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Spatial localization of sounds with hearing protection devices allowing speech communication

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Level-dependent hearing protection devices protect the ear against harmful noise exposure, like impulse noise with high peak pressure levels, but allow unaltered perception of the acoustic environment in quiet. Using this type of protection device, speech communication is possible. For these hearing protection devices (HPDs) two principles exist: 1) passive systems (like nonlinear earplugs) and 2) active systems (talk-through systems) using electronics for the reproduction of acoustic environment. The goal of this study is to quantify the degradation of spatial perception when these protections are worn. Tests are carried out to estimate the localization errors of sound in space with and without wearing level-dependent HPDs. Different kinds of protectors were tested. These tests show that the use of anyone of HPD impedes spatial perception: confusion between top-down as well as between front-back perceptions.

1 Study context

In many situations, it is very important to communicate as well as to perceive and to interpret the sound environment while being protected against the noise. In hearing protection, one distinguishes two types of hearing protection devices (HPDs): protectors with a fixed attenuation which is not depending on noise level and those with a variable attenuation depending on noise level. For this second type of protectors two principles exist:

- Passive protectors, such as nonlinear earplugs, allowing to attenuate impulse noise with high peak pressure levels.

- Active protectors, such as "talk-through" systems, with electronics controlling the sound level underneath the protectors.

Using this type of protection devices, speech communication is possible. They were evaluated for their characteristics concerning noise attenuation and intelligibility, but rarely for their impact on the localization of sound sources in space. The goal of this study is to quantify the modification of spatial perception compared to the bare ear when this type of protection device is worn. The modification is estimated with subjective measurements.

A first study was carried out in 2010 with only four different subjects [1]. This study indicated that wearing of hearing protectors increases confusion between back-front and between top-down. Moreover, with "talk-through" systems the degradation observed is more important than with nonlinear earplugs. The goal of this study is to verify this observation with a statistically relevant number of subjects.

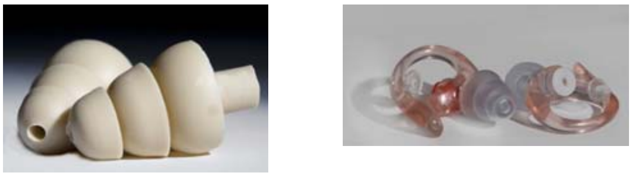
2 Experiment description

In order to quantify this degradation, we determined the ability of subjects to localize a sound source in space with and without wearing a hearing protector.

2.1 Tested hearing protection devices

Five HPDs (four earplugs and one earmuff): two passive protectors and three active protectors were tested (as shown in Figure 1):

- Nonlinear earplug (3M-AEARO) including "ISL nonlinear filter" (special delivery to the German armed forces), noted P1.
- EP4 nonlinear earplug (SUREFIRE) including Hocks-Noise-Braker® nonlinear filter, noted P2.
- QuietPro® earplug (NACRE), active talk-through system, noted P3.
- ComTac® earmuff (PELTOR), active talk-through system, noted P4.
- ISL prototype earplug active talk-through system, noted P5.



3M-AEARO Earplug ***SUREFIRE EP4***

NACRE QuietPro® ***PELTOR ComTac®***

ISL Prototype

Figure 1: Different HPDs used

2.2 Test setup

The localization measurements were conducted at IRBA (Biomedical Research Institute of the Army). Each subject is placed in the centre of a semi-anechoic chamber, on a seat raised to the height of 2 m in the centre of eight loudspeakers (as shown in Figure 2). The subject holds a sphere with eight buttons placed according to the position of the eight loudspeakers. This sphere is represented in Figure 3. The subject must press the button corresponding to the direction where the sound is localized. The responses of the subject and the actual sound source are stored for further analysis.

The noise used for localization tests is a wideband noise with a duration of 230 ms. During the tests, the noise level is fixed to 55 dB (lin) when the subject is without hearing protection and to 65 dB (lin) for protected subjects.

