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Auditory distance perception: criteria and listening room

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ABSTRACT

This paper is the result of a series of listening experiments carried out to investigate the correlation between auditory distance and two criteria : the ratio of direct to reverberant sound energy and the clarity C80. In the first section of this paper, we will determine which of the two criteria is more efficient. The second section compares the values of these criteria when the same signal is played on a well damped control room loudspeaker system and when it is played on a domestic stereophonic loudspeaker system. A second series of listening experiments shows how the auditory distance is perceived in both cases.

1. INTRODUCTION

Auditory distance is a very old topic in audio research. A good review can be found in [9], by Berg and Ekman. Still, there are some unsolved questions. Many authors, like Maté-Cid et al [20] insist on the correlation between auditory distance and direct to reverberated ratio (D/R in the following), whereas Park et al [7] work on the correlation between auditory distance and the clarity C80, which is the ratio between early and late energy. The question is : does early energy added to a direct sound make the sound closer or not ? The first part of this study will try to answer this question.

The goal of this paper is not to study auditory distance in almost any circumstance. This paper aims at a better understanding of the perception of auditory distance in stereophony. The aim is to provide the recording engineer with working directions in order to control auditory distance of any of the sources or ensemble of sources in their recording or mix.

This had lead us to study the variation of auditory distance when one recording is played on different monitoring systems. We have chosen to study two very different types of monitoring : a well damped control room system and a domestic stereophonic system. Typically, this is the kind of variation that a sound engineer can experiment with, when he brings his "wonderful sounding mix on a really nice monitoring system" at home on his "not so well sounding domestic system".

Of course in this case there are many variations. The loudspeakers are different, the signal definition can be different, the electronics which plays the signal is different. All of these variations can cause differences in the perception of auditory distance because all of these variations affect the sound in general, both direct and reverberated sound. But one thing can affect specifically the recorded reverberation : the effect of the listening room.

Therefore, we have chosen to focus on the listening room effect and to experiment with the same loudspeakers and equipment in two control room and two domestic locations in order to study the influence of each specific room effect on the recorded reverberation.

2. EARLY ENERGY AND AUDITORY DISTANCE, 1ST EXPERIMENT

According to Berg and Ekman [9], research has concentrated on six different distance cues : Intensity ; ratio of direct and reverberant sound ; spectral coloration ; early reflections ; the connection between sound and vision ; and the curvature of the wave front.

In this paper, we try to understand what changes occur in the perception of auditory distance for different listening conditions of a stereophonic recording.

Some of these cues are determined by these listening conditions. The curvature of the wave front depends on the distance between the listener and the loudspeakers and the connection between sound and vision depends on the visual environment of the listening room [9]. Some of these cues are determined by the listener : he controls Intensity with the sound volume.

Some of these cues are under the responsibility of the sound engineer : spectral coloration and control of reverberation, whether it comes from the recording location or from an artificial reverberation system. But it may also depend on the listening conditions. This is surely the case for spectral coloration, but that is beyond the scope of this paper. Studying the influence of the listening room is the aim of the second part of this paper, but first, we have to know how reverberation influences auditory distance.

Specifically, we have to study the role of early energy. Does it have to be associated with reverberation ? Does it have to be associated with direct sound ? In the first case, we have to use D/R to explain auditory distance, in the second, we have to use C80.

2.1. Methodology

In the first part of the study, the perception of auditory distance is investigated by using a stereophonic system in an anechoic chamber. After addition to a talking voice of artificial reverberation produced by the spatializer from IRCAM, its amount and shape were both controlled through measurements of the impulse response at the listening position. The reverberation time of the reverberation was two seconds, and the early part of the reverberation (before 80 ms) was varied on request. The variations under study were the Direct-to-Reverberant energy (D/R)[dB] and C80 [dB].

