HOW DOES LOUDNESS OF IMPULSIVE SOUNDS DEPEND ON ENERGY AND DURATION ?

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Meunier Sabine ; Rabau Guy
LMA-CNRS
31, chemin J. Aiguier
13402 Marseille cedex 20
France
33 491 16 41 75
33 491 77 55 65
meunier@lma.cnrs-mrs.fr

ABSTRACT
It has been shown that, for short-duration signals, loudness is proportional to energy (amplitude x duration). However, many studies showed conflicting results. Some researchers found that loudness varies less rapidly than energy when duration increases. Some other found that loudness varies more rapidly than energy when duration increases. We measured loudness of short-duration synthesized signals in which energy and duration can be handled independently. The relationship between loudness, energy and duration depends on signal frequency and level. The results of this study could explain the apparent discrepancy between previous research.

INTRODUCTION

Previous studies on loudness of impulsive sounds showed that, for short duration signals at constant intensity, loudness increases as sound duration increases (Cavé and Chocholle, 1979; Coles and Rice, 1968 ; Mery, 1967; Port, 1963).
The question is to determine how loudness varies with duration :

1) Does loudness increase in proportion to energy (intensity X time) when duration increases ?
2) Does loudness increase more rapidly than energy when duration increases ?
3) Does loudness increase less rapidly than energy when duration increases ?

Scharf (1978) summarized different studies on loudness of impulsive sounds. The results of the different studies are highly discordant. In some studies, the first relationship described above is observed, in some the second relationship is observed, and in some the third. But the signals were different from study to study (frequency, level), and this could explain the apparent contradiction. In a Round-Robin test run in 1977 (Perdersen et al., 1977) these three relationships have also been found. The aim of this Round-Robin test was to give a simple tool for the measurement of loudness of impulsive sounds. The conclusion was that the dependence of the loudness of a brief sound on duration can be described by an exponential function with a time constant of 80 ms. This means that loudness varies in proportion to energy up to a critical duration of 150 to 300 ms.
The aim of our study is to find the relationship between the physical parameters of an impulsive sound and its loudness for different sound frequencies and different levels, to explain the discrepancy between the different studies. In our experiment, the energy of the sound was maintained constant, and the question was to determine how does loudness vary when duration increases.

EXPERIMENT

In a previous experiment on loudness of impulsive environmental sounds (Meunier et al., 2001), it was observed that impulsive environmental sounds (at least for our sample of 24 sounds) have the temporal pattern shown in figure 1 : a short attack (modelled by an linear function), followed by a longer decrease (modelled by a decreasing exponential function), without a steady part at the maximum amplitude. In the study presented in this paper, we choose the same temporal pattern for synthesized sounds.

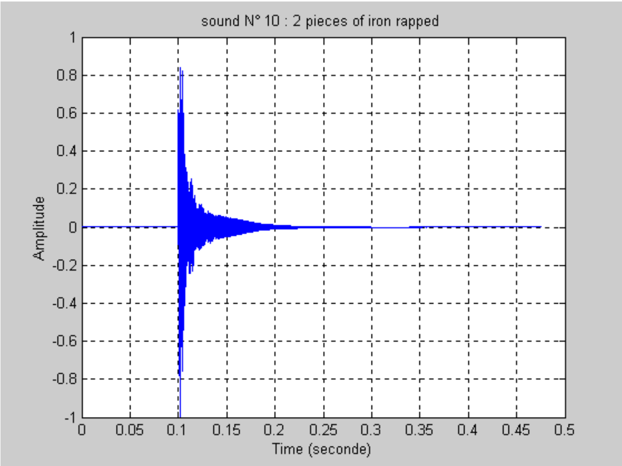

Figure 1 : Temporal pattern of an impulsive environmental sounds.

The sounds were synthesized as follow :
First the envelopes of the signal were defined with the pattern shown in figure 1. Secondly, the temporal fine structure was multiplied to the envelope (see figure 2). Thus, it was possible to handle separately the decay time and the temporal fine structure.

