Continuous evaluation of noise uncomfort in a bus

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Summary : A binaural recording, realized inside an autobus running according to a typical urban sequence, has been used in several ways :

- first of all, listeners had to continuously assess the annoyance of the using the categorical continuous method, introduced by Weber for the assessment of loudness. It has been proved that this task is achievable by listeners, even if it is a difficult one. This evaluation has allowed to identify the events inducing annoyance;
- then, sound extracts representing these annoying events have been numerically modified and assessed by a pair comparison method so as to identify the optimal modification for each of them;
- lastly, the whole signal has been modified in accordance with the results of the previous step. Then, other listeners had to assess both original and modified signals in a continuous and global way. This part has shown that the assessment has undoubtedly concerned the annoyance issue and not the sound level one, because individual differences have appeared among the members of the jury.

It thus seems possible to use this continuous assessment method so that the temporal hedonic evaluation of a long sequence can be obtained and that the most annoying events can be identified.

1 Introduction – bibliography

The goal of this study was to evaluate noise comfort in a city bus in a continuous way. More precisely, our intention was to know if a continuous evaluation can be realized while listening to real stimuli of long duration and to use its results in order to identify the most uncomfortable sound events during the sound sequence. This study was initiated by the parisian transportation company (Ratp), because it considered that noise comfort is important for passengers and wanted to give better requirements to bus manufacturers.

Most of listening test methods deal with short lasting sounds (typically about fifteen seconds). It doesn't seem to be a drawback to assess stationary sounds, because the assessment rapidly reaches a steady value as Paulsen showed it for real sounds or white noise lasting from 1 to 80 seconds [1]. Nevertheless, a large number of real sounds are no stationary ones as it is the case for interior or exterior car noises and methods allowing to know the perceptive assessment of such noises are not so numerous.
Kuwano and Namba [2] used a method of continuing assessment by categories for loudness evaluation. Keys of a computer board had been associated with different quantifications of loudness, varying from "very soft" to "very loud". The listener had to type on one of the keys as soon as his perception varied. Kuwano and Namba used this method for road traffic noise [3] or inside a car [4]. Hellbruck and al. [5] proceeded in a similar way for both road and

railway traffic; the difference being that each of the 7 categories had been subdivided into 10 subcategories and that the listener only had to give an answer each 15 seconds (thus, the purpose wasn't to assess the continuing perception of loudness, but more especially the perception of the 15 previous seconds).
Fastl and al. [6] used a continuing assessment method to compare the sound level of both road and railway traffic noises. In this case, the listener had to adjust the length of a line on a computer screen, so that it could represent his perception of the instantaneous level. Such a method had also been carried out by Kato and al. [7].
Weber [8] adapted an "analog category scale" to continuous evaluation with a cursor sliding along an axis graduated in 7 categories that he had tested in the case of road traffic noise.
Susini [9,11] also used this method for sinusoidal sounds of variable amplitude. On the other hand, he developed an inter-modal coupling method, for which the listener had to adjust a muscular force sensation to the loudness [10]. This adjustment was realized through a back effort lever that the listener moved with his hand. He checked the applicability of this method on the same sinusoidal sounds of variable amplitude and used it for both urban environment and interior noises (real and synthesized ones) of accelerating cars.
Studies are less numerous in the case of sound parameters other than loudness. Hirano and al. [12] used the assessment method by categories to evaluate the pleasantness of interior noises from cars running along a urban or suburban route.
Hedberg and al. [13] used the method introduced by Weber, but with 10 categories along the cursor for brightness assessments of various sounds.
This method was also selected by Gros and al. [14] to assess the quality of the voice altered by phone coding systems. In this case, the scale was divided into 5 categories (from the bad one to the excellent one).

What is the relation between the instantaneous assessment for a non-stationary sound stimulus and the overall assessment the listener can give on this after listening to it ? Previous experiments have shown that the overall loudness assessment given after the listening appears to be higher than the temporal average of the instantaneous loudness. Various explanations have been suggested for this result : preeminence of maximal loudness events [3], and short-time memory effects which consist in giving more importance to the latest moments of the sequence [9,11]. Gottschling [15] suggested a computation method combining these two effects, consisting in applying exponential decreases to local loudness peaks of the time response and then in considering loudness being reached during 5% of the time of the altered sequence.
However, Hellbrück and al. [16] showed that the overall loudness is very close to the temporal average of the continuous assessment when it is given a few minutes later (dedicated by the listener to the remembering of the main events of the sequence), and not just after listening as it had been the case before. They also showed that this overall loudness is close to the average of the loudness assessments of the different sound events which can be identified in the sound sequence (crossing of a car, a train, etc……). The link between continuous and overall assessments can thus be explained thanks to cognitive considerations.

So this study was conducted in three steps : first of all, a continuous evaluation of noise comfort during the driving of an autobus was conducted, and the most uncomfortable events were identified. In a second step, we tried to improve these events through signal modifications; as these events were rather shorts, the benefits of these modifications were evaluated through classical listening tests. Finally, when the best modification of each event had been identified, the whole sequence was modified and the continuous evaluation was

conducted again, in order to check the previous improvements. The whole process is represented in figure 1.