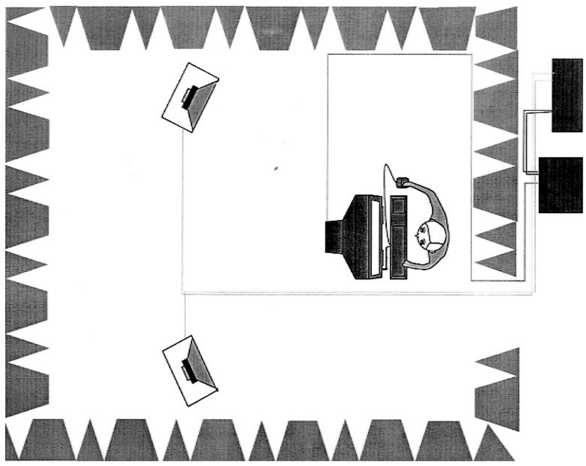

Figure 1 1st experiment setup, anechoic chamber

These configurations were submitted for comparison by pairs, to the thirteen subjects involved in the study. For each couple of configurations, the subjects were asked to express their feelings about the similarity. A multidimensional scaling technique was used to determine in how many ways these configurations were perceived as different. The question was also for the subjects to determine if they perceived one configuration closer or farther than the other.

As auditory distance could be influenced by the spatial distribution of energy, all these configurations have the same : left and right signals of all the reverberation, early and late are uncorrelated. Because the experiment is set in an anechoic chamber, the reverberation comes only from the stereophonic base. It is also influenced by the level. One previous experience established that a 3 dB variation in D/R (as in d1 to d4) could be balanced by a 10 dB variation in overall level. To study the comparison of apparent distance of these configurations, we kept the overall level constant.

2.2. Configurations studied

Here are the shapes of the impulse responses of the configurations studied.

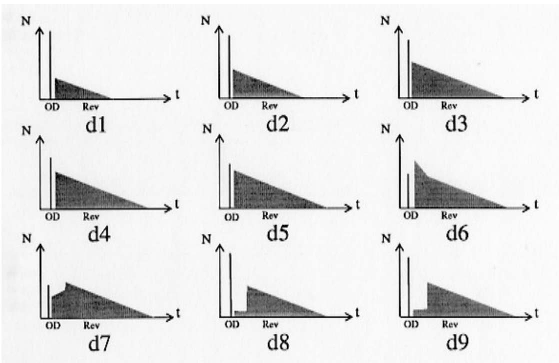

Figure 2 Shapes of the configuration responses

d1 to d5 have a regular reverberation shape of 2 seconds. The variation is only the reverberation level. The d6 to d9 configurations show different repartition of the energy in the reverberation. Some has strong early energy (80 first ms of the response), like d6 and the others has lower early energy. The values of D/R and C80 of the different configurations are the following :

	d1	d2	d3	d4	d5	d6	d7	d8	d9
D/R [dB]	4	1	-2	-5	-8	-11	-11.5	2	-1.5
C80 [dB]	7	4	1.5	-0.5	-3	-0.5	-8	2	-1.5

Table 1 Criteria values of the configurations responses

2.3. Result of 1st experiment

2.3.1. Multidimensional scaling

The following figure shows the result of the multidimensional scaling analysis. Stress was :

- 0.16 for one dimension
- 0.09 for two dimension
- 0.07 for three dimension

We have chosen two dimensions, because three does not add significant fall of the stress

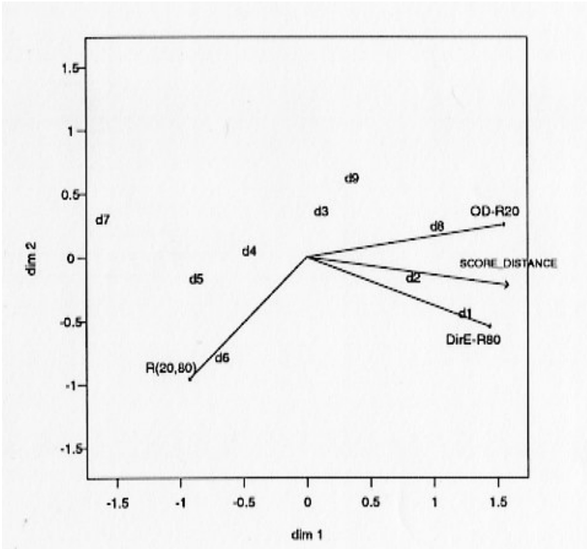

Figure 3 Multidimensional scaling analysis of the result of 1st experiment

This multidimensional scaling analysis shows two main axes. The first one correlates to D/R or C80. The second correlates with the proportion of early energy in the reverberation. As these axes correspond to a subjective test, we can assume that the subjects perceived on one hand the amount of reverberation and on the other hand the proportion of early reverberation in it.

