PERCEPTION OF URGENCY AND SPATIALIZATION OF AUDITORY ALARMS

A. Guillaume, M. Rivenez, G. Andéol and L. Pellieux

Institut de médecine aérospatiale du service de santé des armées
Département de sciences cognitives
Brétigny, France
aguillaume@imassa.fr

ABSTRACT

Alarms can be spatialized in new human-machine interfaces. This includes the perception of distance at different points in space. The aim of this work was to study the interferences between the perception of distance and the perception of urgency. Two experiments used common stimuli. These were sounds recorded on a dummy head from a white noise emitted from 8 directions in the azimuth plane and at 3 distances, inside a closed, empty room. The sounds were then loudness equalized. Experiment 1 consisted of presenting the sounds in pairs to the listeners, who had to designate the sound which was perceived as the most urgent. The results show that, for the same distance, the level of urgency is greater when the virtual source is at ±90°. They also show two types of responses concerning the links between the perception of distance and urgency. Certain listeners perceive near sounds as the most urgent, while others perceive distant sounds as the most urgent. Experiment 2 is a control experiment to check that perception of distance is preserved for these loudness equalized sounds.

1. INTRODUCTION

Auditory alarms are justified by the fact that hearing is a primary alert sense. They are in fact effective in all directions in space, regardless of the position of the head. They play a role in directing the operator’s attention towards pertinent visual information in critical situations. In the new human-machine interfaces, the spatialization of sound is used to reduce the latency of operator reaction. Different studies effectively show that 3D sound enables a reduction in reaction times during search for a visual target [1, 2, 3, 4].

Spatialization of sound includes the notions of location in azimuth and in elevation but also the notion of distance. Technical evolution brings with it an increased need for effective human-machine cooperation and coordination [5]. Distance information is important in piloting or driving tasks, for which the operator must have real time updated or even anticipated situation awareness.

Perceived auditory distance is the result of different sound cues [6]. The most obvious cue associated with an increase in distance is a decrease in intensity. The sound level cue to auditory distance is based upon the decrease in sound level by 6 dB for each doubling of distance in a free field [7]. However the precise nature of this intensity change depends on both environmental characteristics and various properties of the sound source. In particular, the presence of reflective surfaces modifies this relationship. Also, intensity is considered as a relative cue since the accuracy of estimation of distance is better when the stimulus is familiar [8].

Other cues have been proposed when both listener and sound source are stationary [9]. These are the ratio of direct energy to reverberating energy, spectral changes and binaural differences.

The direct-to-reverberant energy ratio is the ratio of energy reaching a listener directly to energy reaching the listener after reflecting surface contact. A large ratio (implying that the direct sound greatly exceeds the reflected sound) generally leads to the perception of a source as being nearby. As the relative amount of reflected sound increases, the perceived auditory distance to the source also increases. Reverberation acts as an absolute cue since it is not necessary for the listener to have already heard the sound before in order to use this cue to judge the distance of the sound source in a given sound-reflective environment [10].

Changes in spectral content can also affect perceived auditory distance as a relative cue [11]. This can occur in two cases. First, according to Blauert [6], the sound-absorbing properties of air cause an attenuation which is greater at high frequencies than at low frequencies. Secondly, in a reverberant environment, when distance increases, the proportion of energy reflected increases and thus potentially modifies the spectrum in each ear [12].

Finally, unlike the far field, binaural time differences and especially intensity differences depend on the radial distance when in the proximal region. They increase as the source approaches the head [13] but not in the median plane (where the differences are 0 anyway).

All these cues can be used to provide distance information in auditory alarms.

The design of an alarm system takes into account the intended function of each alarm. It is therefore necessary to determine the reaction time required in order to assign an urgency level to the alarm. In an auditory alarm, this urgency level is expressed in terms of acoustic parameters. The most important factor in converting urgency into a level is undoubtedly intensity [14]. The louder the signal, the greater the perceived urgency.

