directions is less affected by low-frequency masking, so as the detectability.

Figure 6 shows the comparison between signals with the generic HRTF and individual HRTFs for different signal-masker combinations. As is commonly expected, individual HRTF provided higher detectablity of signals in most signal-masker combinations except in the horizontal direction - broadband masker combination. In this case, the signal detectability from generic HRTF was not weaker than that from each individual HRTF. Another interesting finding in this graph is the symmetrical pattern for both HRTFs. Each front-back direction pair and 30°-150° direction pair showed similar MLD values. Since each pair relates as located in the common *con of confusion* area, it can be interpreted that the signal detectability can be affected by the cone of confusion.

5 Conclusions

Masking level differences of signals filtered with either generic HRTF or individual HRTFs compared to lateralised signals were examined in the presence of the broadband noise or the low-pass noise. In general, HRTF filtered signals provided higher detectability than lateralised signals. For the broadband masker condition, both HRTFs provided masking release in horizontal directions but generic HRTF gave little effect in vertical directions. However, for the low-pass masker condition, generic HRTF showed prominent decrease of MLDs in horizontal directions. Individual HRTFs provided higher signal detectablity in most signal-masker combinations, but generic HRTF gave similar detectability compared to individual HRTFs for horizontal directions - broadband masker combination. These results suggest that HRTF filtering can improve signal detectability in the hear-through technology, and even generic HRTF can provide higher detectability than normal stereophonic presentation in the horizontal plane.

5.1 Further study

A binaural pink noise can be recorded using dummy head in an anechoic chamber, and used for the masker to realise more practical condition for hear-through headphone environment. This approach will provide dichotic masker noise which reflects the coherence of the ears instead of diotic masker noise used in this experiment.

References

[1] Algazi, V., Duda, R., Thompson, D., and Avendano, C. The CIPIC HRTF database. In *Proceedings of the 2001 IEEE Workshop on the Applications of Signal Processing to Audio and Acoustics (Cat. No.01TH8575)* (2001), no. October, IEEE, pp. 99–102.

[2] Buchholz, J. M., Hickson, L., Dillon, H., Glyde, H., and Cameron, S. The importance of interaural time differences and level differences in spatial release from masking. *The Journal of the Acoustical Society of America 134*, 2 (2013), EL147–EL152.

[3] Carhart, R., Tillman, T. W., and Greetis, E. S. Release from Multiple Maskers: Effects of Interaural Time Disparities. *The Journal of the Acoustical Society of America 45*, 2 (1969), 411–418.

[4] Carlile, S., and Wardman, D. Masking produced by broadband noise presented in virtual auditory space. *The Journal of the Acoustical Society of America 100*, 6 (1996), 3761–3768.

[5] Durlach, N., and Colburn, H. *Handbook of perception.* New York: Academic Press, Inc, 1978.

[6] Durlach, N. I. Equalization and Cancellation Theory of Binaural Masking Level Differences. *The Journal of the Acoustical Society of America 35*, 8 (1963), 1206–1218.

[7] EBU-R 128. Loudness normalisation and permitted maximum level of audio signals, 2014.

[8] Edmonds, B. A., and Culling, J. F. The role of head-related time and level cues in the unmasking of speech in noise and competing speech. *Acta Acustica united with Acustica 91*, 3 (2005), 546–553.

[9] Edmonds, B. A., and Culling, J. F. The spatial unmasking of speech: evidence for within-channel processing of interaural time delay. *The Journal of the Acoustical Society of America 117*, 5 (2005), 3069–3078.

[10] Gardner, W. G., and Martin, K. D. HRTF measurements of a KEMAR. *The Journal of the Acoustical Society of America 97* (1995), 1465.

[11] Hall, J. W., Cokely, J. A., and Grose, J. H. Combined monaural and binaural masking release. *The Journal of the Acoustical Society of America 83*, 5 (1988), 1839–1845.

[12] Hall, J. W., Tyler, R. S., and Fernandes, M. A. Monaural and binaural auditory frequency resolution measured using bandlimited noise and notched noise masking. *The Journal of the Acoustical Society of America 73*, 3 (1983), 894–898.