2.3.2. Distance comparison

We can also classify the different configurations regarding their apparent distance, using statistic method on the data of distance comparison :

- d1 is closer than d8
- d8 and d2 are judge at the same distance
- d2 and d8 are closer than d3
- d3 is closer than d6
- d6, d4 and d5 are judge at the same distance.
- d6, d4 and d5 are closer than d7

d9 can't be easily classified : for some people this configuration is perceived as close as d8 and d2 and for some other people as distant as d3. Using these data, we have also built the distance vector in the multidimensional figure. In the figure, C80 is noted DirE-R80. The following figure shows a synthetic view of the distance judgements.

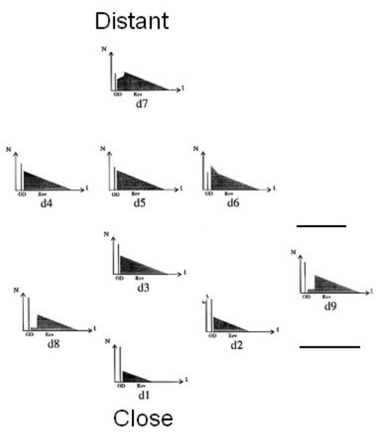

Figure 4 Distance judgements

2.4. Interpretation of 1st experiment

The distance vector seems to be correlated with D/R and with C80. To try to determine which one fits better with the distance judgements, we have to look at the results more precisely.
If the direct sound is louder than the early energy (say for 3 to ten dB), D/R and C80 are strongly correlated. If one increases the direct sound, it increases the C80. This corresponds to the configurations d1, d2 and d8, as shown on the right part of figure 3. Nevertheless, there is a perceptive difference between d2 and d8, d8 having less early energy than d2. This does not lead to a decisive differentiation of the apparent distance of these two configurations because the late reverberation level of d8 is higher, as shows the C80 values.
In this part of the figure, to determine which of D/R or C80 is a better candidate to explain apparent distance, we need to study d8 and d3 : d8 has a stronger D/R than d3 and the values of C80 are the same in both configurations : d3 is unambiguously perceived as farer than d8. Therefore, we can assume that in this conditions, D/R is a better criteria to explain the apparent distance. This is a standard result.
The central part of the figure shows many configurations in which differences are more due to the early energy than to the late reverberation energy. d9 has its early energy concentrated on the direct sound whereas d6 has about the same early energy, but spread over the eighty first milliseconds. As a reference, in d3, d4 and d5, the D/R and the C80 evolve in the same way.
Many studies tend to prove that there is a perceptual difference between a true direct sound and a direct sound with early energy [5][6]. The apparent source width increases with the adding of early energy or other aspects, like spectral balance and inner dynamic. Our study is specifically concerned with how this difference is perceived in regard to the whole reverberation. When the early energy level is lower than that of the direct sound, we perceive a very close direct sound image and a distant reverberation image. When the early energy level is higher than that of the direct sound, we perceive a distant direct sound integrated in the reverberation image. The early energy links the direct sound to the late reverberation.
Following Neher et al's terminology [8], we will call this variation the depth of the sound image, applied to one source. A strong depth is when the perceived direct sound is close and its reverberation distant, a poor depth is when the perceived direct sound is at the same distance as the reverberation.
Otherwise, d6 is perceived at the same distance as d4. The C80 is the same but D/R vary from –11 dB to –5dB. C80 seems to work better than D/R within this range.
When the direct sound has the same level or is weaker than the early energy, the apparent distance of the perceived direct sound, which is in fact the perception of all the early energy perceived as a whole, remains the same. The direct sound is partially masked by early energy. For example, d7 is much further away than d6 and has the same D/R value but a lower C80. This proves that, in this case, C80 commands the perception of apparent distance.
The perception of the reverberation can be seen as a masking process between the direct and the late