However, in noisy environments (industry, aeronautics), the scale over which this parameter can vary is small: if the signal is too weak, it is not detected; if the signal is too strong, it becomes painful and interferes too much with operator activity [15]. So, although intensity is a dominant factor, it is preferable to control it in a systematic way. Thus it is possible to design a loudness equalized system, so that there is nevertheless a gradation of urgency level. Other parameters can be used to translate perception of the level of urgency. Edworthy & coll. [16], Hellier & coll. [17, 18] demonstrate by psycho-acoustic methods that the higher the pitch, the faster the tempo, the more irregular the harmonics, the more the alarm is perceived as urgent.

It therefore appears that if an alarm is spatialized, the intensity is both a distance cue and an urgency cue. If the sounds are equalized in loudness, this major cue for the perception of distance and urgency disappears. The next question is to know whether the other distance cues will influence the perception of urgency.

Two experiments were carried out in order to answer these questions. The sound stimuli common to the two experiments were obtained by recording a white noise using a dummy head in 8 directions of space at 3 fixed distances. The sounds were then equalized in loudness.

In the first experiment, the sounds were presented in pairs through a headphone and the participant had to choose which sound seemed the most urgent. The assumption underlying this experiment was that the nearest sounds should be considered as the most urgent. However, in the absence of the intensity cue, the reverberation extends the duration of the sound and could interfere with this assumption. In fact, Hellier & coll. [17] showed that increasing the duration of a sound increases the perceived urgency. This assumption assumes that distance cues other than intensity enable perception of distance. This is what the second experiment tested, i.e. it checked that distance was well perceived with these loudness equalized stimuli.

2. EXPERIMENT 1

2.1. Context

The aim of Experiment 1 was to study the role of distance cues (except for intensity) on the perception of urgency. Similar work was carried out by Häkkila and Ronkainen (2003). They studied the ways of modifying a sound in such a manner that the importance level changed, but the sound still retained its identity. The sounds used included differences some of which concerned acoustic cues indicating distance. The parameters modified, apart from sound length and vibrato speed, were filtering of high-frequency components and direct-to-reverberated sound ratio associated or not with filtering of high frequencies. The cut-off frequency was either 2kHz or 4kHz. Reverberation was obtained from a reverberation model. Early reflections were not utilized, but only late reverberation. The results showed a significant effect for filtering of high frequencies and the speed of vibrato. On the other hand, there was nor significant effect of reverberation neither of increase in duration of the sound. The authors noted contradictory responses between the different participants. Only three participants out of ten mentioned the notion of distance of the sound source when listening to sounds with reverberation. However, the sounds used were artificially modified by low pass filtering and/or addition of a reverberation effect.

Experiment 1 tested more realistic sounds since they were recorded on a dummy head. All the cues indicating distance were involved except for intensity whose influence is neutralised by loudness equalization.

2.2. Methodology

2.2.1. Stimuli

The sounds were recorded by a dummy head (Neumann KU 81i) in 8 directions in the horizontal plane: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°. Three distances were considered in each direction: 8 cm, 64 cm and 256 cm (figure n°1). For the direction 0°, the distance of 8cm was not possible owing to the prominence of the nose and it was replaced by a distance of 16 cm.

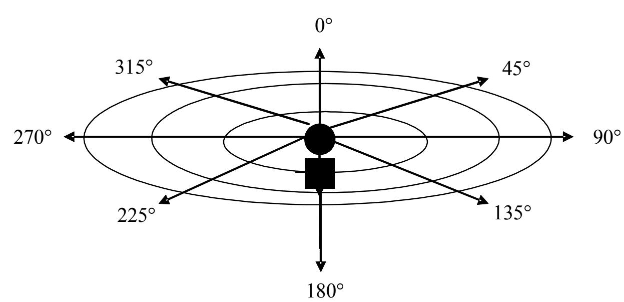

Figure n°1: The participant heard two sounds one after the other and had to indicate which seemed the most urgent. These sounds were produced by a virtual sound source potentially located in 8 directions in the azimuth plane and at 3 possible distances.

