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► To cite this version:

Isabelle Boulet, Jérémy Marozeau, Sabine Meunier. Temporal summation of loudness as a function of frequency and temporal pattern. 33rd International Congress and Exposition on noise control engineering (Internoise), 2004, Prague, Czech Republic. ⟨hal-00088684⟩

HAL Id: hal-00088684

<https://hal.science/hal-00088684v1>

Submitted on 24 Mar 2021

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Temporal summation of loudness as a function of frequency and temporal pattern

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Abstract [513] This research is part of a study designed to propose a new model of loudness applicable to impulsive sounds. The purpose of the research was to study the effects of duration, frequency and temporal pattern of the signal on loudness. The aims were to determine: 1) critical duration as a function of frequency, 2) how does the loudness decrease below this critical duration, 3) and whether the results depend on temporal pattern (rectangular signal, signal with exponential decay). To measure loudness we selected the method of adjustment for its good precision/duration compromise. The stimuli used in this study were five pure tones, with durations of 5 ms to 1 s. We will present the values of critical durations that we obtained for rectangular and impulses signals. The time course of loudness change will be describe both for rectangular and exponential-decay patterns. The data of this study, added to results from the literature, are used to make a synthesis on loudness of impulsive sounds. Moreover, new results are given on more natural sounds that have mostly an exponential decay.

1 INTRODUCTION

The sensation of loudness of stationary pure tones can be easily predicted as a power function of intensity [Ste57]. This relation is independent of the duration when the stimulus is longer than one second. Below this temporal threshold, the loudness decreases in a monotonic way with duration. Munson [Mun47] proposes as a model of this effect, a leaking integrator which stores at least momentary the energy. The relation between the intensity of an infinitely long and stationary sound (I_∞) and the intensity of a tone burst with a duration T which is perceived with the same loudness can be describe as follows:

$$I_\infty = I_T(1 - e^{-\frac{t}{\tau}}), \quad (1)$$

where τ is a time constant. Many studies (see [BJ86] for a complete review) were dedicated to estimate this time constant, although results often differ (from 23 ms [H.59] to 120 ms [M73]), but the usual value seems to be around 100 ms. This time constant can also be used to estimate the threshold above which the duration does not affect anymore the loudness. Many different values have been proposed, but they also differ among studies (from 15 ms [SAMG62] to 500 ms [EGU66]). The effect of level and frequency on this time constant has also been widely studied. Results again are not unanimous. If a good compromise seems to emerge concerning

the effect of the level with a time constant of 200 ms at hearing threshold and 100 ms above, no unanimous result has been found for the influence of frequency. The great variance of the results can be explained by the difference of nature of stimuli (their temporal shape, frequencies, level, spectral composition) and by the experimental protocol used to estimate loudness [FM96].

The present study is a part of a research project designed to elaborate a better predictor of the loudness of impulsive sounds. The temporal shapes of the stimuli used here are chosen to mimic as close as possible natural impulsive sounds, with a short attack time, no sustain and an exponential decay. To the authors' knowledge no or only few studies [ISA citation PLEASE] have used this kind of sound. Additionally, rectangular temporal patterns have also been used. The aims of this study is dedicated (1) to estimate the threshold above which the duration does not influence anymore the sensation of loudness of impulsive sounds, (2) to study its decrease below this threshold and (3) to evaluate whether the results depend on temporal pattern (rectangular signal, signal with exponential decay).

2 EXPERIMENT I

2.1 Stimuli

The stimuli were composed of pure tones of 125 Hz, 350 Hz, 1 kHz, 3 kHz and 8 kHz. Two types of temporal shapes have been used: a rectangular, and an impulse. Each type of shapes varies in duration. The rectangular shape is composed of an onset and offset made of a half Hanning window ramp of 5 ms each and a sustain part lasting 0, 12, 40, 90, 210 or 490 ms. The impulsive shape is composed of a linear slope that goes from 0 to a maximum value in 5 ms, followed by an exponential decay characterized by the duration needed for the amplitude to decrease from 90 % to 10 % of the max. The duration used were 2, 5, 10, 22, 50, 100, 220, 500 or 1000 ms. The number of stimuli were thus 75 ($6 * 5 + 9 * 5$). The maximum level of each stimulus was set at 72.5 dB SPL.