reverberation sound, the early energy being a kind of bridge between the two. If there is some early energy, there is no interruption in the energy of the frequency bands corresponding to the reverberated sound. If there is none, the energy gap produces an isolation of the direct sound, which reduces the masking process.
This analysis is close in some respects to that of David Griesinger in [16]. It sees the sounds as streams : there is a direct stream which is the pure direct sound if there is no early energy, or the pure direct stream plus the early energy if there is sufficient early energy. There is the reverberant stream which is late reverberation. These two streams are fused if there is early energy, these two streams are split if there is no early energy.
However, this masking process is influenced by the nature of the sound : if the components of the direct sound are very long, the direct sound and the reverberated sound are in a masking situation, even when there is no early energy. In the case of transients and of a lack of early energy, there is no mask between the reverberation and the direct sound. If there is some early energy, the early energy masks the direct sound and the following reverberation.
That's why d9 can't be easily classified, for some people this configuration is perceived as close as d8 and d2 and for some other people as far as d3. It may depend on the ability of some people to isolate the transients from the reverberation. This ability could be strongly related to listening experience.

2.5. 1st experiment conclusion

To sum up, this first study showed that when the direct sound was louder than the early energy, the apparent distance was correlated with D/R ; on the other hand, when the direct sound was at about the same level or weaker than the early energy, the apparent distance was correlated with C80. Practically, foregrounds are controlled by D/R and backgrounds are controlled by C80. If you want to have deep foregrounds, you can't only have low direct sound level, you must also have low early energy related to late energy and a low level, too.
Another thing which has to be said is that the aim of C80 is to take into account the amount of early energy which fuse with the direct sound in a single percept and then increase the apparent level of a "perceived direct sound". The amount which has to be taken into account is an average because it depends on the signal feeding the reverberation process, as has already been mentioned by many authors (see for example Ando on the influence or the autocorrelation of the signal on the perception of reverberation [22]). It is probably not the same for a snare drum or for an organ. Therefore, the value of 80 ms in the integrator has to be taken as an average, depending on the nature of the reverberated sound, but it doesn't affect our discussion.

3. INFLUENCE OF LISTENING ROOM, 2ND EXPERIMENT

In a natural listening situation, only one room is involved. In a stereophonic listening situation, at least two places are involved : the hall or room where the recorded situation took place ; the room where the listening situation takes place. There could be more with artificial reverberation. The question is : how does our perception deal with this, what does it hear? In this set of experiments, we compare two different listening situations for the same recording location : a well damped control room, and a domestic listening situation (living room). These two room effects are not of the same nature. The recorded hall can have true reverberation, but as shown by Toole in [17], the room effect in the domestic situation is merely early energy..