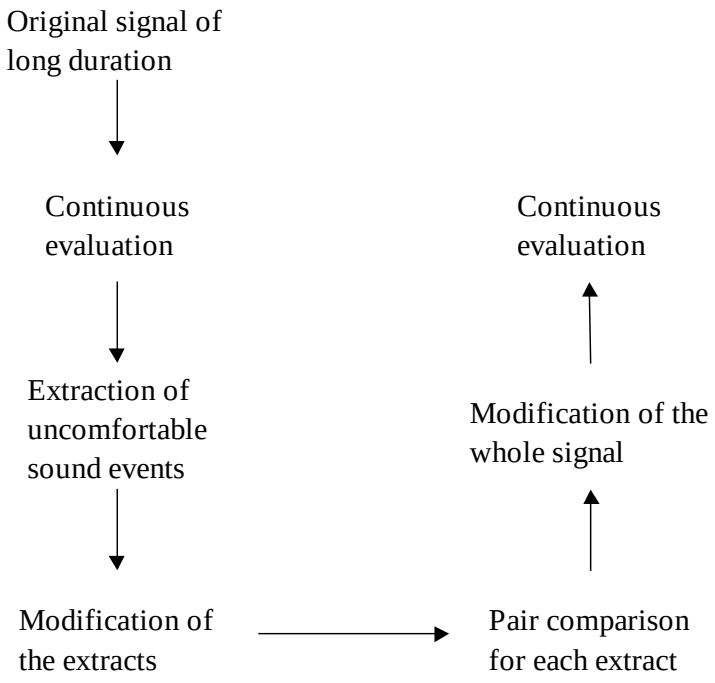


Figure 1 : Schematic view of the study.

2 Recording

An acoustic dummy head (Bruel & Kjaer 4100) was placed on a seat just ahead of the rear wheels of an autobus containing no passenger. The signals measured by the microphones were recorded on a DAT with a sampling frequency of 48 kHz; also, two tachometric signals were recorded : the first one measured the rotational speed of the engine and the second one, the speed of the rear axle (due to the torque converter of the automatic gearbox, the relation between these two rotational speeds could not be easily computed).

The autobus was driven in order to represent a portion of a typical journey of such a vehicle ;

- short idle phase;
- slow acceleration till 50 km/h and then about ten seconds of constant speed;
- deceleration and braking till a complete stop;
- about thirty seconds of idle, during which doors are opened; then closed and lastly air conditioning is switched on;
- a new acceleration till 50 km/h, immediately been followed by a slow deceleration till a complete stop.

The total duration of this sequence is of 162 seconds.

3 First Test

3.1 Procedure

The continuous analog category scale method proposed by Weber [8] was used. The listener had a box containing a cursor sliding along a scale graduated in five categories in front of him. As it was decided to use a scale not related to annoyance, but to noise comfort, which

has a more positive meaning, the graduations were worded as follows :"very comfortable", "comfortable", "little comfortable", "uncomfortable" and "very uncomfortable". Though that scale does not follow the recommendations from the ICBEN working group [17], which lead to an ISO normalization of socio-acoustics surveys, it was assumed that it provides equally-spaced categories.
The cursor controlled a potentiometer which modulated the tension of a 1 kHz sinusoidal signal, provided by an external generator. The task of the listener was to adjust the position of the cursor so that his sensation could be described by the semantic scale. The signal being modulated in this way was sampled by an audio card of a computer at the frequency of 8 kHz. Meanwhile, a second card played the audio sequence. At the end of the assessment, the modulated amplitude 1kHz was modified through Hilbert's transform, which allowed to obtain its envelop; this envelop represented the instantaneous position of the slider and was finally down-sampled at 50 Hz.

The signal was presented to listeners through earphones (Sennheiser 600) in a quiet room.

The test consisted in the following steps : first of all, an explanation concerning both the recording conditions of the sequence and the task of the listener was given to him; then the sequence was presented to the listener just for him to discover it. During a second listening, the listener had to assess noise comfort with the help of the slider. At the end of this second step, he was asked to evaluate the realism of the recording, the difficulty and the apparent length of the test and the overall comfort of the whole sequence. Finally, the continuous assessment was repeated, in order to evaluate the stability of the answer. The overall process lasted about twenty minutes.

3.2 Listeners

The jury consisted in 52 people paid for their participation. Most of them were students (the average age was 24 years old, the range being between 18 and 45). The proportion of men and women were equivalent. No audiogram has been carried out from listeners, but none of them reported any auditory trouble.

3.3 Feasibility of the task

The first question concerns the feasibility of the task asked to listeners : is a continuing assessment realizable ? The coefficient of correlation between the results of both assessments (figure 2) has been computed for each listener to have an idea about the repeatability of the results, which can not be high if the task is too difficult.