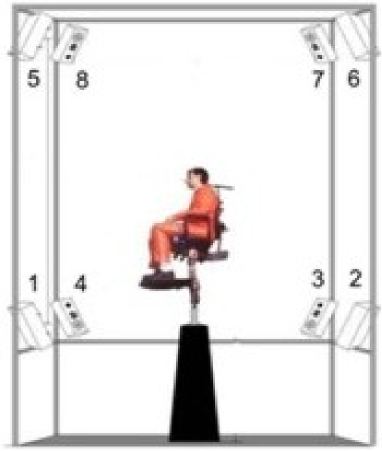


Figure 2: Representation of the arrangement of the semi-anechoic chamber for 3D localization of sound sources

Figure 3: Pointing device used by the subject (sphere with eight buttons) for localization response

2.3 Experimental procedure

20 subjects took part in the test: 10 women and 10 men. They were between 24 and 47 years old and had all normal hearing. Before the tests, each subject passed otoscopic and audiometric tests. All subjects were remunerated.

Before beginning the measurements, each subject passed three training series to become familiarized with the setup. These series were made up of eight sounds (one sound per loudspeaker) presented in random order.

After these training series, localization measurements were started. During a series, the subject listened to 80 sounds (ten sounds from each loudspeaker) in random order. Each subject participated in three series without hearing protector and two series with each of the tested protectors. Overall, each subject was exposed to 13 series.

In order to avoid lack of concentration the subjects were never exposed to more than four series during one test. Therefore the tests were run in four phases on four different days:

- First day: Explanation of the experimental setup and running of three training series and one series without hearing protectors.
- Second day: Running of four series with four different HPDs.
- Third day: Running of one series without hearing protector and three series with three different HPDs.
- Last day: Running of three series with three different HPDs and one series without hearing protection.

All tests were spread out over four weeks. The order of HPDs tested can vary. The five different orders given in Table 1 were used. Subject 1, subject 6, subject 11 and subject 16 had the same order of HPDs and so on.

Table 1: Different orders of HPDs

	Second day				**Third day**				**Last day**			
1	P1	P2	P3	P4	P5	TN	P1	P2	P3	P4	P5	TN
2	P2	P3	P4	P5	P1	P2	P3	TN	P4	P5	P1	TN
3	P3	P4	P5	P1	P2	P3	TN	P4	P5	P1	P2	TN
4	P4	P5	P1	P2	P3	P4	P5	TN	P1	P2	P3	TN
5	P5	P1	P2	P3	P4	P5	TN	P1	P2	P3	P4	TN

3 Results

For the analysis of the results, three types of localization errors and their combinations were taken into account:

- Confusion between top-down
- Confusion between back-front
- Confusion between right-left

On the 260 series conducted (on the 20 subjects), a few right-left confusion was observed. Table 2 shows the different responses observed:

Table 2: Distribution of the localization error in the confusion matrix

Emitted loudspeaker	HP6	🟪			🟩	🟦			⬛
	HP7		🟪	🟩			🟦	⬛	
	HP8		🟩	🟪			⬛	🟦	
	HP5	🟩			🟪	⬛			🟦
	HP2	🟦			⬛	🟪			🟩
	HP3		🟦	⬛			🟪	🟩	
	HP4		⬛	🟦			🟩	🟪	
	HP1	⬛			🟦	🟩			🟪
		HP1	HP4	HP3	HP2	HP5	HP8	HP7	HP6
		Subject's choice							

⬛	Correct response
🟩	Top-down confusion
🟦	Back-front confusion
🟪	Combined confusion (front-back and top-down)
	Other: 1- right-left confusion 2- combined confusion (right-left and top-down) 3- combined confusion (right-left and back-front) 4- combined confusion (right-left and top-down and back-front)

3.1 General results

After analyzing the responses of the subjects, we noticed that no subject obtained a more important rate of correct responses with HPDs than without HPDs. We applied the analysis of variances (ANOVA) to the data using two parameters: the HPDs (without and with) and the subjects. The main effects of HPDs ($F_{(5,114)}$=41.2, p<0.0001) were statistically significant. The main effects of subjects ($F_{(19,100)}$=0.41, p=0.98) were not significant. Also, the number of good responses is only depending on the HPDs and not on the subject.