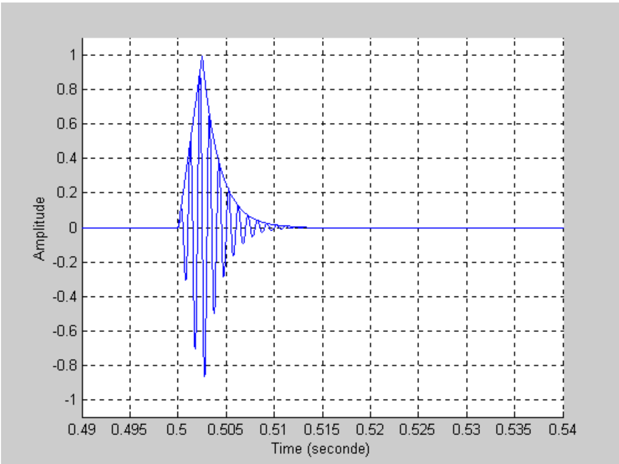

Figure 2 : exemple of a synthesized sound

Two different temporal fine structures were used : a band of noise centered at 1 kHz with a bandwidth of 300 Hz and a 4-kHz pure tone. The rise time of the signals was set constant at a value of 2 ms and the decay time varied from 4 to 1000 ms (4, 5, 10, 15, 20, 40, 60, 80, 100, 200, 300, 400, 500, 600, 700, 800 and 1000 ms). It has also been shown that the loudness of an impulsive sound, at constant intensity, increases when the rise time decreases for durations less than 0.3 ms (Ross and al., 1968) or 1.5 ms (Guftaffson, 1974), depending on the study. These signals were tested at three different levels. For a decay time of 4 ms, the level of the maximum of the envelope was 100 dB, 85 dB and 70 dB.

For a particular temporal fine structure and a particular level, the energy of the sounds was set constant for all decay times. Thus, the maximum of the envelope was decreased when the decay time was increased according to a rule allowing to keep the energy constant (the rule was different for the band of noise and for the pure tone).

The sounds were played via a D/A interface (OROS sound card), then attenuated with a programmable attenuator (Wilsonics). The level of the sounds were calibrated with a 1-kHz pure tone at 100 dB SPL, level measured at the center of what whould have been the place of the listener's head during the experiment (for the calibration, the attenuation of the programmable attenuator was O dB). A fixed attenuator was used for this calibration. This 1-kHz pure tone is used as the reference signal to calculate the levels of the impulsive sounds. The sounds were then played via a GENELEC loudspeaker (1031A) in an anechoïc chamber (figure 3). They were presented in a random order (2 different fine strutures X 17 decay times X 3 levels = 102 sounds in a same session).

As a control of the energy, the sounds were recorded at the place of the subject and afterward their energies were calculated. The sounds with the same fine structure and the same attenuation had equal energies with a precision of ± 1 dB.

Loudness was evaluated using magnitude estimation without reference (Stevens, 1975). Twelve subjects took part in the experiment.

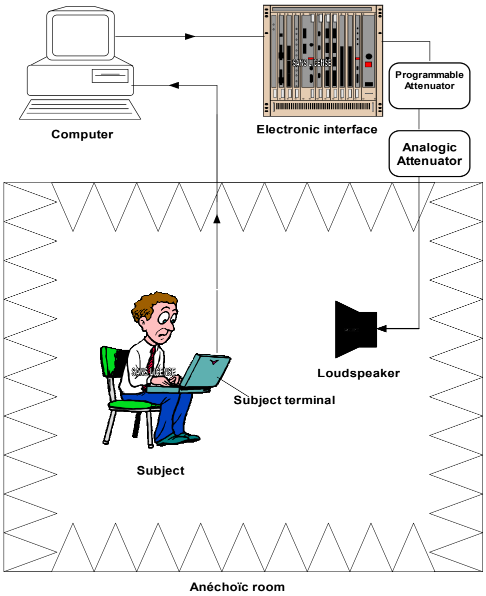

Figure 3 : experimental set-up

RESULTS

The results of the experiment are shown in figures 4 and 5 for the band of noise and for the 4-kHz pure tone respectively. Figures 4 and 5 show that loudness increases as decay time increases whereas the energy stay constant. This relationship is true for the lower signal levels (for the higher attenuations). For high levels, loudness stays constant when duration increases. An exponential function was found as a best fit to the data. The relation between loudness and decay time could be written as:

$$N = A.T_d^{\gamma},$$

where N is the estimated loudness,
A is a constant,
T_d is the decay time,
γ depends on signal level and temporal fine structure.

An analysis of variance was run on the data. It shows that, for the band of noise, the variation of loudness with decay time is significant when the peak level of the minimum fall time is 100 dB (F(N=12, dl=16) = 1.89, p=0.02)) and when the peak level of the minimum fall time is 70 dB (F(N=12, dl=16) = 2.4, p=0.002)). When the peak level of the minimum fall time is 85 dB the variation is not significant ((F(N=12, dl=16) = 0.9, p=0.55)). This result could appear surprising, but it is certainly due to the number of subjects that is low compared to the degrees of freedom. We should use more subjects to get statistically significant results. But the figures show the trend, that is that the influence of the decay time is more important at low than at high levels.