The recording was made inside an empty rectangular room of approximately 100m³. The walls were plasterboards. The pulse response of the set including the dummy head, the room and the loudspeaker with its enclosure was measured by a loudspeaker Fostex 103Σ moulded in a closed enclosure of size: 11x14x15 cm^3. The free field pulse response of the moulded loudspeaker was then removed from the pulse response of the set for the computation of spatialized sounds. Only the 2.7 first seconds of the pulse response of the subset including the dummy head and the room were restored in the stimuli. The same white noise was used in all the configurations.

After the sound gathering phase, the sounds were loudness equalized in accordance with the paradigm of Florentine & coll. [20]. There were two loudness equalization phases. The first phase consisted of equalizing those sounds whose virtual sound source was at equal distance from the participant's head. The second phase consisted of equalizing sounds from a single direction but at different distances.

In both cases, the stimuli were presented in a two-interval, two-alternative forced-choice paradigm. In each trial, the listener heard two sounds separated by 500 ms in a random order. The task was to indicate which sound was louder by pressing a key. The level of the variable sound was adjusted according to an up-down procedure. If the variable sound was perceived as the louder one, its level was reduced, otherwise it was increased. The step size was 5 dB until the second reversal after which it was 2 dB. This procedure converges at the level corresponding to the 50% point on the psychometric function.

A single match included two interleaved adaptive tracks: one track started 10 dB above the expected equal-loudness level and the other track started 10 dB below it. Each track ended after nine reversals. The equal-loudness level for one track was calculated as the average of the last four reversals. The average equal-loudness level for the two tracks gave the result for one match. The final equal-loudness level for each condition corresponded to the average of three matches for all participants. 8 participants carried out the sound loudness equalization. They were different from the participants of experiments 1 and 2.

2.2.2. *Participants*

11 participants with normal hearing (tested with an audiogram) participated in this experiment. Experimenters were not included.

2.2.3. *Procedure*

Participants were first familiarized with the task (5 trials). Sounds were presented in pairs in a random order. Every possible pair of sounds (among (24x23)/2 = 276 pairs) was presented. A single order of the pairs was tested, as it has been previously demonstrated that the results did not depend on the order [21]. The entire experimental session lasted about 30 minutes with two short breaks. The participants indicated which sequence in the pair seemed the most urgent (forced-choice urgency judgement). They could listen to each pair as many times as they wished.

2.2.4. *Data analysis*

Each sound was presented 23 times so that its urgency level was evaluated with respect to all the other sounds. At the end of the test, an urgency score out of 23 was defined; corresponding to the number of times the sound was chosen as the most urgent. To examine the statistical significance of the effects of localization parameters and differences among listeners, a two way ANOVA (azimuth x distance) was performed. The dependant variable for this analysis was the score of urgency. Secondarily, a three way ANOVA (azimuth x distance x group) was performed. Scheffé *post hoc* tests for contrast were performed when appropriate to explore sources of significant effects and interactions.

2.3. Results

The results show a significant effect of azimuth (p<0.01). The perception of urgency was greatest for lateral stimuli at +/-90° or opposite the participants (figure n°2);

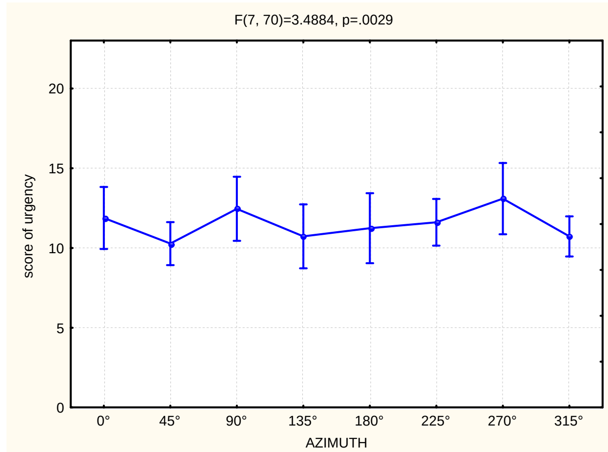

Figure n°2: The urgency score is greater for the directions 0°, 90° and 270. Error bars are standard deviations.