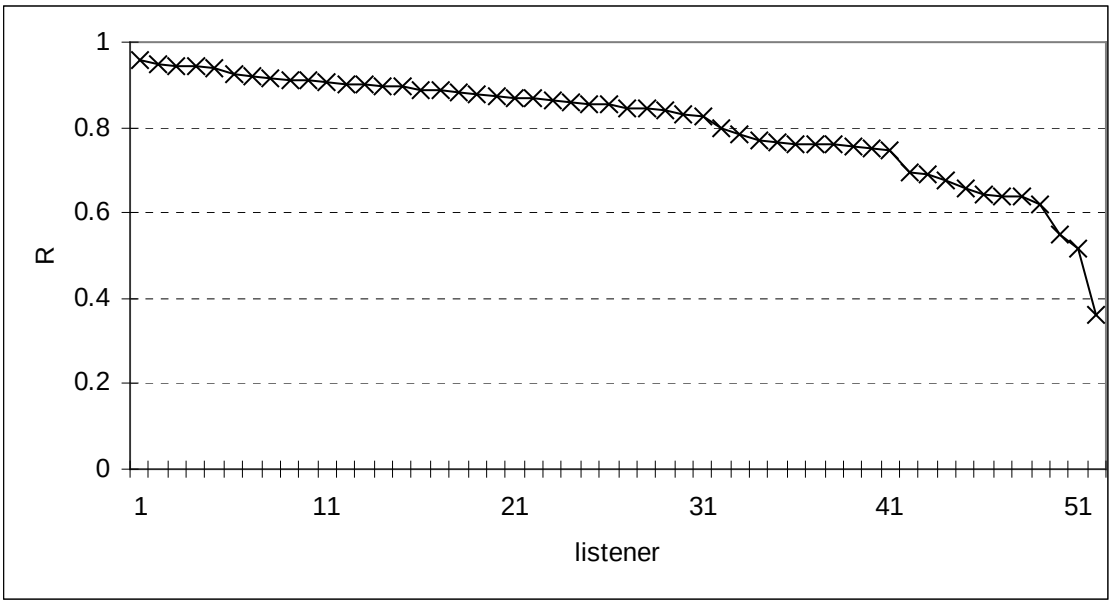


Figure 2 : Individual correlation coefficient between the two continuous evaluations.

The correlation is clear except for about ten listeners. The task thus seems to be realizable, even if the questionnaires reveal that listeners consider it to be as a rather difficult one (figure 3). Other questions show that the sequence accurately reproduces the interior noise of an autobus (which is familiar to all listeners) and does not seem too long to them : the expressed difficulty has undoubtedly been linked to the required task.

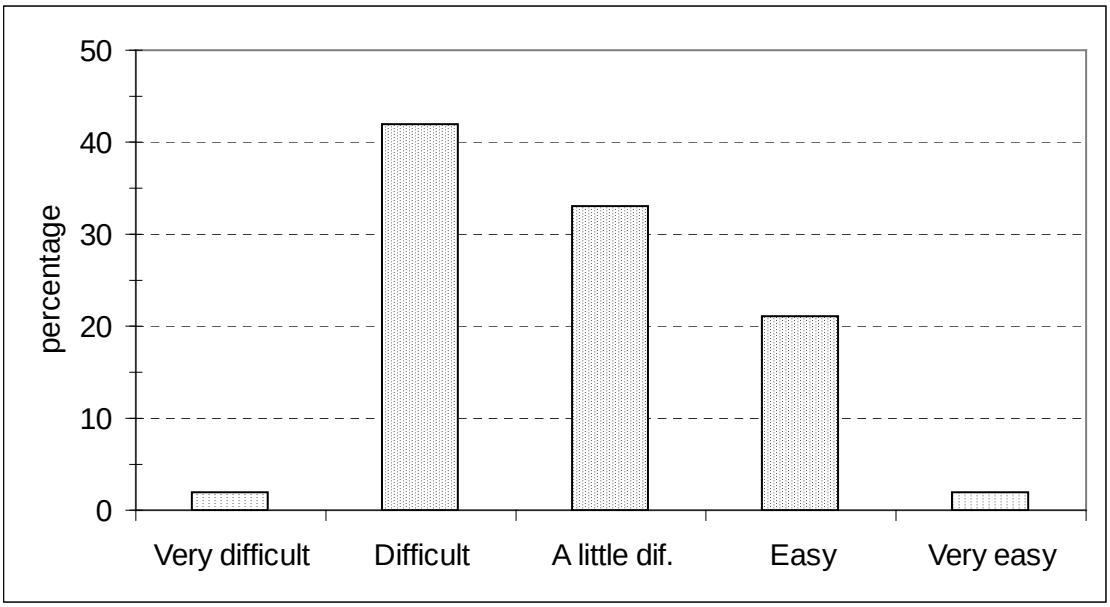


Figure 3 : Evaluation of the difficulty of the task.

3.4 Continuing assessment

The examination of individual answers shows the same tendencies as the ones already pointed out by Weber : some listeners try to accurately follow variations of their sensation, whereas others only make their answers vary when their sensation is clearly different (figure 4). Listeners are nearly equally divided up in these two categories.

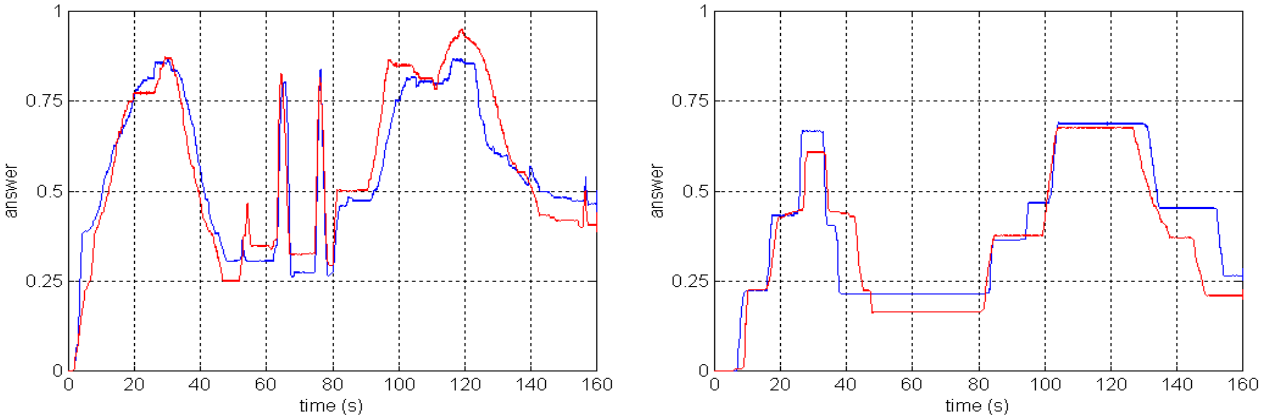


Figure 4 : Example of the answers of two listeners. In these drawings and all the similar ones in the following, the categories of the response box are replaced by numbers. 0 : very comfortable; 0.25 : comfortable; 0.5 : little comfortable; 0.75 : uncomfortable and 1 : very uncomfortable

