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SUBJECTIVE EVALUATION OF LOUDNESS MODELS USING SYNTHESIZED AND ENVIRONMENTAL SOUNDS

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ABSTRACT
Loudness of different sounds was measured in order to evaluate Zwicker's and Moore's loudness models (published in Acta Acustica [3] and in the J. Audio. Eng. Soc. [4]). The test signals were synthesized bands of noise and environmental sounds. For synthesized noises, Zwicker's model fits highly well with subjective results, it is a little bit closer to the data than Moore's. For environmental sounds, calculated values from Moore's model fit very well with subjective results for low-level signals. In this case, Zwicker's model is close to the subjective data for loud signals.

1 - INTRODUCTION

In 1965, Zwicker and Scharf proposed a model for calculating the loudness of complex sounds [1]. A BASIC-Program of that model (usually called Zwicker's model) has been published [2]; we used it to develop our own program. This model has recently been revised by Moore and Glasberg [3, 4]. Zwicker's model have been evaluated for bands of noise [1] and for environmental sounds [5]. Moore et al. compared their model to Zwicker's for bands of noise [3, 4]. The aim of this paper is to compare the loudness calculated using the two models with loudness estimated by listeners both for synthesized noises and for environmental sounds.

2 - EXPERIMENT 1: LOUDNESS OF SYNTHESIZED NOISES

2.1 - Method

In a first experiment, the loudness of synthesized bands of noise has been evaluated. Three different center frequencies were chosen. For each center frequency, we selected two different bandwidths and for each bandwidth two sound pressure levels. Altogether, twelve bands of noise have been used (Table 1). Eight listeners with normal hearing participated in the experiment. Their age ranged from 20 to 29 years, and their thresholds were 10 dB HL or lower for frequencies from 0.5 to 8 kHz (BK 1800 audiometer). The task of the listener was to make loudness matches between bands of noise. For each run, the reference noise had a fixed level, and the comparison sound (called the test sound) was varied in level to achieve equal loudness. The sound durations were 1 s with a 500-ms interstimulus interval.

sound number	Central frequency (Hz)	bandwidth (Hz)	Level (dB SPL)	sound number	Central frequency (Hz)	bandwidth (Hz)	Level (dB SPL)
1	400	50	40	7	1420	120	50
2	400	420	40	8	1420	1000	50
3	400	50	60	9	3000	240	60
4	400	420	60	10	3000	2040	60
5	1420	120	30	11	3000	240	70
6	1420	1000	30	12	3000	2040	70

Table 1: Physical parameters of the twelve synthesized noises used in experiment 1.

In a first test, the reference noises were the twelve bands of noise described in Table 1 and the test sound was a noise band centered at 1 kHz, with bandwidth of 90 Hz (less than 1 ERB). In a second test, reference and test sounds were reversed. The reference sound was a band of noise centered at 1 kHz with a bandwidth of 90 Hz and its level was fixed at the value adjusted by the listener in the first test. The test sound was one of the twelve bands of noise. The second test was done to balance systematic errors due to unilateral matching [6].
The point of equal loudness of each of the twelve bands of noise is:

$$Y1 + \frac{\Delta L}{2}, \text{ where } \Delta L = Y2 - X$$

$Y1$ is the level of the test sound obtained in the first test, $Y2$ the level of the test sound obtained in the second test, and X the level of the reference noise in the first test.
The sounds were recorded in a DAT recorder using Bruel & Kjaer microphone and amplifier (Nexus). The microphone was set at the center of what would have been the place of the listener's head during the experiment. The recorded sounds will be used to calculate the loudness using the models. Thereby, the whole transfer function of the system is taken into account.

2.2 - Results

The noise band centered at 1 kHz with a bandwidth of 90 Hz was made of a broad band noise (from a Hewlett Packard generator) filtered by a KEMO filter. The slope of the filter was 80 dB/oct. Thus, part of the energy of this band of noise fell outside 1 ERB of the center frequency and the matching levels had to be transformed in order to obtain the level in phons. This transformation involved two stages:

1. A function relating the level of the 90 Hz wide noise to its loudness level in phons was calculated.
2. This function was used to transform the matching levels of the 90 Hz wide noise to equivalent loudness level in phons (called "ajusted loudness" in the figures below).