However, the effect of distance was only just significant (p=0.08). Interaction between the « azimuth » effect and the « distance » effect was significant (p<0.001). On studying the participant's responses, it appeared that two types of response can be distinguished depending on the type of participants. Some participants (5 out of 11) considered near sounds as the most urgent, whereas the other participants (6 out of 11) considered distant sounds as the most urgent.

A second analysis was made taking into account the "group" factor of the participants as well as the "azimuth" and "distance" factors.

The following were defined :

- Group 1 which included the participants who considerd near sounds as the most urgent
- Group 2 which included the participants who considered distant sounds as the most urgent.

The interaction distance x group was significant (p<0.001) as well as the interaction azimuth x distance x group (p<0.005). The latter interaction is shown in figure n°3.

For group 1, near sounds were significantly perceived as the most urgent (p<0.01).

For group 2, distant sounds were significantly perceived as the most urgent (p<0.01).

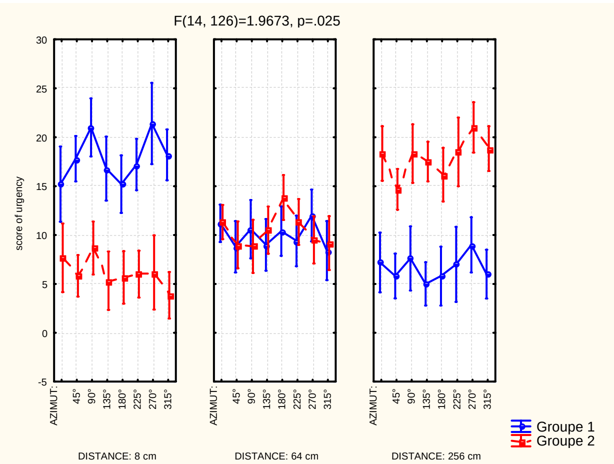

Figure n°3: Interaction azimuth x distance x group. Error bars are standard deviations.

In figure n°4, the azimuth effect persisted for group 1; in particular, lateral stimuli were perceived as more urgent than the others for the proximal stimuli (p<0.001).

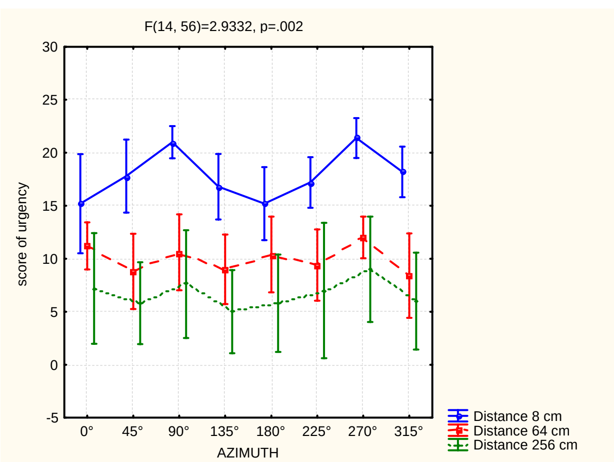

Figure n°4: interaction azimuth x distance for group 1. Error bars are standard deviations.

In figure n°5, the azimuth effect was also preserved for group 2. Lateral sounds are perceived as more urgent than the others for distal stimuli (p<0.01).

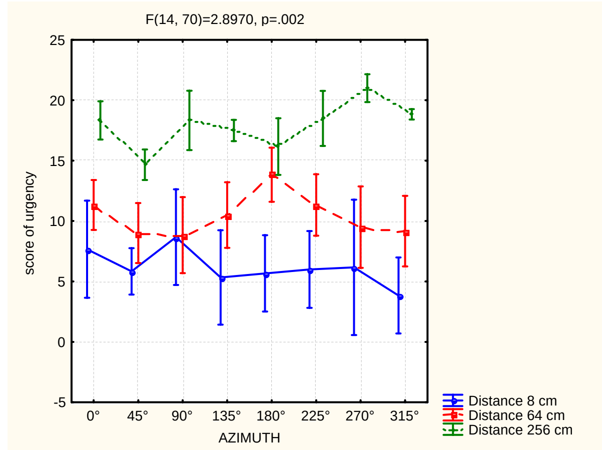

Figure n°5: interaction azimuth x distance for group 2. Error bars are standard deviations.

