Degradation of front-back spectral cues induced by tactical communication and protective systems

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Abstract

Tactical communication and protective systems (TCAPS) correctly protect the listener's ears from hazardous sounds and preserve intelligibility, thus allowing low-level speech communication. Our actual problematic deals with the conservation of the sound localization capability when wearing TCAPS. A previous subjective experiment, in which listeners were asked to localize sound sources in the horizontal plane with and without acoustically transparent earmuffs, highlighted that wearing this hearing protection significantly degraded the listeners' localization capability. This degradation was mainly caused by front-back confusions. It has therefore been concluded that the hearing protector altered the spectral cues used in open ear condition for the resolution of front-back ambiguities. In order to characterize the TCAPS-induced degradation of the spectral cues, directional transfer functions (DTFs) have been measured in the horizontal plane on an artificial head with and without different TCAPS. DTFs are first averaged in each quadrant and the number of measurement positions which are needed in each quadrant is discussed. Front-back spectral cues are then defined, separately for ipsilateral and contralateral side, as the difference between front and back mean DTF. Results show that wearing TCAPS affects not only ipsilateral but contralateral spectral cues. A quantitative study confirms that ipsilateral cues are preponderant for the resolution of front-back ambiguities in open ear condition. Finally, an index characterizing the alteration of the spectral cues allows the ranking of the different TCAPS according to how they induce degradation of the sound localization capability.

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1. Introduction

In many military or civilian situations, it is important to be able to communicate, perceive and interpret the acoustic environment while still being protected against damaging continuous and impulsive noises. Hearing protection devices (HPDs) are divided in two categories: HPDs with fixed attenuation, like traditional foam or premolded earplugs, and HPDs with level-dependent attenuation, called Tactical Communication and Protective Systems (TCAPS). Only the latter category will be studied here because, in addition to maintaining correct protection against hazardous sound as traditional HPDs, TCAPS also preserve intelligibility, thus allowing low-level speech communication.

Our actual concerns deal with the conservation of the horizontal sound localization capability while wearing TCAPS. In open ear condition, sound sources can be localized by the mean of binaural and monaural localization cues. The difference in arrival time and of the sound level of the incoming acoustic wave between the left and right ear are respectively known as the interaural time difference (ITD) and the interaural level difference (ILD). These two binaural cues enable horizontal localization, but with the limitation that there are areas in which they are constant, the so-called cones of confusion, which lead to front-back ambiguities [1]. Those ambiguities are resolved by monaural spectral cues coming from the directional filtering of the incoming sound signal by the listener's pinna, head and torso [2]. The binaural and monaural localization cues are contained in the transfer functions between the sound sources and the listener's ears, the Head-Related Transfer Functions (HRTFs), and their time-domain counterparts, the Head-Related Impulse Responses (HRIRs). The TCAPS-induced modifications of HRTFs and HRIRs could therefore be exploited to study the conservation of the sound localization performance while wearing TCAPS.

Previous psychoacoustical studies showed that hearing protectors degrade listeners' localization performance [3, 4]. In particular, they highlighted that TCAPS increase the number of elevation errors and of front-back confusions [5, 6] and rarely the number of left-right errors [7]. This kind of study are essentially based on subjective psychoacoustic experiments in which listeners are asked to localize sound sources with and without wearing hearing protection devices. Such an experiment needs a large number of participants and repeated measurements and is therefore time-consuming. In order to develop an objective method predicting the degradation of the sound localization performance caused by the use of TCAPS, a preliminary subjective experiment has been conducted in which listeners were asked to localize sound sources on the horizontal plane with and without wearing talk-through earmuffs (P4 in the present study). Results showed a significant increase of localization errors ($p < 0.0001$), mainly caused by front-back confusions. The mean number of correct localization responses across all listeners dropped from 94% in open ear condition to 57% with the acoustically transparent earmuffs while the mean number of front-back confusions increased from 2% to 30%. It has therefore been concluded that the TCAPS-induced degradation of the sound localization capability in the horizontal plane comes from the degradation of the spectral cues. In the continuation of these researches, the present paper aims to characterize the degradation of the localization cues due to different TCAPS from HRTF measurements on an artificial head.

2. Materials and Methods

In order to compare the localization cues used in open ear condition and in protected ear condition, HRTFs are measured in open ear and protected condition on an artificial head.

2.1. Hearing Protection Devices

Five different TCAPS shown in Figure 1 have been used for the HRTF measurements. The following list sums up their principal characteristics:

- P1 is a polymer earplug including an ISL non-linear filter [8] with triple-flange design, which will be used by the french army.