Fig. 1 shows the adjusted loudness as a function of the loudness calculated using the two models. The experimental data fits very well with Zwicker's model and well with AES Moore's model (but at a lower degree). The Acustica Moore's model overestimates the loudness.
Moore et al. [3] compared their model to empirical data with bands of noise geometrically centered at 1420 Hz. They showed that their model predicts an increase in loudness with bandwidth greater than observed empirically. One can observe this result with sound n°10 and 12 especially (Fig. 1, Moore's model (Acustica)).

3 - EXPERIMENT 2: LOUDNESS OF ENVIRONMENTAL SOUNDS

Twenty-four listeners with normal hearing participated in the experiment. Their age ranged from 20 to 58 years, and their thresholds were 20 dB HL or lower for frequencies from 0.5 to 8 kHz (BK 1800 audiometer).
The task of the listener was the same as described in section 2-1. The bands of noise were replaced by 24 environmental sounds (Table 2). The sounds were chosen to be steady over a duration of 1 s.

Sound	Abbreviation	Sound	Abbreviation
Blowlamp	Blowlamp	Flute at 39 dB SPL	Flute_39
Guitare	Guitare	Flute at 54 dB SPL	Flute_54
Harmonica	Harm	Flute at 69 dB SPL	Flute_69
Rumpled paper	Paper	Flute at 84 dB SPL	Flute_84
Computer hard disk	Disk	Motorcycle at 28 dB SPL	Moto_28
Telephon in an Anechoïc Chamber	Tel_AC	Motorcycle at 43 dB SPL	Moto_43
Telephon in an office	Tel	Motorcycle at 58 dB SPL	Moto_58
Bicycle in an Anechoïc Chamber	Bicy_Ac	Motorcycle at 73 dB SPL	Moto
Bicycle	Bicy	Drilling at 35 dB SPL	Drill_35
Car	Car	Drilling at 50 dB SPL	Drill_50
Woman voice	Voice_W	Drilling at 65 dB SPL	Drill_65
Man voice	Voice_M	Drilling at 80 dB SPL	Drilling

Table 2: List of the environmental sounds.