2.4. Discussion

The aim of Experiment 1 was to study the relationships between the perceptions of distance and urgency on loudness equalized sounds. It appears that we can distinguish two categories of listeners.

Some of the listeners considered the near sounds as the most urgent. The acoustic cues which may be involved in this judgement are spectral modifications or binaural differences. Given the moderate distances tested (< 3m), the spectral modifications involved would be linked to reflected energy modifying the spectrum in each ear. Binaural cues can also play an important part because the distances tested were very near to the head.

The other listeners considered the distant sounds as the most urgent. The acoustic cue involved was *a priori* reverberation. The greater the reverberation, the more the sound was considered as urgent. The addition of reflected waves increased the duration of the sound. But Edworthy & coll. [16] showed that increasing the duration of sound sequences influences the perception of urgency by increasing it. It is possible that the increase of the sound duration was responsible for increasing the perceived level of urgency.

It is remarkable to observe that for both groups, there was a maximum azimuth effect when the perception of urgency was highest, i.e. when the sounds were near for Group 1 and when they were distant for group 2. The maxima were observed when the virtual sound source was at ± 90°.

The question which then arises is to determine whether this observation was based on the perception of urgency, as would seem to be indicated by the fact that this azimuth effect occured when perception of urgency was maximum, regardless of the distance depending on the group in question. But this effect could also be linked to the perception of distance. Experiment 2 was designed to test the perception of distance with loudness equalized sounds.

3. EXPERIMENT 2

3.1. Context

The aim of experiment 2 was to check that acoustic cues other than intensity are sufficient to enable the perception of distance in the different directions of the azimuth plane.

3.2. Methodology

3.2.1. Stimuli

The stimuli were the same as for experiment 1. These were 24 sounds recorded from white noise on a dummy head in 8 directions in the azimuth plane and at 3 distances. They were loudness equalized in accordance with the Florentine & coll. paradigm [20]. There were two loudness equalization phases. The first phase consisted of equalizing those sounds whose virtual sound source was at equal distance from the participant's head. The second phase consisted of equalizing sounds from a single direction but at different distances.

In both cases, the stimuli were presented in a two-interval, two-alternative forced-choice paradigm. In each trial, the listener heard two sounds separated by 500 ms in a random order. The task was to indicate which sound was louder by pressing a key. The level of the variable sound was adjusted according to an up-down procedure. If the variable sound was perceived as the louder one, its level was reduced, otherwise it was increased. The step size was 5 dB until the second reversal after which it was 2 dB. This procedure converges at the level corresponding to the 50% point on the psychometric function.

A single match included two interleaved adaptive tracks: one track started 10 dB above the expected equal-loudness level and the other track started 10 dB below it. Each track ended after nine reversals. The equal-loudness level for one track was calculated as the average of the last four reversals. The average equal-loudness level for the two tracks gave the result for one match. The final equal-loudness level for each condition corresponded to the average of three matches for all participants. 8 participants carried out the sound loudness equalization. They were different from the participants of experiments 1 and 2.

3.2.2. Participants

The participants were the same as those for experiment 1 apart from one missing participant (10 participants in all). This was a participant from group 1 who was not available for the rest of the experiments.

3.2.3. Procedure

Participants were first familiarized with the task (2 trials). Participants listened through headphones to stimuli and had to indicate the positions where they located the sound source (figure n°6). The sounds were presented in random way, each sound being repeated five times. The entire experimental session lasted about 20 minutes.

3.2.4. Data analysis

For the 24 sounds, the number of correct responses in distance was recorded without taking into account the responses in azimuth.

To examine the statistical significance of the effects of location parameters and differences among listeners, a three way ANOVA (azimuth x distance x group) was performed. The dependent variable of this analysis was the number of correct responses in distance.