3.1. Methodology

The second set of experiments was aimed at studying the evolution of both D/R and C80 criteria in casual practice, from the recording studio to the control room, and then to domestic listening conditions. The measurements were, thus, carried out under conditions close to usual recording situations. As they may be very different, we tried to select a set of representative conditions. The chosen room was a 3 000 m3 concert hall (salle "Maurice Fleuret" du CNSMDP : Conservatoire de Paris) with a TR varying from 1.1 to 1.8 s. This hall being equipped with curtains to damp the reverberation, it allowed us to vary it. To change the difference of levels between the direct and the reverberant sound, the experiments were carried out at different distances (1.25, 2.5 and 5 m) from the two-way loudspeaker system A2T used as a source. A total of six configurations was thus investigated in this hall (TR = 1.1 and 1.8). To study what happens to these six signals in a well damped control room or in a domestic listening situation, we measured the changes undergone by the original criteria when the signal which came from the microphones was fed to the listening room. We did so by successively recording the results of the first responses in the recording room, feeding the monitoring systems with this signal and then recording the new response at the listening position with the same microphone. The final measurement was made through de-convolution of the final signal by the measurement signal. Comparison of this method to a direct measurement of the whole chain led to the same result. The measurements were made in two control rooms and two domestic listening situations with the same loudspeakers and a 3m stereophonic base. The results between the two control rooms and between the two domestic situations proved to be very similar. Our method was validated through comparisons of several microphones and direct measurement of the recording location plus control room. It also proved to work with convolution reverberations, which is a simpler way to test it. To validate the impression that the changes observed in the criteria values corresponded to a change in auditory distance, new experiments were made as follows : for each configuration, a test signal (a voice) played on the loudspeaker used to make the measurement in the concert hall was recorded with a dummy head at the listening position in the control room and in the domestic situation. Pairs of these configurations were compared by the subjects, with headphones, who were asked to say whether they perceived one configuration as closer or farther than the other one. The test was checked (validated by an ACP), and the results corroborated the changes previously observed in the values of the criteria.

3.2. Results of the 2nd experiment

3.2.1. IDC and criteria

The following figures show the evolution of the first 100 ms of the integrated decay curves (IDC in the following) of the impulse response of the :

- recording system in the hall: FL
- recording system plus control room: LEDE
- recording system plus domestic listening situation, living room: SAL

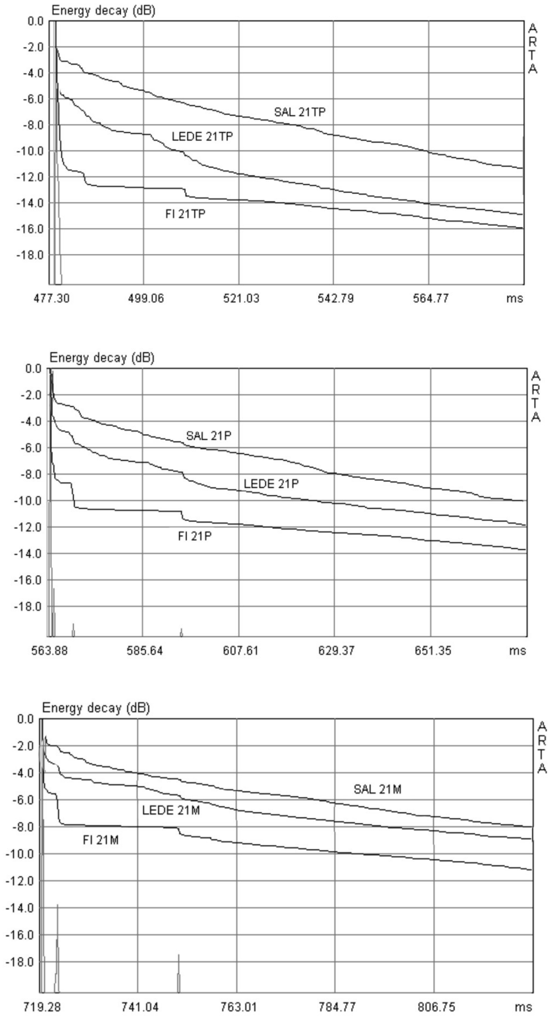

Figure 5 IDC of the impulse responses for the three rooms and three microphone distances.

The three figures correspond to the 3 distances of the microphone (TP 1.25m, P 2.5m, M 5m), when the reverberation time of the hall is set to 1.8s. And here is a table of the corresponding criteria :