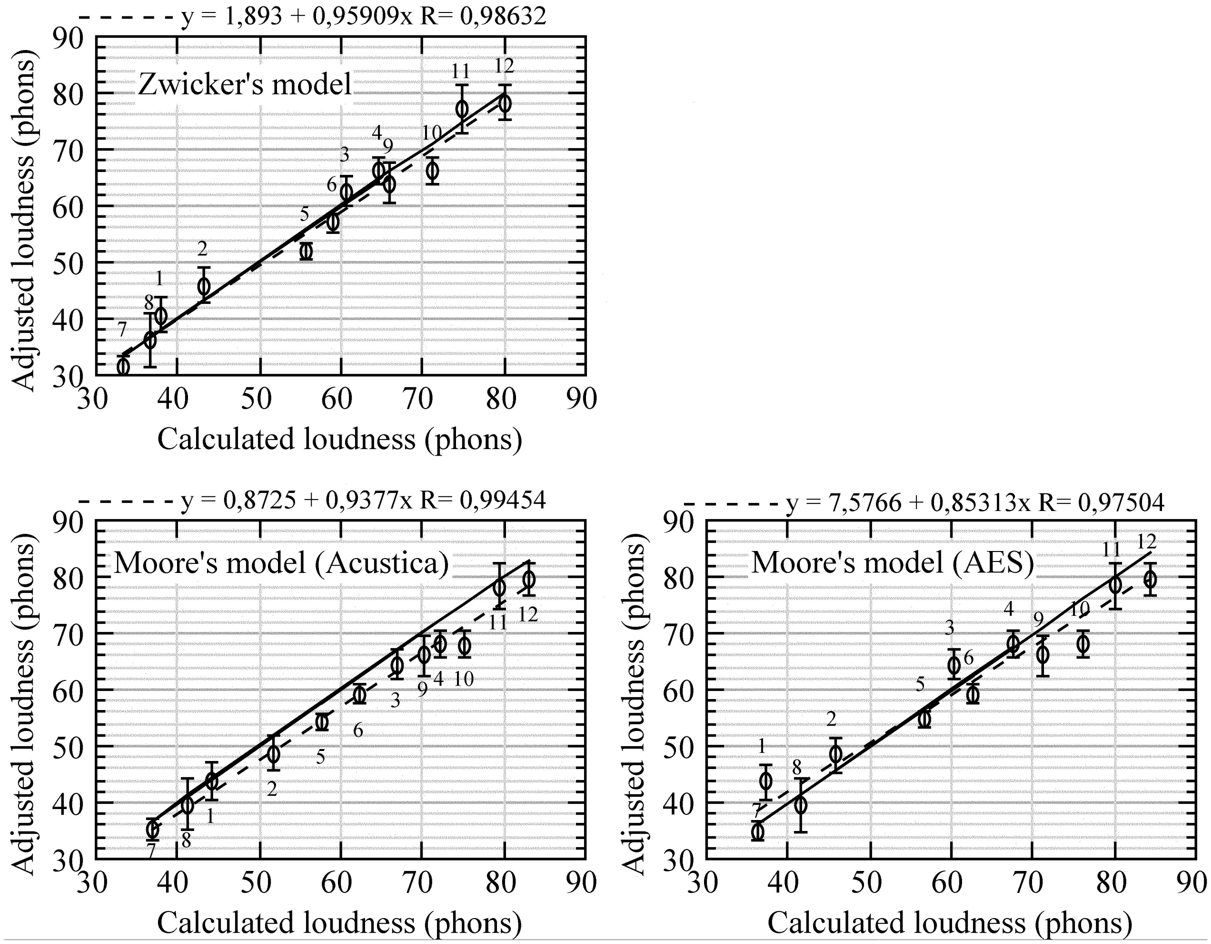

Figure 1: Adjusted loudness as a function of the calculated loudness for the synthesized noises: the top graph shows the comparison with Zwicker's model; the bottom graphs show the comparison with Moore's models; open circles − adjusted loudness; solid line − predictions of the model; dashed line − fitting with the data; the number next to the symbols are the sound numbers.

In this experiment, the noise band centered at 1 kHz with a bandwidth of 90 Hz was synthesized using Matlab in order to make the energy outside 1 ERB equal to zero.
Fig. 2 shows the adjusted loudness as a function of the calculated loudness for the environmental sounds. Moore's model (Acustica) overestimates the loudness. In Zwicker's model, calculated and estimated loudness values agree very well for louder sounds (>70 phones); but the model underestimates loudness of sounds less than 70 phones, the more so for softer sounds. On the other hand, in Moore's model (AES), loudness calculations are close to estimated loudness for loudness levels below 70 phones; but the model overestimates higher loudness levels, the more so for louder sounds.

4 - DISCUSSION

Figs. 1 and 2 show that Moore's models ([3], [4]) overestimate loudness at high levels. This is a limitation of the model noted by Moore et al. [3]. Auditory filter shapes have not been measured at very high sound levels (above about 90 dB), so Moore advises to use the model with caution for sounds with very high levels.
We observed that Moore's models are very sensitive to background noises in the sound. Because the sounds we used to test the model were recorded and not calculated, there was some electronic and acoustic (non audible) noises. Thus, these noises could produce an increase in the loudness calculated by Moore's programs which were not heard by the listeners.
One can note that the noise band centered at 3 kHz, with bandwidth of 2040 Hz and level of 60 dB SPL (sound n°10) is overestimated by all models. We have no explanation for this observation.
Fig. 3 shows the estimated and calculated loudness for each of the twenty-four environmental sounds and the scattering of the perceptive data. The 75th percentiles vary between 3 and 10 phons. For about