[13] Härmä, A., Jakka, J., Tikander, M., Karjalainen, M., Lokki, T., Hiipakka, J., and Lorho, G. Augmented reality audio for mobile and wearable appliances. *AES: Journal of the Audio Engineering Society 52*, 6 (2004), 618–639.

[14] Iida, K., Itoh, M., Itagaki, A., and Morimoto, M. Median plane localization using a parametric model of the head-related transfer function based on spectral cues. *Applied Acoustics 68*, 8 (aug 2007), 835–850.

[15] Jot, J.-M., and Lee, K.-S. Augmented Reality Headphone Environment Rendering. In *Audio Engineering Society Conference: 2016 AES International Conference on Audio for Virtual and Augmented Reality* (2016).

[16] Levitt, H. Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical society of America 49*, 2B (1971), 467–477.

[17] Martin, A., Jin, C., and Van Schaik, A. Psychoacoustic evaluation of systems for delivering spatialized augmented-reality audio. *AES: Journal of the Audio Engineering Society 57*, 12 (2009), 1016–1027.

[18] Moore, B. C. J., and Edition, S. *An Introduction to the Psychology of Hearing*, vol. 6. 2012.

[19] Sutojo, S., van de Par, S., and Schoenmaker, E. Contribution of binaural masking release to improved speech intelligibility for different masker types. *European Journal of Neuroscience*, May (2018), 1–14.

[20] Valimaki, V., Franck, A., Ramo, J., Gamper, H., and Savioja, L. Assisted listening using a headset: Enhancing audio perception in real, augmented, and virtual environments. *IEEE Signal Processing Magazine 32*, 2 (2015), 92–99.

[21] van de Par, S., and Kohlrausch, A. Dependence of binaural masking level differences on center frequency, masker bandwidth, and interaural parameters. *The Journal of the Acoustical Society of America 106*, 4 (1999), 1940–1947.

[22] van der Heijden, M., and Trahiotis, C. Binaural detection as a function of interaural correlation and bandwidth of masking noise: Implications for estimates of spectral resolution. *The Journal of the Acoustical Society of America 103*, 3 (1997), 1609–1614.

[23] Zurek, P. M., and Durlach, N. I. Masker bandwidth dependence in homophasic and antiphasic tone detection. *The Journal of the Acoustical Society of America 81*, 2 (1986), 459–464.