For the 4-kHz pure tone, the analysis of variance shows that the variation of loudness with decay time is significant when the peak level of the minimum fall time is 85 and 70 dB (F(N=12, dl=16) = 2.23, p=0.005 et F(N=12, dl=16) = 2.16, p=0.008 respectively). The variation is not significant when the peak level of the minimum fall time is 100 dB (F(N=12, dl=16) = 0.6, p=0.88).

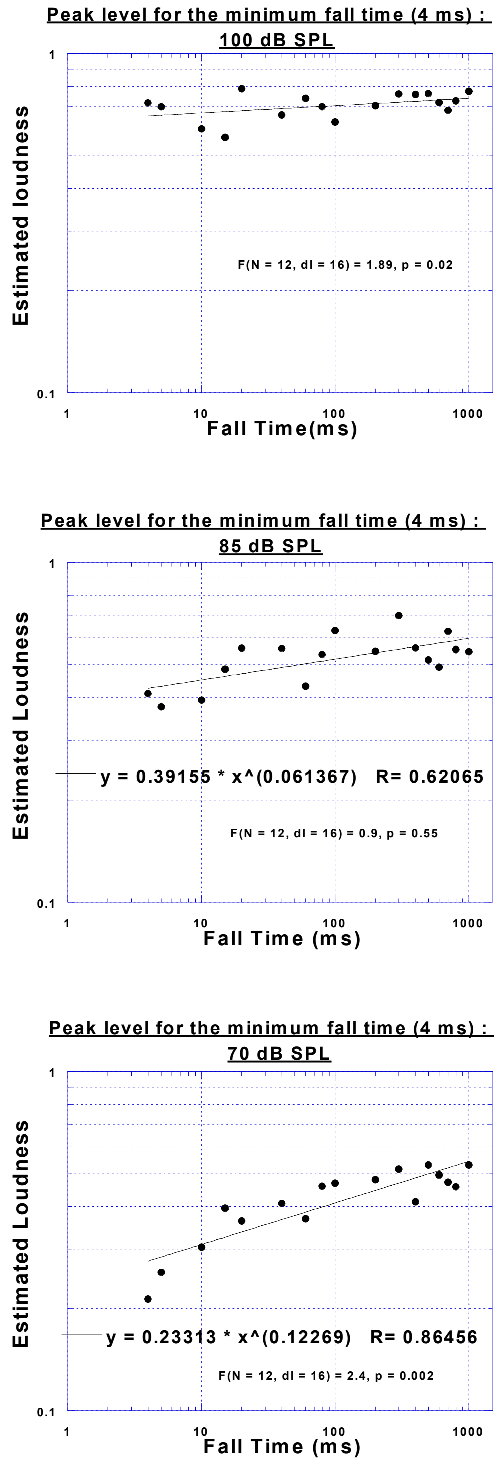

Figure 4: estimated loudness as a function of decay time for a band of noise with a central frequency of 1 kHz and a bandwidth of 300 Hz

