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Electronic pass-through hearing protection and directional hearing restoration integrated in a helmet

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Compared to standard earplugs used for hearing protection, electronic pass-through earplugs provide better sound localisation, provided that the bandwidth is sufficiently wide and the earplugs do not change the shape of the pinnae. However, when in addition a helmet is worn that covers the ears, the directional hearing capability might be further diminished.

We attempt to restore directional hearing when wearing a helmet by attaching a microphone array to the helmet. A pilot study has been performed to determine the influence of electronic pass-through hearing protection and of helmets on sound localisation. Participants had to localise short sound bursts and perform a speech intelligibility test.

The preliminary results showed that wearing helmets that covered the ears decreased the sound localisation performance significantly compared to when the ears were left free. However, the speech intelligibility increased. When participants wore active hearing protection instead of helmets the directional hearing capability decreased and the speech intelligibility remained equal.

1 Introduction

Nowadays in-ear electronic pass-through hearing protection become increasingly popular. These earplugs contain a small microphone outside the ear and a speaker inside the ear canal. Under normal conditions environmental sounds will be fed unattenuated to the ear canal as if there were no earplugs present. When the ambient noise level becomes too high, the sounds will be electronically attenuated. Communication signals from radio or intercom can be mixed in. However, like ordinary hearing protection the sound localisation is reduced [1, 3, 4, 6, 7, 17, 18]. Electronic pass-through hearing protection changes the shape of the pinna; the concha is often totally covered and the microphone sticks nearly outside the ear. The pinna plays an important role in sound localisation; it colours sound differently when coming from different directions. This is primarily important for distinguishing sounds coming from different elevations. Sounds coming from different azimuths are mainly distinguished by interaural level and time differences [16], however they are preserved in pass-through hearing protection. Brungart [7] showed that the localisation error increased to approximately 40 degrees when electronic pass-through earplugs were worn. The loss of directional hearing reduces the ability to separate multiple sound sources or voices. Probably, speech intelligibility will decline in crowded places when electronic pass-through earplugs are worn.

Often a helmet is worn in combination with hearing protection. A helmet changes the shape of the head. On its own it will influence the perception of sounds, especially when the ears are partially or completely covered. In the latter two cases sounds from behind will be shielded by the helmet. The effect of hearing protection and helmet combined on directional hearing is yet unclear. One might argue that the helmet colours sounds coming from behind, reducing the number of front-back confusions.

In an attempt to restore the directional hearing when electronic pass-through earplugs and a helmet are worn together, Bronkhorst proposed a microphone array based system that can be attached to a helmet [5]. This was also proposed by Goldstein [11, 12]. We followed this approach. In our implementation the signals from the microphone array are filtered with Finite Impulse Response (FIR) filters to recreate an individual or generic open-ear Head-Related Transfer Function (HRTF) and effectively recreate the normal open ear condition. The filters are designed by minimisation of an error measure in the frequency domain. The error measure incorporates both the log magnitude and the phase differences between the original and the recreated HRTF. The global minimum is found using modern optimisation techniques like Particle Swarm Optimisation (PSO) or Differential Evolution (DE) [8]. These techniques reduce the chance of finding a local minimum instead of the global minimum.

In order to evaluate this solution we designed an experimental setup that provides a novel way for subjects to indicate the direction where a sound comes from. Often participants have to point to the location with a stick, or their arm. This results in parallax errors. Or they have to indicate the location on a miniature sphere. In our approach it is a nose pointing task that is assisted with a head-mounted display (HMD). In the HMD the participant sees a virtual sphere that is aligned with the measurement setup and the direction he or she is looking at.

We used this method in a pilot study in which the influence of electronic pass-through earplugs and of helmets on the directional hearing performance was examined. In addition, we tested the speech intelligibility of a target talker with two spatially separated interfering talkers. In this paper the preliminary results are listed.

2 Experimental setup

The experiment was performed in an anechoic chamber at the TNO facilities. Both directional hearing performance and speech intelligibility were tested under five conditions. These conditions are listed below. The helmet worn by the participants in some conditions was an army helmet. Originally the helmet partially covers the ears. The parts that covered the ears were removed to leave the ears free, but they could be reattached. The pass-through hearing protection was a HiFi commercial in-ear system meant for musicians. The claimed bandwidth of the system was 20 Hz–16 kHz. The system's earplugs primarily filled the conchas.

1. Open ears;
2. Helmet that leaves the ears free;
3. Helmet that partially covers the ears;
4. Electronic pass-through hearing protection;
5. Electronic pass-through hearing protection together with a helmet (ears partially covered).