Figure 1. Tactical Communication and Protective Systems used in this study

- P2 is another polymer earplug including a Hocks-Noise-Braker® non-linear filter, with a triple-flange design, used by the french army.
- P3 is a commercial active earplug with a talk-through system and with modifiable foam tips.
- P4 is a commercial acoustically transparent earmuff.
- P5 is another commercial acoustically transparent earmuff.

As these 5 hearing protectors have a level-dependent attenuation, HRTFs measured on the artificial head wearing them are dependent on the sound level. It has been chosen to make the transfer function measurement at a sound level around 70 dB(SPL) because the conservation of the sound localization capability while wearing TCAPS is particularly important for low-level sounds (e.g. orders, speech).

2.2. HRTF Measurements

The derivation of the localization cues has been made from HRTF measurements on an ISL artificial head [9] in the horizontal plane. This fixture was placed at the center of a circle (2.60 m in diameter) made of 8 loudspeakers spaced 45° in an audiometric cabin (see Figure 2) with a background noise, with all devices turned on, of less than 20 dB(A). Measurements are made for 12 loudspeaker positions: every 22.5° without trivial positions at 0°, 90°, 180° and 270°. For each position, the transfer function between the loudspeaker and the artificial head's ears is obtained using swept-sine transfer function measurements with a Stanford spectral analyzer for frequencies from 100 Hz to 16 kHz.

HRTFs are obtained from these transfer functions by deconvolving them with a reference measure made at the center of the artificial head with the head removed in order to delete the contributions of the setup

Figure 2. Audiometric cabin with loudspeaker circle and artificial head

(e.g. the loudspeakers' response). Non-directional spectral characteristics are then dismissed using diffuse field equalization: HRTFs are deconvolved with their average across all loudspeaker positions [10]. Resulting transfer functions are called Directional Transfer Functions or DTFs [11] and no longer contain ear canal resonances or microphone and recording amplifier transfer functions. These DTFs are the functions which are used in this study to estimate binaural and monaural localization cues.

2.3. Localization cues

2.3.1. Interaural Time Difference

The ITD is derived, for all loudspeaker positions and all hearing conditions, from the measured HRIRs. Right and left HRIRs are used to produce the interaural cross-correlation function and ITD is estimated as the parameter of the maximum of this function. This estimation method is more robust than HRIR threshold estimation or linear phase hypothesis method [10].

2.3.2. Interaural Level Difference

We have estimated the ILD at one loudspeaker position as the difference in dB between the Root-Mean-Square value (RMS) of right and left DTF. The calculation are again made for all loudspeaker positions and all hearing conditions. The ILD is sometimes calculated in different frequency bands as an interaural spectral difference [6], but here we wanted to keep the ILD frequency-independent and we consider spectral cues to be only monaural.

2.3.3. Front-back spectral cues

Recent subjective experiments [5, 6] showed that the main cause of localization errors in the horizontal plane is front-back confusion. Spectral cues are therefore studied as front-back DTF differences. For each ear, DTFs are averaged on each quadrant and front-back spectral cues are then defined, separately for ipsilateral and contralateral side, as the difference in dB between the front and back mean DTF. Considering the hypothesis that the TCAPS and the DTFs are symmetrical about the median plane, front-back spectral cues calculated for the left and right ear are finally also averaged. This procedure consists mainly in averaging DTFs across loudspeaker positions because we are not interested by sound localization precision but by quadrant confusions. DTFs are measured in only 3 positions per quadrant for this reason, as we believe it is sufficient to provide a representative average.

3. Results and discussion

Figures 3(top) and 3(bottom) show respectively interaural time and level differences estimated for each hearing condition. The three earplugs P1, P2 and P3 don't seem to degrade ILD while the two acoustically transparent earmuffs P4 and P5 induce a decrease in absolute value of the ILD for all positions. It seems therefore to be associated with earmuffs. This kind of ILD degradation could lead to the concentration of the localization responses near the median plane when ILD is the preponderant cue for localization (i.e. for high frequency sounds [1]). This effect has not been seen during the subjective experiment with P4 because listeners heard broadband sounds for which ITD is preponderant. On Figure 3(top), we can observe that ITD is slightly increased for positions near the interaural axis with the three systems P3, P4 and P5 which are all electronic talk-through devices. Unlike the ILD case, this could this time lead to the concentration of localization responses near the interaural axis. However, this increasing of ITD near the interaural axis could have a negligible effect on sound localization performance because it has about the same magnitude as the just noticeable difference of the ITD for these positions [10]. These results concerning interaural time and level differences confirm that binaural cues for broadband sound localization are not significantly degraded by TCAPS. Loss in localization performance can be attributed to spectral cues deterioration.

