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Hearing protections: Effects on HRTFs and localization accuracy

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Abstract

Protecting the auditory system from dangerous sound pressure levels is essential for many professionals and people in daily life. Wearing hearing protections devices (HPDs) or tactical communication and protection systems (TCAPS) modifies the geometry of the auricle. The user cannot adapt instantaneously to the modified HRTF, leading to a less accurate sound source localization. Listening test showed that front-back confusions are the major error type. Three different models of TCAPS were analysed to gain information about their influence on sound source localization capabilities and on the modifications in the listener's HRTF. HRTF measurements on different dummy heads were done during four scenarios: dummy head without TCAPS, dummy head wearing two different in-ear TCAPS (earplugs) and one on-ear TCAPS (earmuffs). Sound source localization tests were conducted with subjects under the same four scenarios. Based on those results concepts for prototype of new generation TCAPS are presented.

Keywords: hearing protection, sound source localization, HRTF, front-back confusion, TCAPS

1 INTRODUCTION

Sound source localization is performed by the brain and the auditory system and helps humans in daily life to orientate them and to analyze their environment. With the natural hearing sound source localization is a quite simple task, which is performed by the brain with high accuracy. It allows separating the individual sound sources in a multi-source scene and recognizing dangers. Beside the interaural time difference (ITD) and the interaural level difference (ILD), the individual Head-Related Transfer Function (HRTF) contributes in identifying sound sources [1]. The HRTF filters the incoming sound depending on the angle of incidence and introduces spectral cues, containing directional information. The HRTF is defined by the individual geometry of the listener's anatomy (torso, head, and auricle). The listener's brain is well trained to his own HRTF and hence sound source localization is performed with high accuracy [2].

In certain situations it is necessary to wear hearing protection to prevent hearing disorders. Either hearing protection devices (HPDs) or tactical communication and protection systems (TCAPS) can be used, but independently of the model, they all change the geometry of the auricle. This change in geometry leads to instantaneous changes in the HRTF and in the spectral cues. The listener cannot adapt instantaneously to the modified HRTF. This results in a less accurate sound source localization. Listening test showed that independently of the type of TCAPS the accuracy of sound localization decreases significantly and front-back confusion is the major error type [3][4][5][6][7]. The loss of localization accuracy with hearing protection is reported by many authors, but only few provide solutions to preserve the localization performances. Joubaud [9] and Rubak and Johansen [8] propose to integrate an auricle like geometry on the outside of an earmuff shelf, such that directional information is introduced to the sound that is captured by the TCAPS's outside microphone.

Also hearing aids have to deal with the issue of modified directional cues and the degradation of the accuracy of sound localization by the user. It is reported by Biggins [10] and Bishop [11] that with reduced geometry of the hearing aid's earplug improved sound source localization is obtained. The performance obtained with in-the-ear (ITE) hearing aids was quite poor and with in-the-canal (ITC) devices it was already acceptable. With complete-in-the-canal (CTC) hearing aids the performance was nearly as good as with a healthy natural hearing.

Four different TCAPS are used in the presented work to identify their influence on the sound localization performance and on the HRTF. Protection P1 (*BANG* by ISL) and protection P3 (*QuietPro* by Nacre) are earplug-based talk through TCAPS with dynamic talk through gain. Protection P2 (*Z111* by Z-Tac) is a talk through earmuff TCAPS with dynamic talk through gain and protection P4 (*X5A* by 3M) is a passive earmuff hearing protection. These TCAPS are used for the localization tests with human subjects and the HRTF measurements on dummy heads. The HRTFs are measured with three different dummy head configurations: DH1 (ISL dummy head with Type 3.4 ear simulators), DH2 (ISL dummy head with Type 3.3 ear simulators) and DH3 (B&K Head and Torso simulator with Type 3.3 ear simulators).

2 METHODS

2.1 Localization test

The localization test is intended to be conducted with subjects having a normal hearing. The hearing performance of the subjects is obtained by measuring the left and right ear audiogram, with the help of a Bekesy test. The tested frequencies range from 125 Hz to 8 kHz in steps of octaves.