It has also been tried to assess the reaction time of each listener, using both opening and closing events of the car doors, because these events are very limited in time. Figure 4 shows that one of the listeners (on the left side of the figure) clearly noted these events (between 65 and 75 seconds), which is not the case of the other one (on the right side).
The reaction time of each listener has thus been computed when it has been possible to do so (they are presented in figure 5). When the answer of the listener exhibits a strong decrease in comfort in the five seconds (i.e. a peak in the response curve) following the instant of the door opening (or closing), his reaction time is defined as the difference between the times of the physical event and of the peak of the answer.

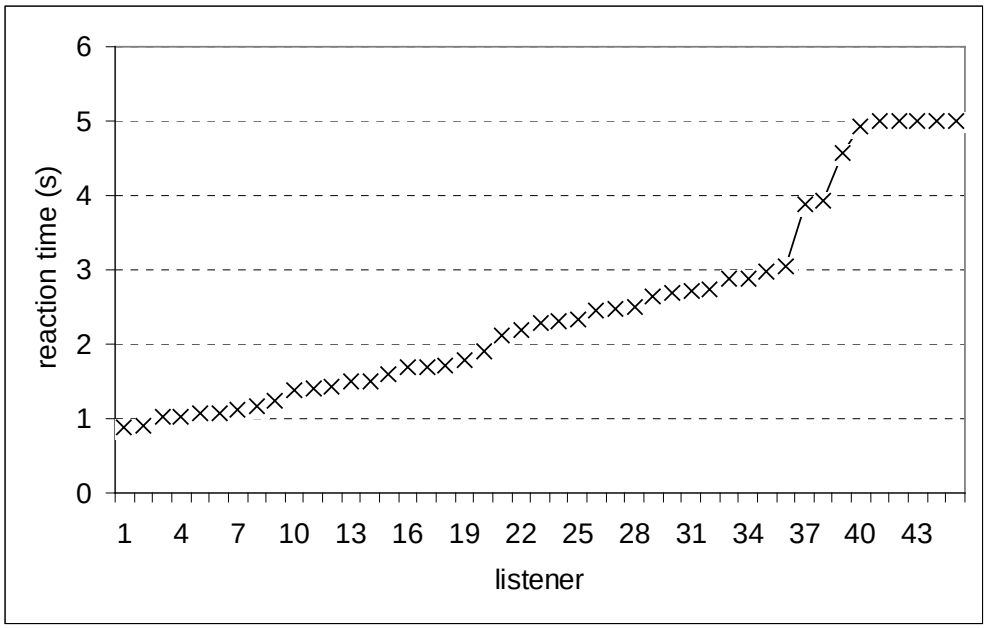


Figure 5 : Reaction time of listeners.

Here the values are more important than the ones presented in previous studies : between 0.9 and 3 seconds (average value : 1.9 s), whereas both Kuwano and Namba [3] mentioned reaction times included between 0.7 and 2.3 s, and Weber [8] suggested an interval included between 0.5 and 1.5 s. The reason for this can be based on the different nature of tested

noises. The mentioned studies concern traffic noises, the variations of which are slower than the ones observed with an opening or closing of bus doors. An increase in the time of reaction had already been noticed for quicker variable events by Kuwano and Namba.
Later on, the averages of continuous evaluations that will be presented, have been obtained while correcting each individual answer by the reaction time of reaction of the listener, computed –as it is mentioned above- when it has been possible to do so. The correction was applied by shifting each individual answer backward by the reaction time. Then the answers were arithmetically averaged.

The average on the whole panel (using both answers of each listener) is represented on figure 6.

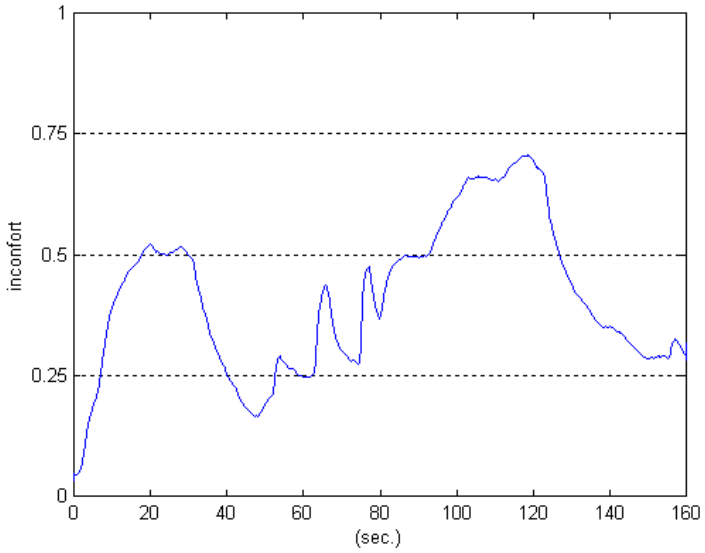


Figure 6 : Average discomfort evaluation.