2.2 Methods

Loudness evaluations were collected using an adjustment method [Ges76], in which the listener has to change the level of a comparison sound to set it to the same loudness of stimuli separately. Each stimulus was judged twice: once the comparison sound was presented before the stimulus, and once after. The comparison sound was a narrow band noise around 1kHz with a bandwidth of 120 Hz with rectangular temporal envelope of 500 ms. A silence of 400 ms was inserted between the two sounds. All stimuli were presented randomly.

Ten subjects participated in this experiment, including 6 women and 4 men with normal hearing. This experiment takes place in an anechoic chamber. Stimuli were played via a Genelec 1031A loudspeaker.

2.3 Results

For each stimulus, averages were computed from the two judgments of the ten subjects. Figure 1 shows the measured loudness levels as a function of duration for rectangular (left panel) and impulsive (right panel) sounds. In order to keep a common definition of duration, the time when the amplitude is above -6dB of its maximum was used (as proposed by [FM96]).

These graphs show that the loudness increases as expected exponentially with the duration, but much more interesting is the great similarity between bursts of sounds and impulses. The temporal shape of the stimuli seems not to interact with the effect of duration on loudness.

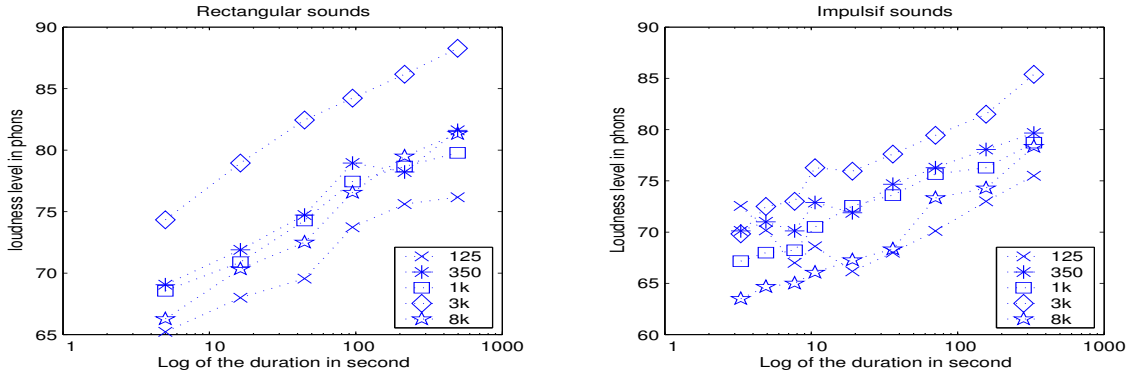


Figure 1: Results of the experience I, for the rectangular on the left panel and the impulsive sounds on the right

Unfortunately, because the durations used are not exactly the same, there is no way to evaluate statistically the similarity between the two sets of data. However it is possible to run an analysis of variance (ANOVA) for each type of shape separately. Two repeated-measured ANOVA were performed with the frequencies (5) and the durations (6 for burst, 9 for the impulsive) as main factors. For burst sounds, as expected the two main factors were significant at 5 % [$F(4, 40) = 10.86$; $p < 0.001$ for the frequency and $F(5, 50) = 120.9$; $p < 0.001$ for the duration]. But much more interesting no significant effects were found for the interaction between the two factors [$F(20, 200) = 1.14$; $p = 0.3$]. This result suggests that no effects of frequency on influence of duration on loudness were found. All the lines in the left panel of figure 1 can be so considered as parallels. For impulsive sounds, the two main factors were also significant [$F(4, 40) = 7.47$; $p < 0.001$ for the frequency and $F(8, 80) = 36.43$; $p < 0.001$ for the duration]. But the interaction was also significant [$F(320, 320) < 3.04$, $p < 0.001$]. This result can be ascribable mainly to the short 125-Hz stimuli. Figure 1 shows explicitly that the loudness of these stimuli were judged much louder than expected for short durations. This can be explained by an error in the conception of these sounds, since a short temporal impulsive envelope cannot properly modulate a low frequency signal. When this frequency is discarded from the analysis, the interaction becomes also not significant [$F(24, 240) < 1$].