The listening test is performed in a listening room, which is optimized for speech listening test. The RT60 reverberation time of the listening room is 290 ms. The subject takes place on a seat at the listening positions. A circular loudspeaker array of 16 equally spaced JBL Control 1 Pro speakers surrounds the listening positions. The loudspeakers are located at $\phi_{SP} = 0°, 22.5°, 45°, ..., 337.5°$. If not otherwise stated, the reference coordinate system is a right hand coordinate system with its origin at the center of the circular array. The angle direction $\phi = 0°$ is directly in front of the listener. The diameter of the array is 2.20 m. The seat is adjustable in height, such that the interaural axis of the subject aligns the speaker's plane. A curtain is mounted in front of the speakers, such that the subject can't see the speaker's location.

Two groups are defined: the test group and the control group. The subjects are randomly attributed to those groups. Members of the test group complete a training and before they perform the actual test, those of the test group perform directly the actual test. The subjects have to steer a cursor on a tablet computer in the direction where he located the presented test sound and confirm his answer. The localization test is designed as unforced choice test, thus the cursor can be positioned to point in any direction. The test sound consists of 200 ms of white noise. Only real sound sources are tested. The sound level at the listening position is 72 dB SPL $\pm$ 3 dB. For each test sound the sound level is chosen randomly within the limits of this interval. Each of the sound source directions is presented twice during training and five times during testing. The order of presenting the 32 resp. 80 directions is chosen randomly. During training the subject gets a visual feedback on the tablet computer of the actual direction after having confirmed his answer.

Each subject has to perform the localization test under multiple hearing conditions (HC). The first hearing condition is always the natural hearing (HC0), followed by a random order of HC1 (hearing condition with protection P1), HC2 (hearing condition with protection P2), HC3 (hearing condition with protection P3) and HC4 (hearing condition with protection P4). Prior to the localization test each subject gets 60 s to familiarize with the test. They can freely set the direction of a music sound source by pointing the cursor on the table in the desired direction.

The data which is collected for each tested sound is called *data set*. It includes the gain factor of the SPL modulation, the true sound direction ϕ_t, the subject's response ϕ_u and the response time t_r. The metadata contains information about the subject, including the group, the gender, the year of birth, the handedness and the hearing condition.

2.2 Metrics for localization test

Based on the error ε, defined in equation 1, nine metrics for the evaluation of the localization test are defined:

$$\varepsilon = \Phi_u - \Phi_t \begin{cases} +360 & \Phi_u - \Phi_t < -180 \\ -360 & \Phi_u - \Phi_t > 180 \end{cases} \tag{1}$$

M1: Standard deviation error

$$sde = std\,(\varepsilon) \tag{2}$$

M2: Root mean square error

$$err = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} \varepsilon(i)^2} \tag{3}$$

M3: Accuracy

$$accu = mean\left(abs\left(\left(\frac{\Phi_u}{22.5} \mod 1\right) - 0.5\right) \cdot 2\right) \tag{4}$$

M4: Front-Back Confusion Rate The Front-Back confusion rate is defined as the ration of the number of samples where the subject's response and the true direction are front-back inverted to the number of overall tested samples.

M5: Left-Right Confusion Rate The Left-Right confusion rate is defined as the ration of the number of samples where the subject's response and the true direction are left-right inverted to the number of overall tested samples.

M6: Mixed Confusion Rate The Mixed confusion rate is defined as the ration of the number of samples where a front-back and left-right confusion appear to the number of overall tested samples.

M7: Left-Right Drift

$$\begin{aligned} n^+ &= count\,(\varepsilon > 0)\,|\Phi_t \in [0,90[\cup]270,360] \\ n^- &= count\,(\varepsilon < 0)\,|\Phi_t \in [90,270[\\ n &= count(\Phi_u)|\Phi_t \in \Phi_s \setminus \{90,270\} \\ d_{LR} &= \frac{n^+ + n^-}{n} \end{aligned} \tag{5}$$