This figure clearly emphasizes the different events of the sequence : both accelerations and decelerations, the opening and closing of the doors (at t = 65 s and t = 75 s), the function of a drying system for the pneumatic circuit (t = 52 s) and the switching on of the interior ventilation (t = 78 s). It also shows :

- The asymmetry of the answer during a short event as in the opening of car doors. The increase of the answer is much quicker than the decrease. After the end of the opening signal, the answer has no time to converge at the level it had before the opening.
- For such short events, the answer seems to be given more as an increase of discomfort (with regard to the previous situation) than as an absolute assessment for the event. For example, the maximum level of discomfort is stronger for the doors closing than for their opening. However, this is certainly linked to the previously mentioned asymmetry of answer : the increase of discomfort is similar between opening and closing of doors. This is also visible when the ventilation is switched on, which creates a strong increase of discomfort. But, at the end of the sequence, the noise is quite similar to the noise after this switching on : the engine is running at idle and the ventilation system is on. Nevertheless, the subjective evaluation is more favorable at the end of the sequence. The answer is thus given more in concordance with discomfort variations than according to its absolute level.

Lastly, the link between continuous assessments and the overall evaluation of the sequence has been looked for. The overall evaluation was expressed by the listener on a five levels

scale, whose terms were the same as those appearing on the slider box. The sequence has been evaluated as "Comfortable" by 21 listeners, "Little comfortable" by 22 of them and "Uncomfortable" by 9 other people. The averages of continuous assessments computed from these three groups of people are represented on figure 7. They are correctly and expectedly formed into a hierarchy : the more the continuous assessment is favorable, the better the overall assessment of the sequence will be. However, the differences between these three average curves are smaller than those of the answers for overall evaluation : differences reaching a category of answer cannot be found between the curves of figure 7 (this is due to the fact that continuous answers are expressed on an analog scale, while overall evaluation is given on a categorical scale).
By computing Student's t in the time domain between two categories, it can be seen that, at a confidence level of 5% :

- the continuous results for the "Comfortable" and "Uncomfortable" classes are significantly different all over the signal, excepted at the end of the second acceleration (around 12 s);
- those for the "Comfortable" and "Little comfortable" classes are different only during the first acceleration and door opening and closing;
- those for the "Little comfortable" and "Uncomfortable" classes different only at the end of the two slow-downs.

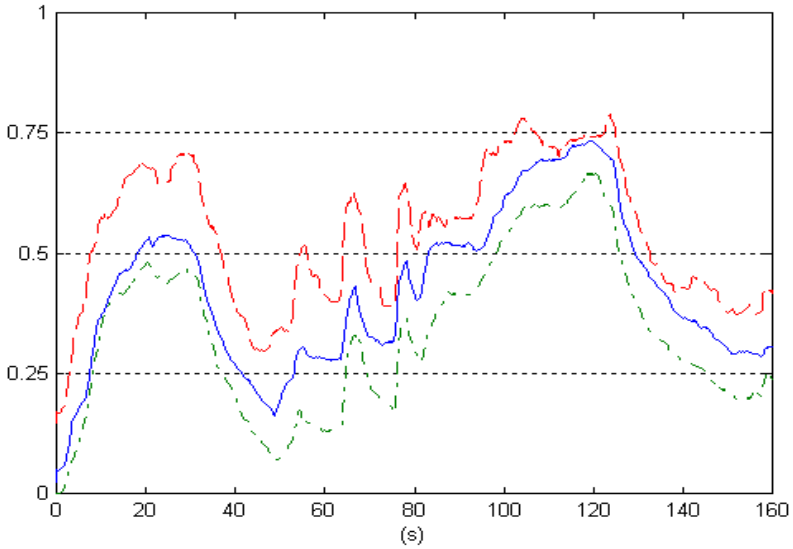


Figure 7 : Discomfort evaluations, averaged over the three categories of listeners, as defined by the overall evaluation.

It can also be noticed that differences between men and women are not significant for each type of evaluation. These differences have been tested through a χ^2 test for the overall evaluation (because, in that case, the answers are discontinuous) and by the computation of Student's t, at each moment of the continuous assessment.

Finally, the close link between loudness and uncomfort has also be found, as in many other studies. The figure 8 shows the loudness computed over the whole signal according to ISO 532B regulation (by the MTS *Sound Quality* software, diffuse field correction). The tendencies between this curve and the subjective evaluation presented in figure 6 are clearly the same; nevertheless, some discrepancies exist :

- some increases of loudness during accelerations and coasts down are not detected by listeners;

- on the other hand, the switching on of the ventilation system (at *t = 80 s*) appears to be more annoying than one could expect from the increase of loudness due to it.