3 EXPERIMENT II

Because no explicit temporal threshold was found, a new experiment was run with stimuli with a wider duration range. Also because no effect of the frequency has been found, only one frequency at 1-kHz was used. The two shapes were kept. The sustain part of the rectangular sounds lasted either 10, 22, 50, 100, 220, 360, 500, 1000 or 1500 ms. Durations needed for the impulses amplitude to decrease from 90 % to 10 % of the max were either 2, 5, 10, 22, 50, 100, 220, 360, 500, 1000, 2000, 4000, or 8000 ms. Figure 2 shows the loudness evaluation as function of the log of the duration (defined again as length were the stimulus were above -6dB of its maximum values) for the rectangular (left panel) and the impulsive (right panel) sounds.

In order to describe the effect of duration on loudness, the equation 1 which describe the relation intensity-duration was transformed to a loudness-duration relation as follows:

$$L_{comp} = L_{T\infty} + 10 * \log_{10}(1 - e^{-\frac{t}{\tau}}) \quad (2)$$

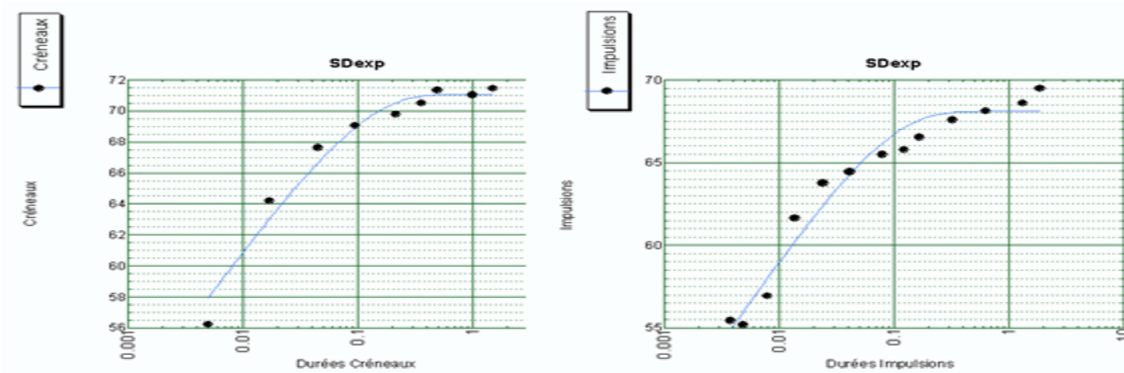


Figure 2: Results of the experience II, for the rectangular on the left panel and the impulsive sounds on the right

where L_{comp} is the level of the comparison sound, and $L_{T\infty}$ the level of the tested sound at a duration above the temporal threshold. The time constant for rectangular sounds was 100 ms, which corresponds perfectly with the literature. Time constant of 77 ms for impulses is more delicate to comment because the figure shows explicitly that the model does not fit well the data. We can observe that the loudness still increases in a monotone way with duration but the leaking integrator does not model well this relation. This can be explained partly by the apparition of another mechanism used by subjects to judge the global loudness of a time varying sound [MM02].

4 CONCLUSIONS

These experiments were dedicated to study the effect of duration on the loudness of impulses sound. The first experiment reveals that for short sound (under 500 ms) no effect of the frequency was found. The loudness of impulses sounds seems to be affected by the duration approximately in the same way that the rectangular sounds. When considering a wider scale of duration, differences between bursts of sounds and impulses appear. The first one can be described efficiently with a leaking integrator with a time constant of 100 ms, and a threshold above which the duration does not affect anymore the loudness can be determined approximately around 500 ms. For impulses sounds, no threshold was found. Loudness still increases with duration above 1 second and more data have to be collected to model this phenomenon.

ACKNOWLEDGEMENTS

We would like to thank Georges Canevet for his useful help and advices.

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