Figure 4 shows the average rate of correct responses for each HPD, each gender and standard deviation. Figure 5 shows for each HPD the maximum and minimum values for the rate of correct responses. These figures show that the rate of correct responses without HPD is clearly more important than the one with HPD. This rate is about 95% with 5% standard deviation. We also noticed that this rate does not depend on the gender of the subject (except for HPD P1). As expected, all subjects could localize the sound in space without hearing protection.

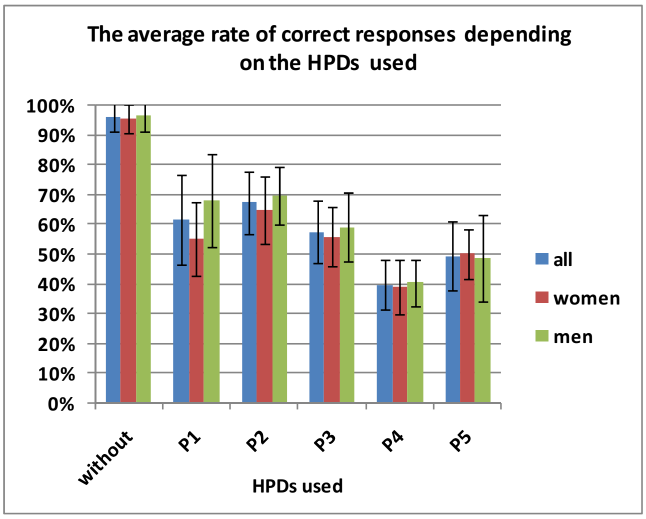


Figure 4: Average rate of correct responses with standard deviation for each HPD

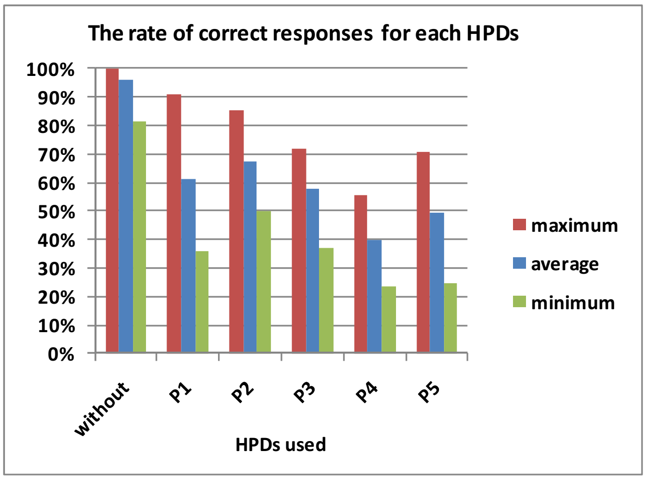


Figure 5: Dispersion of the rate of correct responses for each HPD: maximum in red, average in blue and minimum in green

In both figures, we notice that the average rate of correct responses with HPDs is relatively poor. Indeed, the average rate is lower than 70% whatever HPD is used. Besides, it can be observed that the two nonlinear earplugs (P1, P2) allow a better localization of sound than the talk-through systems (especially talk-through earmuff P4). The protector P1 has the largest standard deviation (15%) as well as an important dispersion (difference between maximum and minimum equal to 56%).

The standard deviation for the earmuff is lower (8%) than for earplugs (12%). As for the attenuation performance, the localization performance of earmuff depends less on the user than on the earplug. Indeed, all the subjects wear the earmuff in the same manner, but this is not the case for earplugs.

3.2 Confusion matrix

Below, the confusion matrices are given for each HPD:

- Table 3 without hearing protection
- Table 4 with P1
- Table 5 with P2
- Table 6 with P3
- Table 7 with P4
- Table 8 with P5

We note on these matrices that there is only little left-right confusion (White Square) whatever HPD is used. The top-down confusion (Green Square) is the most important for the four upper loudspeakers (HP5 to HP8), except for the P4 and P5 protectors for which the top-down confusion is equivalent between upper and lower loudspeakers.