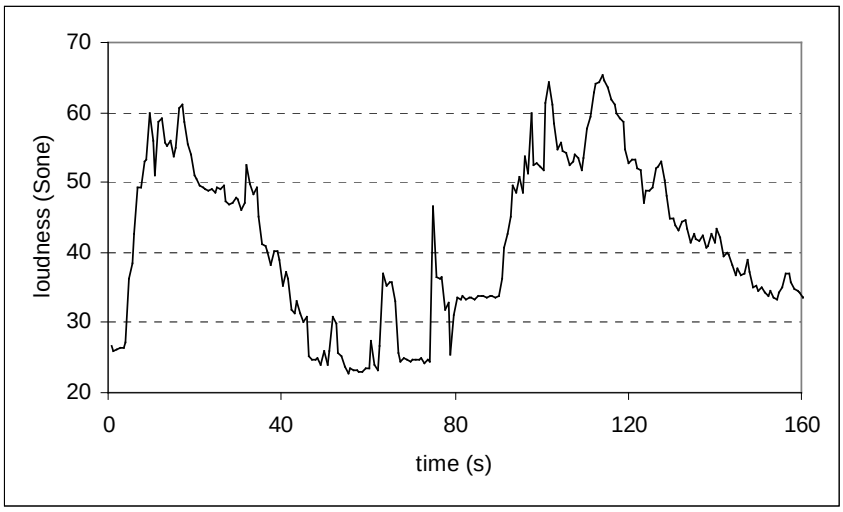


Figure 8: Loudness versus time of the signal.

In that case, the use of Widmann's psychoacoustic annoyance model [18] give similar results, because sharpness, roughness and fluctuation strength values are very small over the whole sequence : the values of Widmann's PA are only influenced by loudness ones.

4 Second experiment

From the results of the previous experiments, four sequences have been selected because they strongly contribute to the acoustical discomfort : a part of the first acceleration, the releasing of the pumping dry system of the pneumatic circuit, the opening of doors and the starting up of the ventilation. The duration of each sequence is between 8 and 10 seconds.

4.1 Procedure

Selected sequences are short enough so that paired comparison tests can be used. Each of them has thus been modified in different ways.

For instance, in the case of the acceleration noise, the three modifications have consisted in attenuating some harmonics of rotation speed of either the engine or the rear axle :

1) attenuation of a whine frequency noise of rear axle (34^{th} harmonic). Practically speaking, this attenuation can be achieved on the bus by using helicoïdal gears instead of spur ones;
2) previous attenuation, plus the one of the predominant (3^{rd}) harmonic engine,
3) previous attenuations, plus the ones of two other harmonics (engine and axle). These two last modifications can be achieved by increasing the decoupling and sound insulation of the engine.

The result is thus a corpus of four sounds (including the original sequence) which have been presented by pairs in an order respecting Ross series [19], the listener having to indicate his preference on a continuous category scale. The five categories were labeled "I prefer sound A a lot", "I prefer sound A", "sounds A and B are equivalent", and so on. Some pairs have been repeated so as to assess the stability of the listener's answers.

Three other tests have been carried out, one of them being done for each of the other sequences. They have also brought both the original sequence and three modified versions into action (except for the opening of car doors, for which four modifications have been kept). These modifications have mainly consisted in attenuating the sound level in different

frequency bands or in softening the opening of car doors. These four tests have been submitted to each listener in a random order.
Sounds have been presented to listeners through the same headphones as in the first experiment.

4.2 Listeners

The jury consisted of 48 people (25 women and 23 men) who mostly already have participated in the continuing assessment. They were between 18 and 45 years old (the average being people who are 23).

4.3 Results for the acceleration

The results of each listener have been expressed as numbers included between 0 (if the answer was "I prefer sound A a lot") and 1 (corresponding to "I prefer sound B a lot"). The preference matrix of the listener has been built in this way, which has allowed to compute the different merit scores of sounds for this listener. A first analysis (repeated pairs and computation of circular error rates) has allowed to keep the overall number of listeners in the jury. Then, a research of homogeneous groups has been carried out using the K-means technique [20]. It has allowed to distinguish two groups of 17 and 31 listeners. Both the averages of the computed scores for these two groups and the average of the whole jury are represented on figure 9. In this case, the scores can vary between 0 and 3.

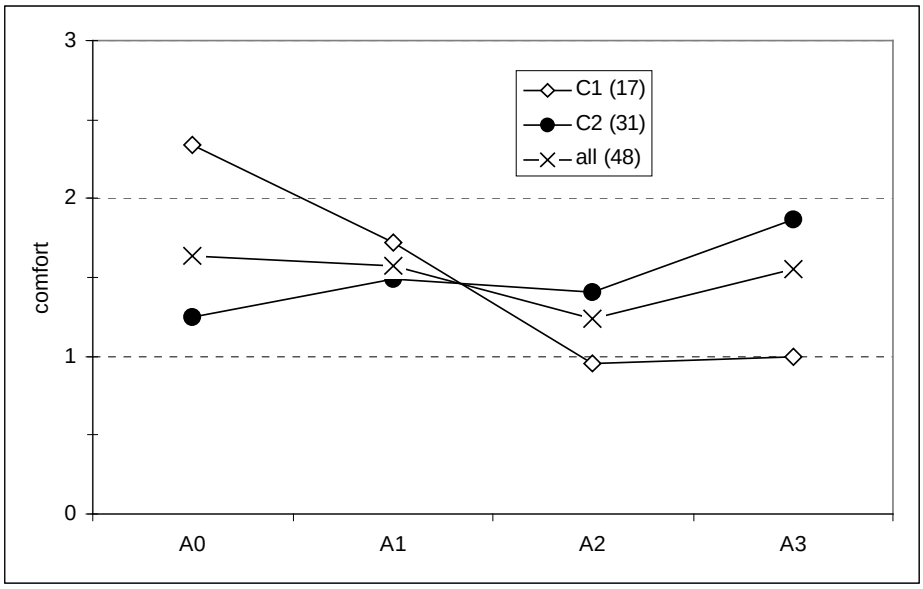


Figure 9 : Results of the pair comparison test for the acceleration noise.