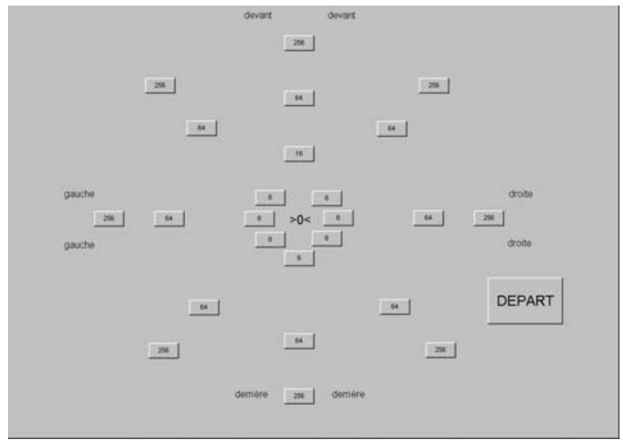

Figure n°6: Copy of the screen presented to the listener for his response. The listener had to tick one of the locations.

3.2.5. Results

The results showed that the listeners perceived distance with loudness equalized sounds. In fact, for each distance (for all azimuths) the number of correct responses was significantly higher than the random level ($p<0.001$) represented by a black line in figure n°7.

There was a significant difference between listener performance in relation to distance ($p<0.01$). Performances were best in proximal and fell off as distance increased.

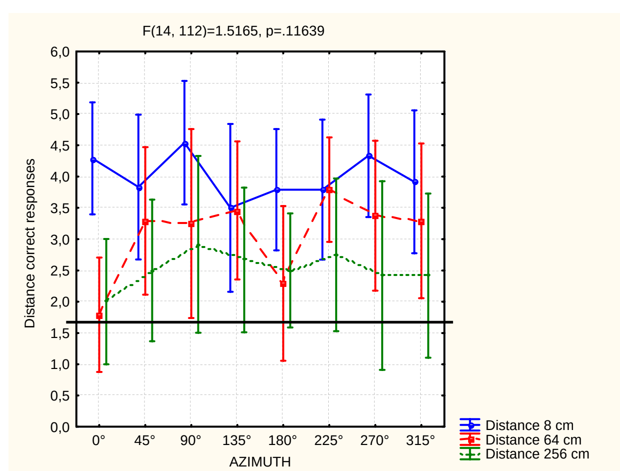

Figure n°7: The listeners perceived distance with loudness equalized sounds. Their performances were better than random (shown by the thick black line).
Error bars are standard deviations.

No overall azimuth effect was found nor any azimuth x distance interaction. However if an azimuth difference was distinguished for the different distances, there was a significant azimuth effect for the distance 64cm ($p<0.05$).

Neither was there any evidence of a group effect nor in distance x group or azimuth x distance x group interactions (figure n°8). Both groups of participants had equivalent performances, better in the proximal region than in the distal region.

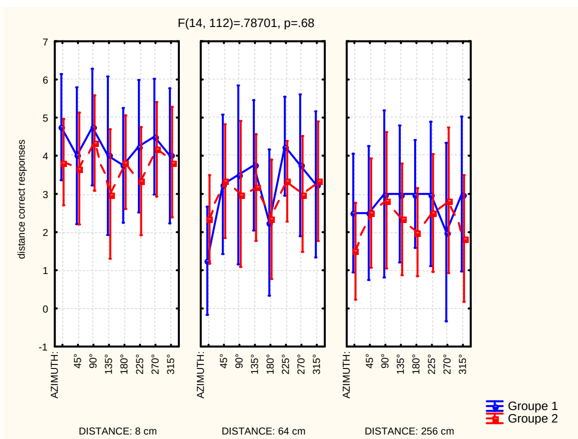

Figure n°8: azimuth x distance x group interaction for the perception of distance. Error bars are standard deviations.

3.2.6. Discussion

The cues involved in the perception of distance apart from intensity provided sufficient information to enable the listeners to discriminate among near, intermediate or distant sound sources. Participant performance was better in the proximal region than in the distal region. This result is in agreement with the observations of Brungart and coll. [22] who studied location in the proximal region. However, the experimental conditions were very different, since the participants listened to real sounds in the proximal region in an anechoic chamber.