2.1 Sound localisation

For the sound localisation experiment the participants were seated on a swivel stool placed at the centre of a movable hoop (see Fig 1). Attached to the hoop was a trolley with a single loudspeaker. The movements of the hoop and the trolley were computer controlled enabling us to deliver sounds from almost any position on a sphere enveloping the participant. The participants wore a lightweight HMD (Z800 3DVisor from eMagine). Attached to it was a 3Space Fastrack head tracker from Polhemus. The HMD showed the inside of a sphere that was aligned with the hoop. The sphere had three grid lines: one at 0 degrees azimuth, one at 90 degrees azimuth and one at 0 degrees elevation. Colour gradients were used to give the participants a sense of left, right, up and down. A cursor at the centre of the HMD indicated the looking direction of the participant. When the participant moved his or her head or swivelled around with the stool, the sphere remained stationary relative to the hoop.

During the experiment the participants had to locate pink noise bursts of 250 ms at 75 dBA measured at the centre of the hoop. The sounds came from 42 different directions between −30 and +30 degrees of elevation. Eleven directions were located both in the front and rear quadrant, ten direction in both the left and right quadrant. The location had a random offset in both azimuth and elevation of −5, 0 or +5 degrees. The participant had to look straight forward when a sound stimulus was presented. Then by rotating the swivel chair and by moving the head, the participant had to align the cursor with the perceived direction of the sound and press a button. After the participant had returned to his starting position (within 5 degrees) the loudspeaker moved to a new position on the sphere. The sounds of the moving hoop and trolley were masked with noise to ensure that the participants could not track the position of the speaker. In addition, the experiment was run in complete darkness.

Figure 1: The measurement setup for the sound localisation experiment in the anechoic room. The participant wears a HMD and is seated on a swivel stool. He can turn around 180 degrees to the left and the right. The loudspeaker is attached to a trolley and can move along the hoop that can rotate around the participant. The experiment took place in the dark.

2.2 Speech reception threshold

The speech intelligibility was tested using the Speech Reception Threshold (SRT) test [9]. Participants were seated again on the same swivel stool. Three loudspeakers were placed around the participant at 0 degrees of elevation. One loudspeaker was in front at 0 degrees of azimuth. The other two loudspeakers were placed behind the participant at −120 and +120 degrees azimuth. The front loudspeaker presented a male target talker, the rear loudspeakers two different male competing talkers. The task of the participant was to reproduce short sentences uttered by the target talker without a single error. If the participant failed to do so, the loudness of the target talker was increased, else the loudness was reduced. The relative loudness was determined at which the participant could reproduce 50% of the sentences correctly. All sentences were presented at 60 dBA at the location of the participants head.

3 Data analysis

3.1 Sound localisation

For each stimulus direction a response direction is measured. The error angle ($\theta_{E,i}$) between the ith stimulus-response pair is calculated using

$$\theta_{E,i} = \arccos\left(\vec{x}_{S,i} \cdot \vec{x}_{R,i}\right), \qquad (1)$$

in which $\vec{x}_{S,i}$ and $\vec{x}_{R,i}$ are respectively the ith stimulus and response directions expressed in 3D Cartesian coordinates. The value of $\theta_{E,i}$ is always between 0 and 180 degrees. For the analysis the error angles are grouped per condition and all the data of the participants are pooled. For each condition the mean direction $\bar{\theta}_E$ is calculated for $i = 1, \ldots, n$ with n the total number of stimulus-response pairs [10, 15].

$$\bar{C} = \frac{1}{n}\sum_{i=1}^{n} \cos\theta_{E,i}, \qquad (2)$$

$$\bar{S} = \frac{1}{n}\sum_{i=1}^{n} \sin\theta_{E,i}, \qquad (3)$$

$$\bar{\theta}_E = \arctan\left(\bar{S}/\bar{C}\right). \qquad (4)$$

The error angles are distributed on a finite scale and the distribution is highly skewed. This makes ANOVA analysis of the data unreliable. The skewness also limits the possibility of fitting a circular distribution like the Von Mises distribution [10, 15], because it is a symmetric distribution. Parametric testing is not feasible, therefore we follow MacDonald [13] and calculate the 95% confidence interval of the mean error angle for each condition. The 95% confidence limits of the means are estimated with bootstrapping [14]. If the confidence intervals belonging to two conditions do not overlap, than they are statistically significant. If they do overlap, the amount of overlap gives an indication how similar the means are [2].