The majority group has perceived an increase of acoustical comfort due to the modifications applied to the signal; the third version (which is the most deeply modified) appears to be preferred by listeners who belong to that group. However, the second group has perceived a decrease of comfort under the same conditions, this decrease being much more important than the improvement noticed by the first group. This shows once more the necessity to examine the homogeneity of a jury before giving a conclusion on the hierarchy of signals : when computed over the whole panel, the average score of sound A3 is not significantly different from the one of sound A0 (*t=0.558, 47 dof*). But, when computed over each of the two sub-panels, these scores are significantly different one from each other.

4.4 Results for the other sequences

Results do not show the inter individual variabilities of the previous case for the three other sequences which have been modified. Scores of preference have clearly been linked to the loudness of each stimulus for all listeners.

5 Third experiment

It must be reminded that the purpose of this latest test consisted in modifying the signal of the whole sequence and comparing the continuous evaluation of the modified and original sequences.

5.1 Procedure

The initial long sequence (lasting 162 seconds) has been modified according to the conclusions of the second test :

- the overall filtering of the third modification (cf. part 4.1) has been applied on the overall signal, though the effect has resulted to be essentially audible during the acceleration and deceleration phases;
- the noise of the drying system of the pneumatic control device has been filtered so as to reduce it of about 7 dB frequencies over 7 kHz, and a final creaking has been suppressed;
- the noise of doors has also been modified in the frequency domain (by the same filtering as for the drying system) and in the temporal one (the initial pneumatic impulsion has been softened and a final clattering has been suppressed);
- lastly, from the switching on of the ventilation (t = 78 s), frequencies above 9.5 kHz have been reduced by 5 dB.

All these transformations have been realized using the MTS "Sound Quality" software.

Lastly, the level of presentation of the original sequence was consistent with the one measured inside the autobus. The consequence of the different modifications is that the equivalent level of the modified sequence was slightly inferior to the one of the original sequence; the average reduction, when computed according to the ISO 532B procedure, was 1.9 phon and this difference could reach 4 phon at some moments (especially at the end of each acceleration) (figure 10).

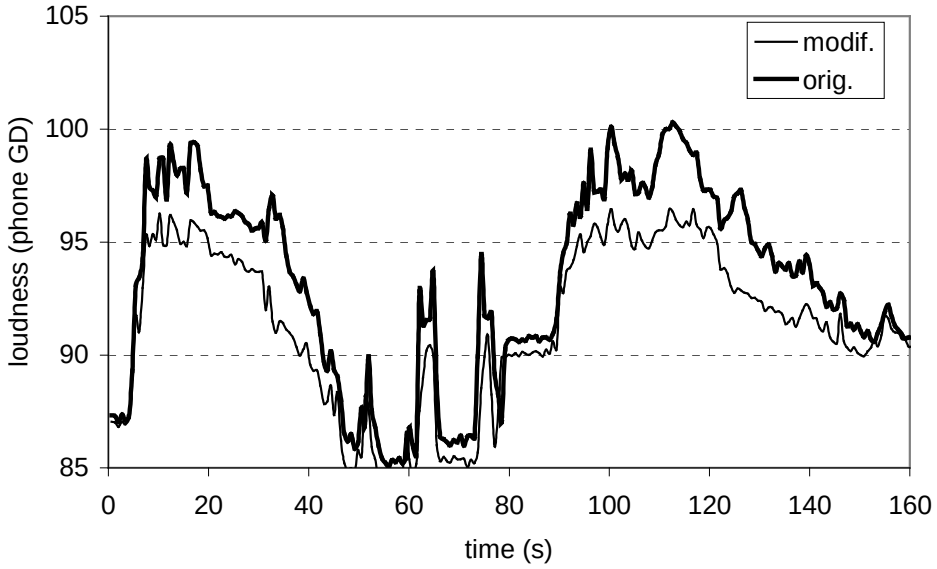


Figure 10 : Loudness vs. time for the original and modified signals.

Each listener listened to each sequence twice and had to evaluate them in a continuous way using the slider, as in the first test. Half of the jury began with both assessments of the original sequence and the other half with the ones of the modified sequence. Between the two repetitions of each sequence, the listener had to answer a questionnaire about his perception of overall comfort and the difficulty of the task (the questionnaire was similar to the one used in the first experiment).

5.2 Listeners

51 people participated to this experience. This panel represented a certain number of characteristics of the customers of the Parisian transportation company (repartition by category : age, sex and professional activity). They have been paid for their participation.

5.3 Results

The examination of continuous evaluations has given the same results as in the first test (feasibility of the task, time of reaction and asymmetry of the evolutions of answers during very short events) and will not be discussed any longer in the present case. Only one of the listeners has given totally incoherent answers, showing that he hasn't understood the required task, and his results have been withdrawn.
The answers about overall comfort evaluation have allowed to divide the panel into three groups :
- in the first one, listeners indicate an improvement in the acoustic comfort resulting from the modifications. This group consists of 21 listeners;
- listeners belonging to the second group (13 people), equally appreciate both sequences;
- lastly, the 16 people belonging to the third group report that the acoustic comfort has been reduced because of the modifications.

It is interesting to note that these differences in the comparison of the two sequences can also be seen in the continuous assessments (figure 11).