M8: Front-Back Drift

$$\begin{aligned} n^+ &= count\,(\varepsilon > 0)\,|\Phi_t \in]180,360[\\ n^- &= count\,(\varepsilon < 0)\,|\Phi_t \in]0,180[\\ n &= count(\Phi_u)|\Phi_t \in \Phi_s \setminus \{0,180\} \\ d_{FB} &= \frac{n^+ + n^-}{n} \end{aligned} \tag{6}$$

M9: Frontal-Median Drift

$$\begin{aligned} n^+ &= count\,(\varepsilon > 0)\,|\Phi_t \in [0,90[\cup]180,270] \\ n^- &= count\,(\varepsilon < 0)\,|\Phi_t \in [90,180[\cup]270,360] \\ n &= count(\Phi_u)|\Phi_t \in \Phi_s \setminus \{0,90,180,270\} \\ d_{FM} &= \frac{n^+ + n^-}{n} \end{aligned} \tag{7}$$

2.3 HRTF Measurement

The HRTF Measurements are performed in an anechoic chamber of a volume of $42.34\,m^3$ and RT60 reverberation time of 240 ms. During the HRTF measurement the current dummy head is mounted on a turn tabled. The position of the turn table can be controlled electronically and the HRTF is measured at an elevation angle $\theta = 0°$ and azimuth angles $\phi = 0°, 22.5°, 45°, \ldots, 337.5°$. A sine sweep signal ranging from 20 Hz to 20 kHz is used for the HRTF measurement, generated by Standford Research Signal Analyzer SR780. The signal is passed through a power amplifier DaytonAudio MA1260 and played back via a JBL Control 1 Pro loudspeaker. The speaker is distanced by 3 m from the center of the dummy head. The signals of the dummy head's left and right microphone are preamplified by B&K Type 5935L and passed to the signal Analyzer. The signal analyzer evaluates the transfer function $\mathrm{HRTF_{RAW}}^{\mathrm{L}}(\mathrm{f}, \phi)$, resp. $\mathrm{HRTF_{RAW}}^{\mathrm{R}}(\mathrm{f}, \phi)$ at 1600 frequency points. The free field transfer functions $\mathrm{HRTF_{FF}}^{\mathrm{L}}(\mathrm{f}, \phi)$ and $\mathrm{HRTF_{FF}}^{\mathrm{R}}(\mathrm{f}, \phi)$ are obtained by dividing $\mathrm{HRTF_{RAW}}^{\mathrm{L}}(\mathrm{f}, \phi)$, resp. $\mathrm{HRTF_{RAW}}^{\mathrm{R}}(\mathrm{f}, \phi)$ by the transfer function of the measurement system. This transfer function is obtained by replacing the dummy head and turntable by a reference microphone, while preserving the remaining measurement setup and measuring the transfer function of the system.

The dummy heads are equipped with matched microphones and their geometries are perfectly symmetric along the median plane, hence it can be assumed that the HRTFs, and consequently $\mathrm{HRTF_{FF}}^{\mathrm{L}}(\mathrm{f}, \phi)$ and $\mathrm{HRTF_{FF}}^{\mathrm{r}}(\mathrm{f}, \phi)$, are perfectly symmetric along the median plane. Accordingly to Jauboud [9] the front-back difference, average for each quadrant are calculated for the ipsi and contralateral side. This representation will be referred to as Ipsi- & Contralateral Front-Back (ICFB) representation. ICFB contains two functions: one for the ipsilateral side and one of the contralateral side. Each of them is based on the difference between the frontal quadrant HRTF and back quadrant HRTF.

The root mean square (RMS) distance is used to evaluate measured HRTFs. The RMS distance $RMS^{\xi}_{i,i+1}$ between two ICFB curves ($ICFB(f)^{\xi}_{i}$ and $ICFB(f)^{\xi}_{i+1}$) can be calculated for the ipsilateral (ξ = I), resp. contralateral (ξ = C) side, as shown in equation 8. $\delta^{\xi}_{i,i+1}$ is the distance between the i-th and $i+1$-th ICFB curve.

$$RMS^{\xi}_{i,i+1} = \sqrt{\frac{1}{N}\sum_{f=1}^{N}\delta^{2}_{i,i+1}(f)} \tag{8}$$

The RMS distance is calculated for the HC0 hearing conditions between the different dummy head configurations. Further, for each dummy head configuration the RMS distance between the HC0 hearing condition and the hearing conditions HC1 to HC4 is calculated.