Table 3: Confusion matrix without protection

Emitted loudspeaker	**6**	**4,3**			**3,2**	**1,8**			**90,8**
	7		**0,8**	**1,2**			**5,7**	**92,2**	**0,2**
	8	**0,2**	**1,3**				**98,2**	**0,3**	
	5	**2,0**				**97,5**			**0,5**
	2				**97,7**				**2,4**
	3			**99,4**				**0,7**	
	4		**96,4**	**1,2**	**0,2**		**0,7**	**1,7**	
	1	**97,0**			**1,7**	**0,7**			**0,7**
	%	**1**	**4**	**3**	**2**	**5**	**8**	**7**	**6**
		Subject's choice							

Table 4: Confusion matrix with protector P1

Emitted loudspeaker	**6**	**18,5**			**20,8**	**21,3**			**39,5**
	7		**21,0**	**14,3**			**23,5**	**41,3**	
	8	**0,3**	**34,5**	**5,3**			**58,3**	**1,8**	
	5	**32,5**			**4,0**	**61,8**			**1,8**
	2	**10,0**			**80,5**	**1,0**			**8,5**
	3		**3 ,8**	**89,8**	**0,3**	**0,3**	**0,5**	**5,5**	
	4		**63,5**	**12,0**	**0,5**		**9,8**	**13,3**	**1,0**
	1	**56,3**		**0,3**	**18,0**	**8,3**			**16,8**
	%	**1**	**4**	**3**	**2**	**5**	**8**	**7**	**6**
		Subject's choice							

Table 5: Confusion matrix with protector P2

Emitted loudspeaker	Subject's choice							
%	1	4	3	2	5	8	7	6
6	17,0			23,5	18,3	0,3	0,3	40,8
7	0,8	19,8	23,3			22,3	33,8	
8		20,8	0,5			77,5	1,5	
5	19,0			1,0	78,5			1,3
2	11,8			71,8	0,3			16 ,3
3		11,0	81,5			1,8	5,5	
4		76,3	6,5	0,3		12,0	4,8	0,3
1	80,5		0,3	6,5	6,5			6,3

Table 6: Confusion matrix with protector P3

Emitted loudspeaker	Subject's choice							
%	1	4	3	2	5	8	7	6
6	16,9		0,3	27,8	11,9			43,1
7		24,7	25,9			17,5	31,9	
8		28,8	0,3		0,3	68,8	1,9	
5	29,1			0,6	67,8			2,5
2	10,0			70,3	3,8			15,9
3		2,8	85,0			0,6	11,6	
4		57,8	9,4	1,3		21,3	10,0	0,3
1	35,6			10,3	29,7			24,4

Table 7: Confusion matrix with protector P4

Emitted loudspeaker	Subject's choice							
%	1	4	3	2	5	8	7	6
6	46,0			12,5	29,3			12,3
7		12,3	23,7			18,5	45,5	
8		28,3	0,3			60,5	11,0	
5	43,3			2,5	44,0			10,3
2	35,8			30,3	15,5			18,5
3		6,5	37,0			5,0	51,5	
4		48,5	2,8			19,8	29,0	
1	40,3			8,3	20,3			31,3

Table 8: Confusion matrix with protectorP5

Emitted loudspeaker	Subject's choice							
%	1	4	3	2	5	8	7	6
6	23,3	0,3		28,8	12,8	1,0	0,3	33,8
7		30,3	20,3			15,3	34,3	
8		28,3				64,8	7,0	
5	22,0			2,0	70,3	0,5		5,3
2	18,0			57,0	1,5			23,5
3		6,3	71,5			0,3	22,0	
4		39,5	11,3			24,5	24,5	0,3
1	23,5			21,5	27,8		0,3	27,0

3.3 Localization errors

Figure 6 shows, for each loudspeaker, the average rate of correct responses for each family of hearing protection: without hearing protection in blue, with nonlinear earplug in red, with talk-through system in green. We note that the two back-top loudspeakers (HP6 and HP7) have the lowest rate whatever configuration is used.