Appendix A MLD data by each individual : KEMAR HRTF

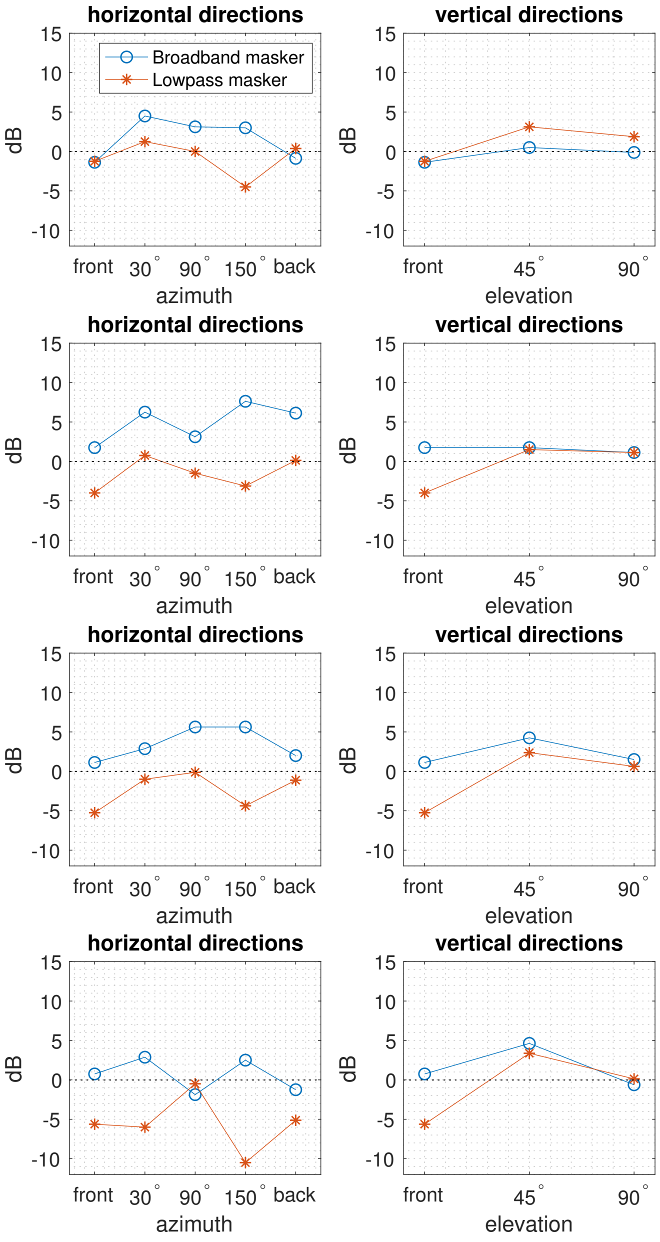


Figure 7: *Masking level difference of signals applied with KEMAR HRTF as a function of signal direction for two subjects*

Appendix B   MLD data by each individual : Individual HRTFs

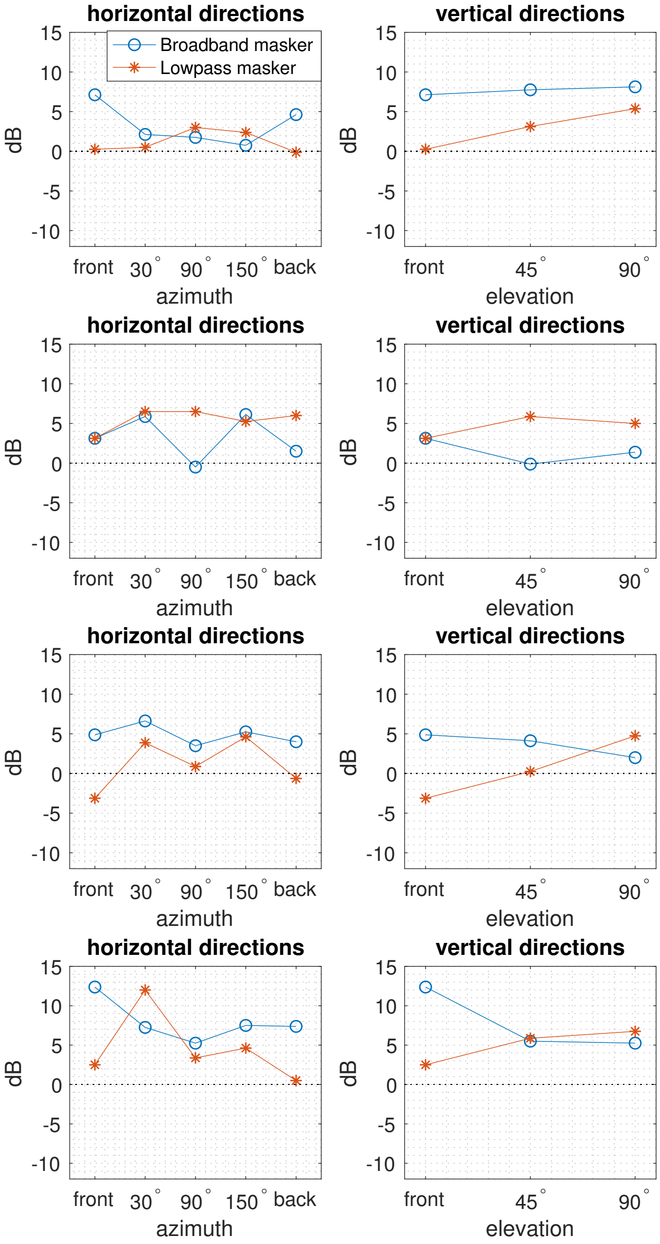


Figure 8: *Masking level difference of signals applied with each individual HRTF as a function of signal direction for two subjects*