The amplitude in decibels of ipsi- and contralateral front-back spectral cues are represented for all hearing conditions in Figure 4. These transfer functions have been averaged in $\frac{1}{6}$-octave bands. Figure 4a, representing front-back spectral cues for the open ear condition, reveals that ipsilateral DTFs with important amplitude between 3kHz and 6kHz are associated with frontal sound directions. This will be called the 3-6kHz cue in the following. Similarly, the frequency band above 10kHz is associated with ipsilateral back DTFs. Contralateral spectral cues seems important too as this graphic shows pics near 1kHz and 10kHz and a notch near 7kHz for the contralateral front-back cues. It can also be observed that spectral cues at frequencies under 1kHz don't seem to contribute to front-back discrimination. From the observation of

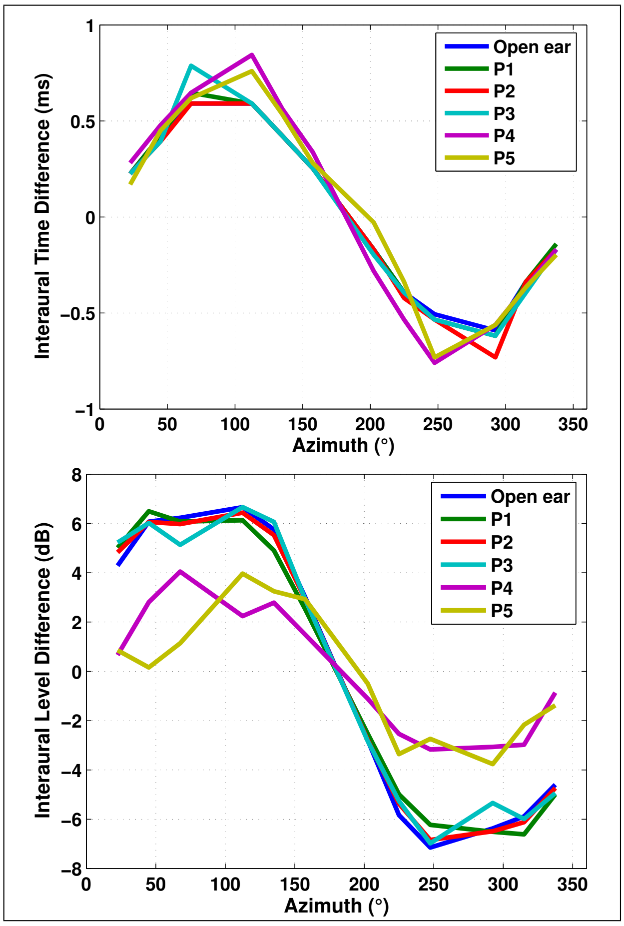

Figure 3. Top: Interaural time differences in milliseconds estimated in each hearing condition. Bottom: Interaural level differences in dB estimated in each hearing condition. Open ear condition (blue), P1 (green), P2 (red), P3 (cyan), P4 (magenta) and P5 (yellow). *Notes: Between 0° and 180°, the ITD of the open ear coincides with the ITD of P2. Between 180° and 360°, the ITD of P1 coincides with the ITD of P3.*

Figures 4b and 4c, we can say that passive earplugs P1 and P2 seem to preserve contralateral front-back spectral cues and the ipsilateral 3-6kHz cue whereas the ipsilateral back cue at high frequencies has been degraded, or even reversed for P1. With P3 (see Figure 4d), the ipsilateral cues are maintained but the 3-6kHz band has been narrowed and contralateral cues above 2kHz are degraded. More important degradations of ipsilateral and contralateral front-back spectral cues are observed with the earmuffs P4 and P5 on Figures 4e and 4f, respectively. This can be interpreted as the result of covering the pinna with earmuffs which prevent the incoming sound wave from being diffracted by the ear's shape. These qualitative observation of front-back spectral cues allows us to predict a classification of TCAPS based on their degradation of spectral cues. It seems that DTFs measured with passive earplugs P1 and P2 are more similar to open ear DTFs than those measured with talk-through earplugs P3.

Table I. ISSD in dB^2 estimated for each TCAPS.

P1	P2	P3	P4	P5
4.5	1.9	4.4	12.5	21.5

Finally, the worst damages are observed with acoustically transparent earmuffs P4 and P5.

In order to provide a quantitative analysis of the DTF measurements, the mean across all directions of the variance of the difference between the protected DTF and the open ear DTF is calculated, in dB^2, for each TCAPS. This metric is similar to the inter-subject spectral difference (ISSD), first introduced in [12] to compare DTFs from different subjects. For this reason, we also call it ISSD in this paper. It has been chosen for DTFs difference measurement instead of simple RMS value of the difference because a variance calculation deletes overall gain difference. Results are shown in Table I. It can be concluded from these results that DTFs measured with P2 are, in average, the most similar to open ear DTFs, then DTFs measured with P1 and P3 are slightly degraded compared to open ear DTFs, and finally P4 and P5 shows the most important dissimilarities.