There was no overall azimuth effect. However, there was an overall tendency towards a better performance for lateral azimuths. For the distance 64 cm, this effect was significant, with clearly poorer performances in the median plane and better performances laterally. This effect could be due to the role played by the binaural cues.

There was no group effect. The two groups were defined from the responses given in experiment 1. Thus, the differences in perceived urgency between the two groups of participants cannot be explained by a difference in perception of the distance of loudness equalized sounds.

4. GENERAL DISCUSSION

The new alarm systems must take into account the possibility of spatialized presentation of sounds. This spatialization may be in direction but also in distance. The aim of the study was to determine the interferences between distance cues, excluding intensity, and the perception of urgency. The results of experiment 1 show a complex relationship between these two perceptions, since two populations of participants emerged. Their judgments of urgency in relation to the sounds presented were opposed. Some of them judged sounds from the proximal region to be more urgent (group 1), and the others considered sounds from the distal region as more urgent (group 2). Häkkilä and Ronkainen [19] had already noted contradictory results between participants in their study on the level of importance of an event. Thus, they did not find any significant effects of an increase in reverberation, or of the duration of the sound.

In Experiment 1, although the effect of distance was not significant when we considered all of the participants, the fact of distinguishing the two groups revealed a clear significance.

The first explanation which we could give is that the participants perceived the stimuli differently in terms of distance.

Experiment 2 aimed to check that the perception of distance was still possible with loudness equalized sounds. It confirms in fact that the stimuli heard by the participants could be located in distance. However it did not show any difference in performance between the two groups of participants.

Another explanation could be a different interpretation of the effects of reverberation by the participants in the two groups.

For group 1, the results could be explained by the fact that an alarm which is perceived as being too near (8cm) can seem like a danger close to the participant. This proximity was perceived thanks to the spectral modifications of the sounds and to interaural differences of level [13]. The effects of reverberation would confirm the participants in their perception of distance [23] and therefore of urgency.

For group 2, perception of urgency would not be linked to perception of distance. Since the effects of reverberation would increase the duration of the sound, it would be perceived as more urgent since it was longer [17]. Another phenomenon might also be discussed. The effects of reverberation could be interpreted as a sign of distancing of the sound source and could cause a subjective compensation effect of the decrease in loudness linked to distance as an inverse phenomenon of loudness constancy with distance [24]. The loudness of the source being considered as the strongest for distant sounds, their urgency level would be the highest.

5. CONCLUSION

Two experiments enabled to study the influence of distance cues other than intensity on the perception of urgency. They showed that the perception of urgency of spatialized sounds equalised in loudness varied, depending on the participants. The difference observed was not linked to a difference in perception of the distance of the sounds but could be due to a different interpretation of the effects of reverberation.

Acknowledgement: This work was supported by Délégation Générale pour l'Armement (PEA n°010801 contrat 07co803).

6. REFERENCES

[1] D.R. Begault, "Head-up auditory displays for traffic collision avoidance system advisories: a preliminary investigation," *Human Factors,* vol.*35*, pp. 707-17, Dec 1993.

[2] W. Todd Nelson, L.J. Hettinger, J.A. Cunningham , B.J. Brickman, M.W. Haas, and R.L.McKinley, "Effects of localized auditory information on visual target detection performance using a helmet-mounted display," *Human factors*, vol. 40, no 3, pp. 452-60, Sep 1998.

[3] P. Flanagan, , K.I McAnally, R.L. Martin, J.W. Meehan , and S.R Oldfield, "Aurally and visually guided visual search in a virtual environment," *Human factors*, vol 40, no 3, pp 461-8, Sep 1998.

[4] R.S. Bolia, W.R D'Angelo and R.L. McKinley, "Aurally aided visual search in three-dimensional space," *Human factors*, vol. 41, pp. 664-9, Dec 1999.