3.2 Speech reception threshold

The SRT test returns the ratio of the sound level of the target talker and the competing talkers for which 50% of the sentences are reproduced correctly. The threshold is expressed in dBs, with 0 dB indicating equal sound levels. A low threshold is better than a high threshold. The SRT values were averaged over the participants.

4 Results

The pilot experiments were performed by four unpaid participants (one female, three males). For each condition first the localisation test was done, then the SRT test. The two tests together took 20 minutes. After each block of two conditions the participants had a break of 10 minutes.

4.1 Sound localisation

The data of all participants for the sound localisation test were pooled. The mean error angle and its 95% confidence interval were calculated for each condition as described in Section 3.1. They are plotted in Fig 2. In this plot condition 1 and 2 have overlapping confidence intervals and mean error angles of approximately 14 degrees. The other conditions resulted in mean error angles that are approximately 10 degrees larger. Apparently, leaving the ears free (conditon 1 and 2) makes the difference. When the ears are partially covered (condition 3) the localisation performance decreases. Wearing electronic pass-through hearing protection (condition 4) seems to result in the largest localisation errors. Adding a helmet (condition 5) seems to reduce the mean error angle a bit, though the difference is not statistically significant. The mean error angle is probably smaller, because the helmet partially shields sounds from behind and colouring them. This reduces the fraction of front-back confusions (on average 14.9% for condition 4 and 8.3% for condition 5).

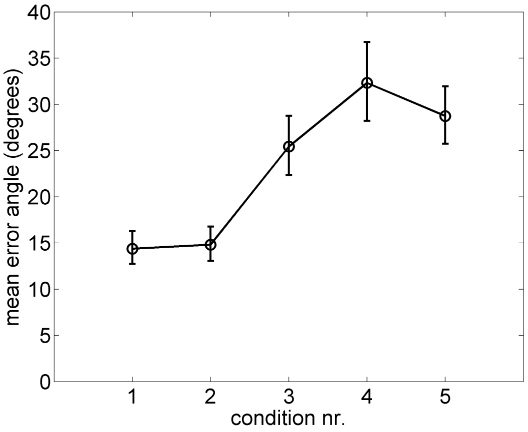

Figure 2: The sound localisation results plotted for each condition. The mean error angles ($\bar{\theta}_E$) and their 95% confidence intervals are shown.

4.2 Speech reception Test

The SRT thresholds of each participant and the average thresholds are plotted in Fig 3 for each condition. Although we have only data from four participant, the data seem to show a decrease in the SRT threshold when a helmet is worn that partially covers the ear (condition 3) compared with the open ear condition (condition 1). Probably, the helmet blocks the competing talkers from behind and catches the voice coming from straight ahead. This benefit does not seem to occur when earplugs are worn in addition to the helmet (condition 5).

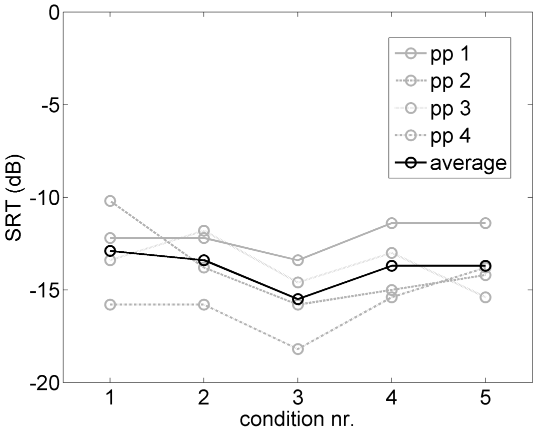

Figure 3: The results from the speech reception threshold experiment plotted for each condition.

5 Discussion

Although we used a different method for indicating the perceived direction, the localisation error of approximately 14 degrees that we have found for the open ear condition is similar to the results for short sound bursts Brungart published in 2003 [6]. Our data show that the mean angle error increases with approximately 10 degrees to 25 degrees when an electronic pass-through earplug is worn. Clearly, earplugs reduce the accuracy of sound localisation. Our results are not comparable with the results Brungart published in 2007 [7]. In that study the mean angle error was approximately 40 degrees. The systems tested in the Brungart's second study were commercially available electronic pass-through earplugs that used compression, whereas in the first study they were custom made. In both studies the bandwidth was limited to 6 kHz. In our study, it was limited to 16 kHz.

Wearing a helmet that partially covered the ear resulted in a mean error angle that was comparable with wearing the electronic earplug system. When the ears were left free, the results were similar to the open ear condition. It shows that the pinnae are important for good sound localisation. However, wearing a helmet that covers the ears did seem to improve the SRT results, because the two competing talkers from behind were shielded by the helmet.