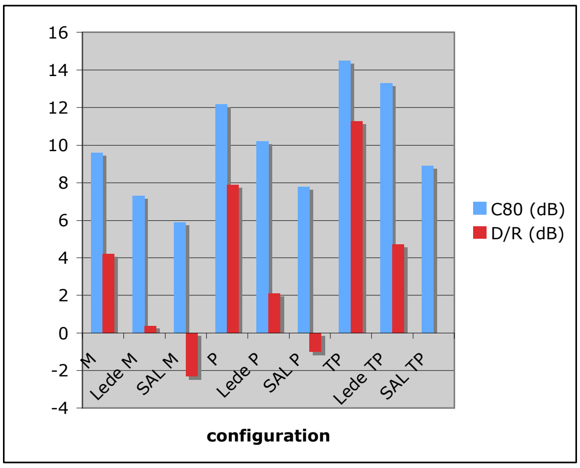

Table 2 Criteria for the three rooms and three microphone distances

3.3. Results : Subjective tests

The result of the subjective test is the following. The letters LEDE stand for “control room”, SAL stand for “living room”, the letter associated indicates the microphone distance (TP 1.25m, P 2.5m, M 5m).

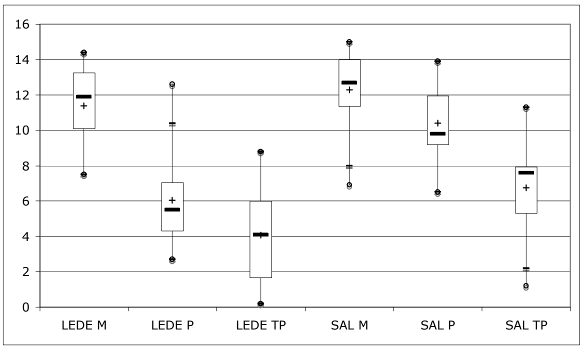

Figure 6 : subjective test : apparent distance

3.4. Interpretation of 2nd experiment

As we could see, there is a strong diminution of the D/R or C80 in the control room and an even stronger one in the domestic situation. The spanning of the values is also reduced. This confirms what we know by experience : there is a strong difference between listening in the hall at the position of the microphones and listening to the recording in the control room.

This listening difference is also due to the spatial distribution of the reverberated sound and the way it is “coded” by the stereophonic system. Therefore, it’s difficult to compare the original binaural situation and the stereophonic one.

We can nevertheless consider that the values of the criteria in the original hall correspond to that of another well-known listening system : headphones. For this stereophonic system, these criteria describe the time distribution of the reverberated energy through time. But headphones are a different listening situation compared to loudspeakers, which does not allow us to compare auditory distance between the two listening systems : the spatial distribution of the reverberation is different.

Therefore, we will focus on the comparison between the two stereophonic situations with loudspeakers, the control room and the living room.

The criteria variation is significant. The values of the criteria were about 3 dB higher in the living room than in the control room. The difference in value is higher when the microphone is closer, so when the true direct sound level is higher in the recording. These results show that the listening room has to be taken into account when considering the signal heard by the listener. This is confirmed by the subjective results.

They follow the evolution of the criteria, both C80 and D/R, with better correlation with C80 when D/R is negative, which is consistent with the results of the 1st experiment. This shows that the changes in criteria have been heard by the subject.

3.5. 2nd experiment conclusion

The first conclusion is that the auditory distance is not the same, moving from the control room to the domestic situation. The source images are further away in the image in the domestic situation.

The second is that one can hardly have a pure direct sound in the domestic situation. Because the listening room adds some reverberation to it. When you add some early energy to a pure direct sound, you change the spatial extension [5][6], you change the inner dynamics of the sound (less attack, more continuous sound), the spectral colour, and you change the way the direct sound integrates itself in the reverberation sound image.

In the reverberation shape, it adds early energy to the direct sound if there is not very much and then it fills the gap with the late reverberation. This leads to a diminution of depth, as described in the first section, for the listener. The difference in auditory distance between the image of the direct sound and the image of the

reverberation is reduced. It changes the shape of the reverberation in time, but also in its spatial distribution, coming from one part from the listening room. If you have some strong early energy coming from the left in your recording, depending on your system, it won't be entirely on the left. There will be a part that can be considered as coming from all around.
It depends on your acoustics but it depends also on the way you place the loudspeakers, and against which walls, the room effect is of course not homogeneous, as shown by Toole in [17]. There are good aspects too, when we listen to 2-channel stereophony, the envelopment comes from the room effect. Those who have listened to stereophony in an anechoic room know that it is a not such a pleasant experience.
This change depends on the recording, sometime it changes a lot and sometime it does not. This depends on how the change in the shape of the reverberation is affected by the listening room reverberation. With low C80 and a long reverberation time, there is no big change. Nevertheless, it can mask subtle information of the reverberation, both in time, and in space, and we have to deal with it. With a true direct sound, even if it is recorded in an anechoic chamber, you had a room effect on it.