[5] N.B Sarter, "The need for multisensory interfaces in support of effective attention allocation in highly dynamic event-driven domains: the case of cockpit automation," *International Journal of Aviation Psychology,* vol.10, pp. 231-45, 2000.

[6] J. Blauert, *Spatial hearing: The psychophysics of human sound localization*. Trans J.S. Allen. Cambridge, MA: MIT. 1983.

[7] M.B. Gardner, "Distance estimation of 0° or apparent 0° -oriented speech signals in anechoic space," *Journal of acoustical society of America*," vol. 45, pp. 47-53, 1969.

[8] P.D. Coleman, "Failure to localize the source distance of an unfamiliar sound," *Journal of acoustical society of America*, vol. 34, no 3, pp. 345-346, 1962.

[9] D.H.Mershon, and E.King, "Intensity and reverberation as factors in the auditory perception of egocentric distance," *Perception and psychophysics*, vol. 18, pp. 409-15, 1975.

[10] D.H.Mershon, and J.N.Bowers, "Absolute and relative cues for the auditory perception of egocentric distance," *Perception*, vol. 8, pp. 311-22, 1979.

[11] A.D. Little, D.H. Mershon, and P.H. Cox, "Spectral content as a cue to perceived auditory distance," *Perception*, vol.21, pp. 405-16, 1992.

[12] P. Zahorik, "Assessing auditory distance perception using virtual acoustics,"*Journal of Acoustical Society of America*, vol.111, pp. 1832-46, Apr 2002.

[13] D.S. Brungart and W. Rabinowitz, "Auditory localization of nearby sources. Head related transfer functions," *Journal of acoustical society of America*, vol. 106, n°3, pp. 1465-1979, Sep 1999.

[14] N. E. Loveless, and A. J. Sanford, "The impact of warning signal intensity on reaction time and components of the contingent negative variation," *Biological Psychology,* vol. *2*, pp. 217-26, 1975.

[15] R.D. Patterson, "Auditory warning sounds in the work environment", *Phil. Trans. R. Soc. Lond.*, vol. B327, pp. 485-492, 1990.

[16] J.Edworthy, S. Loxley, and I.Dennis, "Improving auditory warning design: relationship between warning sound parameters and perceived urgency," *Human Factors,* vol 33, pp. 205-31, Apr 1991.

[17] J.Edworthy, S. Loxley, and I.Dennis, "Improving auditory warning design: quantifying and predicting the effects of different warning parameters on perceived urgency," *Human Factors*, vol. 35, pp. 693-706, Dec 1993.

[18] E. Hellier and J. Edworthy, "On using psychophysical techniques to achieve urgency mapping in auditory warnings," *Applied Ergonomics*, vol. 30, pp. 167-71, Apr 1999.

[19] J. Häkkilä, and S. Ronkainen, "Dynamic auditory cues for event importance level", in *Proc. 9th International Conference on Auditory Display (ICAD)*, Boston, USA., July 2003, pp 233-237.

[20] M. Florentine, S. Buus, and T. Poulsen, "Temporal integration of loudness as a function of level," *Journal of Acoustical Society of America*, vol. 99, pp. 1633-44, Mar 1996.

[21] A. Guillaume, L. Pellieux, C. Chastres, and C. Drake, "Judging the urgency of non-vocal auditory warning signals: perceptual and cognitive processes," *Journal of Experimental Psychology: Applied*, vol. 9, pp 196-212, 2003.

[22] D.S. Brungart and W. Rabinowitz, "Auditory localization of nearby sources. II. Localization of a broaddand source," *Journal of acoustical society of America*, vol. 106, n°4, pp. 1956-1968, Oct 1999.

[23] B.G. Shinn-Cunningham, N. Kopco, and T.J. Martin, "Localizing nearby sound sources in a classroom: Binaural room impulse responses" *Journal of acoustical society of America*, vol. 117, n°5, pp. 3100-3115, May 2005.

[24] P. Zahorik, and F.L. Wightman, "Loudness constancy with varying sound source distance", *Nature neuroscience*, vol. 4, n°1, pp 78-83, Jan. 2001.