Wearing both a helmet and earplugs did not seem to increase the localisation error significantly compared to either one of the two worn separately. However, wear-

ing electronic pass-through hearing protection seems to have more impact on sound localisation than wearing a helmet.
There is a need for a solution that brings the localisation error below the level that was measured when wearing a helmet. In the near future we want to test the microphone array solution mentioned in Section 1. It will be attached to the helmet that covers the ears. In addition, communication earplugs will be worn. We want to compare this system with open ears, electronic pass-trough hearing protection without helmet and with helmet. We will continue to use the nose pointing method assisted by HMD, because it provided the participants with an intuitive way to indicate the sound locations and gave consistent results in the pilot study.

References

[1] S. M. Abel, “Combined effects of hearing loss and hearing protection on sound localization: Implications for worker safety”, In *Scientific Basis of Noise-Induced Hearing Loss*, A. Axelsson et al. (Eds.), Thieme, New York, pp. 286–295 (1996)

[2] Chris Aberson, “Interpreting Null Results: Improving Presentation and Conclusions with Confidence Intervals”, *JASNH*, Vol. 1, No. 3, pp. 36–42 (2002)

[3] R. S. Bolia, R. L. McKinley, “The effects of hearing protectors on auditory localization: evidence from audio-visual target acquisition”, *International Journal of Occupational Safety and Ergonomics*, Vol. 6, pp. 309–319 (2000)

[4] R. S. Bolia et al., “Effects of hearing protectors on auditory localization in azimuth and elevation”, *Human Factors*, Vol. 43, pp 122–128 (2000)

[5] Adelbert W. Bronkhorst, Jan A. Verhave, “A Microphone-Array-Based System for Restoring Sound Localization with Occluded Ears.”, In *New Directions for Improving Audio Effectiveness*, pp. 20–1 to 20–8 (2005)

[6] Douglas S. Brungart et al., “The Effect of Microphone Placement on Localization Accuracy with Electronic Pass-through Earplugs”, In *IEEE Workshop on Applications of Signal Processing to Audio and Acoustics*, pp. 149–152 (2003)

[7] Douglas S. Brungart, Brian W. Hobbs, “A Comparison of Acoustic and Psychoacoustic Measurements of Pass-through Hearing Protection Devices”, In *IEEE Workshop on Applications of Signal Processing to Audio and Acoustics* (2007)

[8] David Corne, Marco Dorigo, Fred Glover, *New Ideas in Optimization*, McGraw-Hill International, London, Great Britain (1999)

[9] Rob Drullman, Adelbert W. Bronkhorst, “Multichannel speech intelligibility and talker recognition using monaural, binaural, and three-dimensional auditory presentation”, *J. Acoust. Soc. Am.*, Vol. 107, No. 4, pp. 2224–2235 (2000)

[10] N. I. Fisher, T. Lewis, B. J. J. Embleton, *Statistical analysis of spherical data*, Cambridge University Press, Cambridge, Great Britain (1993)

[11] Andre Goldstein et al., “Natural Hearing Restoration, Part I: Theory”, In *ACTIVE 04* (2004)

[12] Marty Johnson, James P. Carneal, Andre Goldstein et al., “Natural Hearing Restoration, Part II: Experimental Results”, In *ACTIVE 04* (2004)

[13] Justin A. MacDonald, Phuong K. Tran, “The Effect of Head-Related Transfer Function Measurement Methodology on Localization Performance in Spatial Audio Interfaces”, *Human Factors*, Vol. 50, No. 2, pp. 256–263 (2008)

[14] Bryan F.J. Manly, *Randomization, Bootstrap and Monte Carlo Methods in Biology*, CRC Press, Florida, USA (2001)

[15] Kanti V. Mardia, Peter E. Jupp, *Directional Statistics*, John Wiley & Sons, Chichester, England (2000)

[16] Angélique A. Scharine, Tomasz R. Letowski, “Factors Affecting Auditory Localization and Situational Awareness in the Urban Battlefield”, *Report ARL-TR-3474*, U.S. Army Research Laboratory, Aberdeen Proving Ground, U.S.A. (2005)

[17] G. F. Smoorenburg, F. W. M. Geurtsen, “De invloed van het dragen van gehoorbeschermers en van gehoorverliezen ten gevolge van lawaai op het richtinghoren”, *Report 1991 C17*, TNO Human Factors, Soesterberg, The Netherlands (in Dutch) (1991)

[18] N. L. Vause, D. W. Grantham, “Effects of earplugs and protective headgear on auditory localization ability in the horizontal plane”, *Human Factors*, Vol. 41, pp. 282–294 (1999)