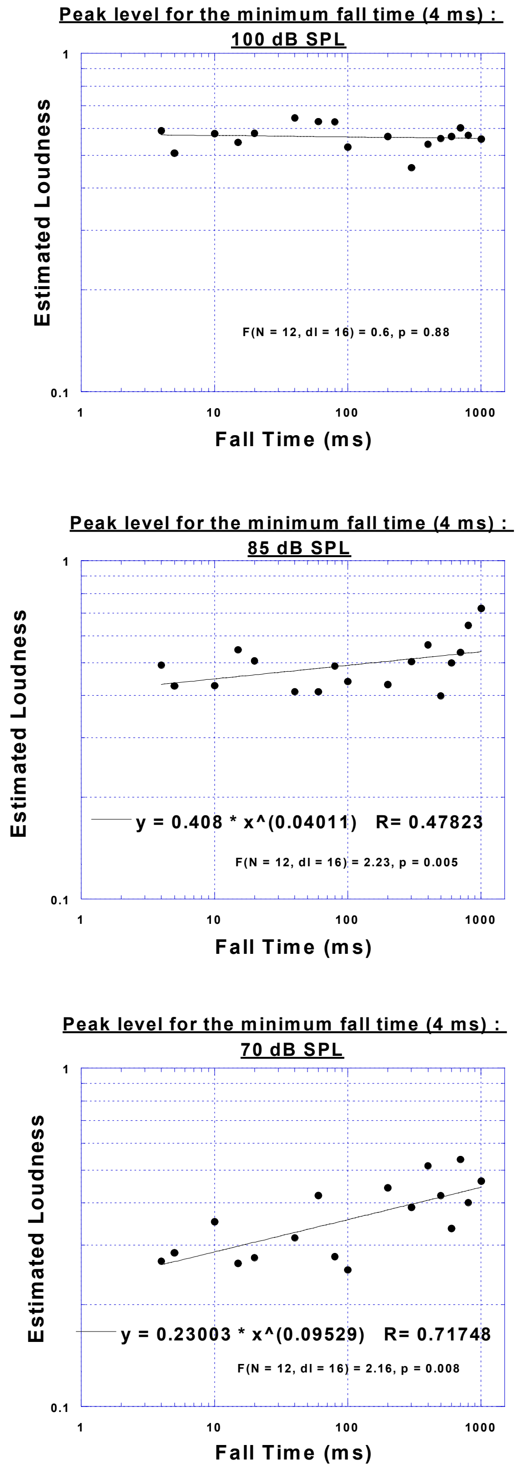

Figure 5: estimated loudness as a function of decay time for a 4-kHz pure tone.

DISCUSSION AND CONCLUSION

Our results confirm the relationships described as 1) and 2) in the introduction. We have shown that the relationship between loudness, energy and signal duration depends on signal level and on its temporal fine structure. For low signal level (70, 85 dB peak at 4 ms), loudness increases when signal duration increases whereas energy is constant. For high signal level (100 dB peak at 4 ms), loudness does not depend on signal duration when energy stay constant. Loudness increases more rapidly when duration increases for the band of noise than for the pure tone. For the band of noise, the variation is still observable for the higer level (100 dB peak at 4 ms), even though it is very small.

In the following part, we will discuss why different studies, in the past, yield different results and we will compare our results to these studies.

One of the possible causes of discrepancy between studies is the method used. In most of the studies, the method was loudness matching. It consists, for the subject, to match the loudness of the tested sound to the loudness of a reference sound. For that, the suject manipulates the level of the reference until he or she thinks that the two signals are equally loud. The duration of the test sound varies during the run whereas the duration of the reference stays constant. The problem with this procedure is that it is very difficult to match the loudness of sounds that are very different.

Reichardt and Niese (1970) noted that "the statistical spread increases with increasing difference between test-tone and comparison-tone durations". In their study, the level difference between the test sound and the reference sound was measured as a function of test-sound duration. They found that an exponential curve can be fitted to the data with a time constant. They used two reference-signal durations : 30 and 450 ms. Whereas the 450-ms reference tends to a time constant of 50 ms, the 30-ms reference yield a time constant of 30 ms. Small et al. (1962) replicated Miller's study (Miller, 1948). Whereas Miller found that loudness increases less rapidly than energy when duration increases, Small found that loudness increases more rapidly than energy when duration increases. The method and the signals were the same in both studies, the only difference was the duration of the reference sound : Miller's reference duration was 1,55 s while Small's reference-duration was 500 ms. In Miller's study, the difference between test-tone and reference-tone durations was greater than in Small's study. Considering Reichardt and Niece's work (1970), the discrepancy between Miller's and Small's results could be explained by the different durations of the reference tone. In the experiments of Perdersen et al. (1977) the reference sound changed from one run to another. The loudness comparison was performed against a similar sound of double duration, i.e., 5–ms signal versus 10-ms signal, 10-ms signal versus 20-ms signal etc... This method allows to compare similar signals and to reduce the bias introduced when two different signals are used as test-sound and reference. Pedersen et al. (1977) found that loudness increases more rapidly than energy when duration increases for the lower sound levels. They found that loudness increases in proportion to energy when duration increases for high levels. Magnitude estimation was used by Stevens and Hall (1966). They found the same result except that they did not find any effect of the level. These results, with methods reducing the spread of data, are in accordance with the results of our study.

Another cause of the discrepancy between studies could be the number of subjects, especially when the method used is loudness matching. Indeed, Reichardt and al. (1970) found that "the use of only a few observer, as is the case in most of the published literature, leads to a high degree of observational error". They have subdivided the group of 50 subject used in their experiment into eight random goups of six subjects each. They have calculated the time constant for each group and found that the results vary widely among groups : time constant could varied from 30 ms to 100 ms from one group to another. In previous studies, the number of subject varies from 3 to 381.

Finally, it appears that, globally, the discrepancy between studies does not come from the use of different signals. A lot of studies using the same stimuli yield to different results (Miller, 1948 versus Small et al., 1962 and Stevens and Hall, 1966 versus Pollack, 1958 Zwicker 1966 ; Munson (1947) versus Reichardt and al. (1970) for example). It seems that the major part of the discrepancy comes from the method and the number of subjects.

In the future, we will test different methods for loudness measurement to compare the inter- and intra-individual variations in order to choose the best method for the study of impulsive sounds. Afterwards, we will investigate the influence of the temporal fine structure of the signal on the loudness of impulsive sounds. Eventually, the loudness variation as a function of the attack will be studied.

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