Moreover, by calculating the variance of ipsi- and contralateral front-back spectral cues of the open ear condition (i.e. the variance of the two curves in Figure 4a), we obtained the spectral difference between front and back mean DTFs. The results, 10.4 dB^2 and 4.7 dB^2 for ipsi- and contralateral side respectively, show that contralateral front and back DTF are more similar to each other than ipsilateral ones. It follows that ipsilateral front-back spectral cues are more important than contralateral ones and may therefore be predominant for the resolution of front-back ambiguities.

4. Conclusion

Study of binaural sound localization cues estimated with five different TCAPS indicates that interaural time and level differences are not influenced by the hearing protection devices, thus preventing broadband sound localization from left-right errors. However restrictions have been expressed for the case of high frequency narrow-band localization with acoustically transparent earmuffs for which ILD is significantly decreased. The most significant degradation of localization cues have been noticed for the monaural front-back spectral cues. They are distorted by all TCAPS with different intensities. We observed indeed that passive nonlinear earplugs induced less degradation of spectral cues than talk-through earplugs, which themselves presented less degradation than acoustically transparent earmuffs. These observations are confirmed by the calculation of ISSD between each protected DTFs and open ear DTFs. The spectral dif-

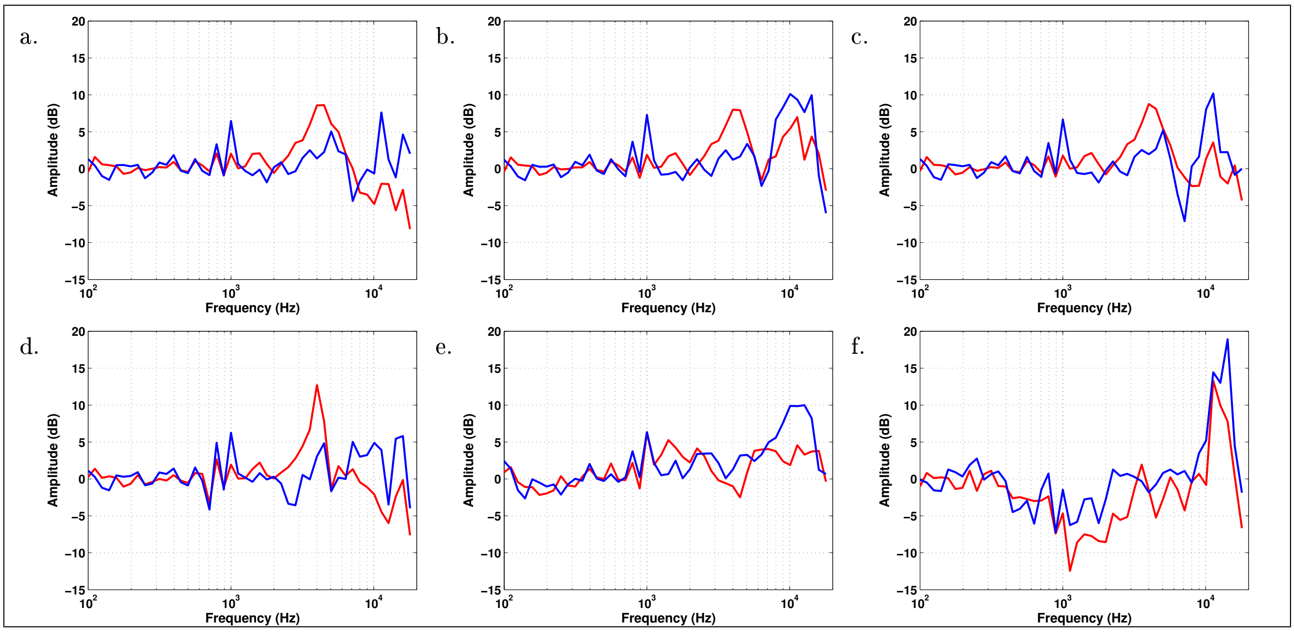

Figure 4. Ipsilateral (red) and contralateral (blue) front-back spectral cues with frequency in open ear condition (a), with P1 (b), P2 (c), P3 (d), P4 (e), P5 (f).

ference between open ear front and back mean DTFs provided also a proof that ipsilateral spectral cues are predominant over contralateral ones for front-back discrimination.

As the goal of our work is to develop an objective head-independent index based on HRTF measurements characterizing the loss in sound localization performance induced by level-dependent hearing protection devices, more precise quantitative study of spectral cues degradation should be conducted from the development of a localization model based on spectral cues comparison [13] or on physiological models and neural network [14]. Finally, the link between an objective index and real sound localization performance with hearing protectors has to be made through subjective experiments in order to validate the TCAPS classification we obtained.

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