3 RESULTS

Note: Due to the number of subjects which has participated so far, the results of the listening test have to be considered as preliminary.

3.1 Listening test

5 subjects (3 male, 2 female) have completed the listening test. The average of their age is 30.6, their age spanned the interval from 20 years to 57 years. 3 subjects were left handed, while 2 were left handed. The Bekesy audiograms showed normal hearing characteristics for all subjects. The average answer time of all subjects was 261 ms. The results of the Standard deviation error (M1), the RMS error (M2), the accuracy (M3), the front-back (M4), left-right (M5), and mixed (M6) confusion rate and the response time t_r are listed in Table 1. The data is shown respectively for the test group and control groups and each hearing condition. The metrics of the left-right drift (M7), front-back drift (M8) and median-frontal drift (M9) are listed in Table 2 with respect to the handedness of the subjects and the hearing condition, regardless of the subject's group.

Table 1. Metrics as defined in section 2.2 and minimum, average, and maximum answer time t_r

		HC0		HC1		HC2		HC3		HC4	
Metric	Unit	TG	CG	TG	CG	TG	CG	TG	CG	TG	CG
M1	deg	21.72	45.24	33.78	61.71	61.44	62.88	53.63	58.86	60.88	59.80
M2	deg	21.89	45.27	33.71	61.59	62.47	62.83	53.52	58.79	60.76	59.68
M3	–	0.61	0.57	0.60	0.54	0.62	0.57	0.64	0.59	0.60	0.56
M4	–	0.06	0.18	0.10	0.31	0.47	0.41	0.26	0.36	0.42	0.29
M5	–	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
M6	–	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.02
min(t_r)	s	1.28	0.78	1.11	0.62	1.03	0.73	1.00	0.81	1.03	0.80
avg(t_r)	s	3.40	2.92	2.61	2.09	2.82	2.40	2.45	2.26	2.82	2.40
max(t_r)	s	6.47	10.94	12.89	5.89	6.75	7.34	5.23	6.67	8.44	12.23

Table 2. Drift metrics M7 (left-right), M8 (font-back) and M9 (frontal-median) of the left (LH) and right handed (RH) subjects for hearing condition HC0 to HC4.

	HC0		HC1		HC2		HC3		HC4	
Drift	LH	RH	LH	RH	LH	RH	LH	RH	LH	RH
M7	0.56	0.53	0.56	0.54	0.56	0.56	0.61	0.54	0.46	0.57
M8	0.79	0.53	0.7	0.48	0.74	0.50	0.70	0.47	0.71	0.48
M9	0.60	0.75	0.68	0.76	0.69	0.90	0.72	0.82	0.67	0.86

3.2 HRTF Measurement

The upper part of Table 3 shows the RMS distance of the ICFB curves obtained with the dummy head configurations DH1, DH2, DH3 during hearing condition HC0. Lower part of the table shows the RMS distance between different hearing conditions of the same dummy head configuration. The columns represent the dummy head configurations in the HC0 hearing conditions.

Table 3. RMS distances between the ipsilateral and contralateral ICFB curves for different dummy head configurations.

	ipsi			contra		
	DH1	DH2	DH3	DH1	DH2	DH3
DH1	–	–	–	–	–	–
DH2	3.94	–	–	3.95	–	–
DH3	3.47	2.08	–	2.41	2.33	–
	HC0			HC0		
HC1	–	2.98	2.63	–	2.39	3.58
HC2	–	4.93	4.51	–	3.57	7.66
HC3	1.93	3.38	3.57	3.73	2.72	2.54
HC4	–	4.56	4.83	–	5.66	3.03

4 DISCUSSION

4.1 Localization test

By its definition in equation 2 the standard deviation error can be interpreted as the precision of a subject. From Table 1 it can be obtained that the standard deviation error and the RMS error are in average linear dependent with a factor of 0.9987. For the hearing condition HC0 and HC1 an improvement of the precision can be obtained by passing the training. The subjects of the test group localize the sound directions nearly twice precise as those who haven't performed the training. This does not hold for hearing condition HC2 to HC4. There no particular improvement or degradation of the precision can be obtained.