4. GENERAL CONCLUSION

This paper has shown that auditory distance judgment, as perception of reverberation in general, is set upon a great variety of factors. This approach comes from the Ircam team analysis [14] [15], which follows the classical works in room acoustics by Beranek [4] and his followers.
We assume that the listener perceives a room effect which is a compound room effect whose characteristics come from one part from the recording location and from the other part from the listening location. Griesinger had shown this in [5] for the reverberation correlation. This is also true for the quantity and shape of the reverberation. This room effect is perceived as a whole and the listener is not able to hear which part comes from the recording location, witch part comes from the listening location. We believe that stereophony is an auditory illusion coming from that very point : for one part a real space (the listening location), from the other a figured space (the recording location).
There is an analogy with perception of lateralisation in stereophony, as defined by Plenge and Theile in [18][19]. They say there is a double stage in the localisation of a phantom source : first we localize loudspeakers as real sources and then, with the information carried by the signal, we judge the place of the phantom source. Here, we have two poles: the direct sound and the reverberated sound. The direct sound auditory distance is perceived as equal to those of the loudspeaker, but without a part of the visual cues, because we identify the source as another thing than a loudspeaker: a voice, an instrument or whatever. The reverberated sound auditory distance, i.e., the background, is perceived as the distance horizon in the room, coming from the reverberation of the room and the visual cues of the room [9]. Localisation of the sound image is set between these two real poles, depending on the information carried by the signal.
This compound room effect takes place in the room where we listen, but it figures the room where we have recorded, distorted by the stereophonic system we have used. The acoustical ambiance of the room figured is affected by the change of shape of the recording reverberation, due to add of the listening reverberation. We can see it on the comparison between the integrated decay curves and in the change of the values of the criteria. We can also hear it, when we listen for a recording from place to place. Especially when coming from a well-damped control room to a casual domestic system. In the second experiment, we asked questions about the changes in reverberation time. We have not included it in this paper because it was not clear enough for all the configurations, but for some of it, it was even changing the perception of the reverberation time for the subjects.
One can argue that there is not a single domestic situation. You can listen to your loudspeaker very closely, especially listening to your computer loudspeakers. You can also listen on headphones, and then there is no room effect from the listening system. We totally agree with that, as you can listen to music in your automobile or listen to music in your kitchen with your loudspeakers in the living room. In these cases, you add a lot of reverberation from the room but you do not even notice if you do not pay attention to it because it is early energy. It does not change all the sound, just some part of it.
That change of some part of the sound is the very thing we want to focus on. It depends on the listening situation and you must be aware that it is part of the changes when you imagine how your mix will sound when later someone will listen to it. There are other types of changes depending on the quality of your loudspeaker system : from a laptop loudspeakers system to a very nice hifi system, that will make changes in spectral balance and of definition in general. But you must also take into account the acoustics of the listening

room as part of your listening system and this is the beginning of a method to do that.

The simplicity of the criteria should not hide the complexity of the phenomena. As shown by Martens in [22], the temptation is a great to simplify the problems in order to resolve it. Again the quantity of early energy associated to the true direct sound in the perceived direct sound stream is in the dependency of the shape of the signal itself and perhaps it has to be considered as a function of frequency.

On one hand, thinking this way allows us to improve the control we can have on the sound the listener perceives. We can anticipate the integration of the foreground into the sound image and design nice backgrounds with low early energy and rich late reverberation. But on the other hand we have to imagine a great variety of listening conditions, leading to a great variety of sound images produced and we can not control each element of it. If this is reality, we have to deal with it.

5. ACKNOWLEDGEMENTS

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