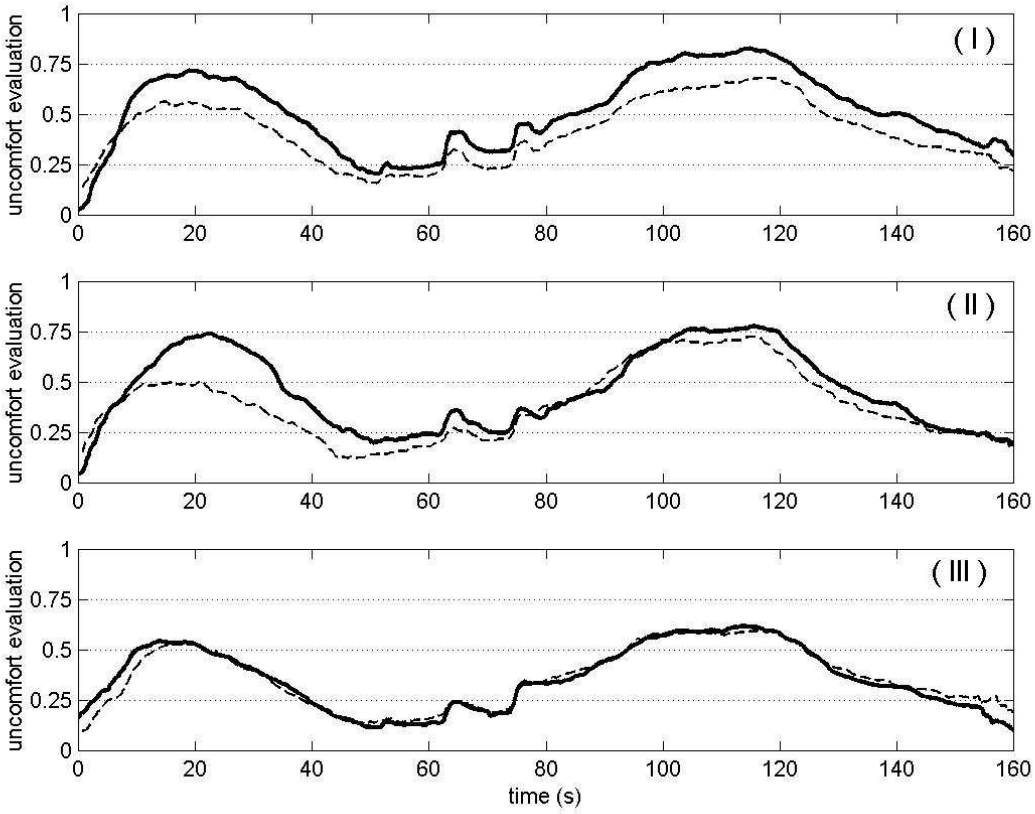


Figure 11 : Averaged evaluations of the original and modified signals, computed over the three categories of listeners, as defined by their overall evaluations of the modifications. Dashed line : original sequence; solid line : modified sequence.

Continuing assessments of listeners from group I are undoubtedly better for the modified sequence during all the length of the signal. The computation of Student's *t* in the time domain (20 *dof*) shows that this difference is nearly always significant ($p < 0.01$).
For group II, the improvement is even more important at the beginning of the sequence, but non significant in the second half of it, which can mean that listeners have used this second half of the sequence to give their overall evaluations.
Lastly, listeners from group III give equal continuous evaluations for the two sequences.

It seems that these results indicate that :

- on the one hand, listeners (at least those belonging to groups II and III) have really assessed the comfort felt during the listening of sequences, and not loudness. Indeed, if loudness had been evaluated, the differences between original and modified sequence would have been more similar between listeners, because loudness evaluation is less dependent on the individual than an hedonic attribute as comfort. For listeners from group I, it cannot be stated whether they evaluated loudness or comfort, this attribute being closely related to loudness for them;
- on the other hand, continuous assessments are expectedly linked to the global assessment of a sequence in a logical way, as it is the case for loudness [3,9,16];
- lastly, continuous evaluation is less accurate than an overall one. Listeners from group III could have been expected to continuously evaluate the modified sequence in a more severe way than the original one, but this is not the case (the small comfort reduction appearing from $t = 125$ *s* in figure 11 is not statistically significant). This cannot be

explained by inter-individual variability (which is not greater for listeners from group III than for the two other groups). In the same way, modifications applied to the opening and closing of doors (between t = 60 s and t = 80 s) are not visible on figure 11, even for listeners from group I. For this group, the average assessment is better for the modified sequence during door opening; but the reason for that must be that the evaluation before door opening is also better. As previously pointed out in part 3.4, for short events, the answer is more related to variation of comfort rather that to an absolute evaluation.

6 Conclusion

This study shows that the method of continuous assessment used by Weber for loudness of road traffic noises can be used for the evaluation of a more subjective attribute as acoustic comfort inside a vehicle. This task is achievable for listeners even if it seems to be a difficult one and differences between individual behaviors, emphasized by Weber, have also been found in that case.

It must be noted that it does not seem possible to have an accurate absolute evaluation of each event of the sequence, because listeners mainly describe decreases of comfort due to a particular event. That conclusion could be checked with the use of an ISO-conformed answer scale; but it can be presumed that it will still be valid and that such a phenomenon is strongly related to perception and not to the listening test procedure.

Nevertheless, that method points out the most uncomfortable events of a long and non-stationary sound, thus allowing the engineer to focus on such events in order to improve sound quality of the whole sequence.

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