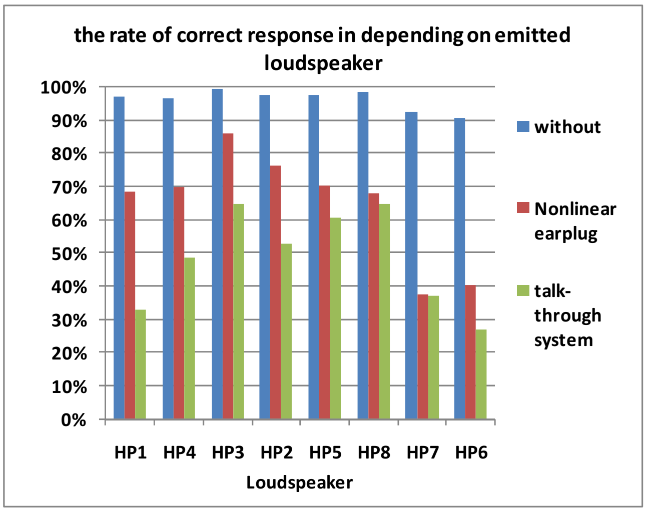


Figure 6: Average rate of correct responses for each loudspeaker

Figure 7 shows, for each HPD, the average rate of confusion. We observe, as previously, that the left-right confusion is small (in red in this figure). In particular for the earmuff (protector P4), there is no left-right confusion. This can be explained by the fact that, with the earmuff, the distance between the two ears is virtually increased (corresponding to the distance between two microphones). In this case, the delay between the right signal and the left signal is increased. The left-right perception sharply depends on the length of this delay. Also it can be noted that the talk-through earmuff allows improving the left-right perception, but the top-down confusion as well as the back-front confusion is increasing.

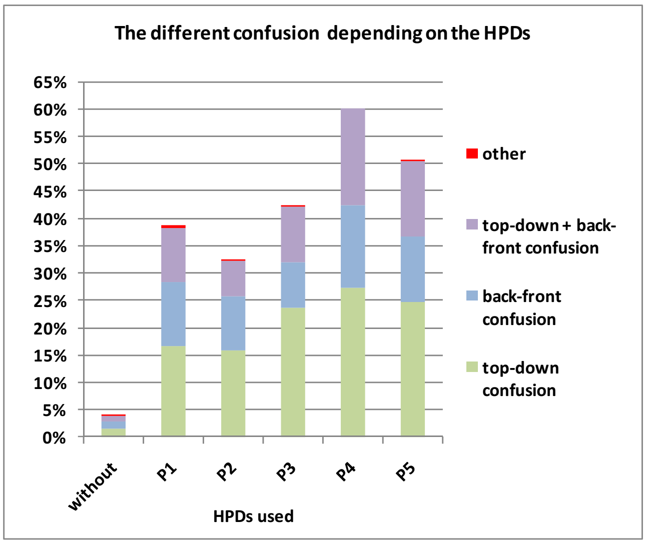


Figure 7: Rate of confusion observed for each HPD

A detailed analysis showed that women were more prone to left-right confusion than men. This is likely due to a smaller distance between the two ears of female subjects. Only one female subject made at least one left-right confusion whatever configuration was used, except for hearing protection P4.

In Figure 7, we also note that the top-down confusion rate is more important with the talk-through system than with the nonlinear earplug.

5 Conclusions and perspectives

This test showed that wearing hearing protectors, even if they allow speech communication, sharply decreases the ability to localize a sound source in space. Besides, it could be demonstrated that there is more confusion with talk-through systems than with nonlinear earplugs. Indeed, the rate of confusion is less than 30% (in average) for nonlinear earplugs and less than 46% for talk-through systems. For the spatial localization, the best results were obtained with the nonlinear earplug P2 (32% of confusion) and the worst results with the talk-through earmuff P4 (60% of confusion).

In order to explain the bad scores obtained with HPDs, it is necessary to measure the HRTF (Head Related Transfer Function) including the hearing protection. These measurements will be carried out shortly for five HPDs and eight positions of loudspeaker.

Acknowledgments

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References

[1] V. Zimpfer, D. Sarafian, P. Hamery, K. Buck, “Localisation spatiale d’un son avec des protecteurs auditifs permettant une communication verbale”, ISL Report, R116/2011.