Regardless of the hearing condition the accuracy gets improved by a least 0.04 when the subjects have completed the training. A learning process can be therefore obtained, which is due to the visual feedback the subjects get during training. They get adapted to the direction of the sound sources and get trained to point more frequently to the direction where they remember the true sound positions. Their responses are closer to a loudspeaker position, than the responses of those subject without training.

The highest front-back confusion rates is obtained with HC2 which has an asymmetric distribution of microphones. Its microphone on each side is oriented towards the front. The least front-back confusion rates is obtained with the natural hearing (HC0). There appear no modifications in the HRTF and the subjects are best trained to this hearing condition. Regarding the front-back confusion rate two trends can be obtained: With HC0, HC1, and HC3 less front-back confusions are obtained for the test group than for the control group. With HC2 and HC4 more front-back confusions are obtained for the test group than for the control group. P2 and P4 are earmuffs covering the entire outer ear in contrast to the in-ear devices P1 and P3 which don't. Reducing the size of the earplug and avoiding earmuff designs help to decrease the front-back confusion. This effect was also obtained by Zimpfer [5] and Biggins [10].

Mixed confusion rates and left-right confusion rates are nonzero in four hearing conditions. The nonzero values reach a maximum of 0.02. Hence these hearing protections do not have any remarkable effect on this type of localization error.

The average response time is the highest for the test group with hearing condition HC0. The reduced average response time in the hearing conditions HC1 to HC4 might be due to adaption process, but also due to the subject's motivation. HC0 is the first round in the test, where the subjects might be highly motivated to achieve good localization results. After having passed in the HC0 hearing conditions, the test does not provide new motivation to the subject, consequently the subjects accelerate.

The results in Table 2 show that there is no particular drift to the left resp. right side as a function of the subject's handedness. For left and right handed subjects the M7 metric (left-right drift) varies between 0.46 and 0.61 without a link between the drift direction and the handedness of the subject. Same holds for the M8 metric (front-back drift). For the M9 metric (frontal-median drift) a trend towards the median plane (values greater than 0.5) can be observed for all hearing conditions. Sound sources are perceived more frequent towards 0° and 180°, than towards 90° and 270°. As this trend can be also observed for the hearing condition HC0, this effect is not only due to the hearing protection, but also to the concept of the localization test.

4.2 HRTF measurement

The RMS distances of the ICFB curves, obtained with the different dummy head configurations with hearing condition HC0, define the range of tolerance. HRTF whose RMS distances values lie within this interval are considered not to be modified seriously. The interval of tolerance range to 3.94. Applying this interval to the lower part of Table 3, it can be obtained that the HRTFs measured with P2 and P4 show important modifications. This holds for all of the measured ipsilateral HRTFs and dummy head configurations. P2 and P4 are earmuff based HPDs introducing high HRTF modifications. P1 and P3 which are in-ear devices introduce HRTF modifications which lie in the tolerance interval. Hence the smaller the geometries of the hearing protection is and the less it covers the geometry of the helix, the less HRTF modifications are caused.

5 CONCLUSIONS

A localization test was conducted with subjects under five hearing conditions. The subjects had to perform the localization with their natural hearing and with four different models of TCAPS. HRTF measurements were performed on different types of dummy heads in an anechoic chamber. The HRTF measurements were done with the same hearing conditions which were used for the localization test. The degradation of the HRTF introduced by TCAPS was presented and discussed. The performance of the subjects during the localization test was discussed and compared to the obtained HRTF degradation. It was obtained that a training can help to improve the sound localization and reduce the front-back confusion for certain TCAPS.

The design of the new TCAPS either have to consist of a small dimensions of the in-ear earplugs to avoid any major modifications of the geometry of the helix. Or, in the case of earmuff devices, they have to be equipped with additional signal processing elements, e.g. microphones and filters to reconstruct the original directional information and to prevent any HRTF modifications. The design of signal processing chains mounted on earmuffs based TCAPS is the task of current studies and this work will be presented in the future.

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