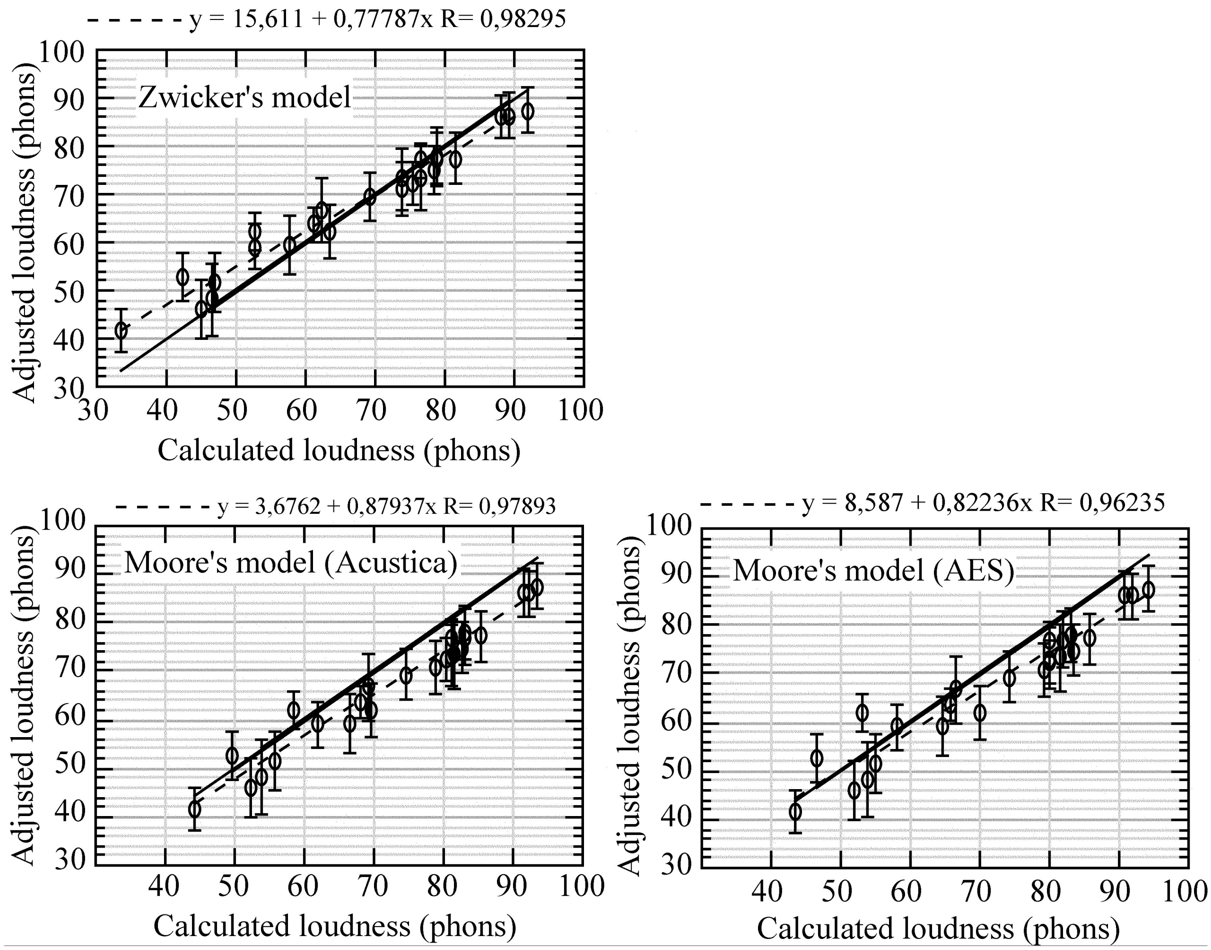

Figure 2: Adjusted loudness as a function of the calculated loudness for the environmental sounds: the symbols are the same as in Fig. 1.

half of the sounds the 75th percentiles is less than 6 phons. The loudness predicted by the models is almost always in the 99th percentiles and often in the 75th percentile.

5 - CONCLUSION

The models predict very well the estimated loudness, for synthesized noises as well as for environmental sounds. Calculated values for loudness usually lie within the variability of the subjective data. For environmental sounds, Zwicker's model underestimates the loudness of soft sounds (<70 phons). In this case, Moore's model overestimates the loudness of loud sounds (>70 phons). A better knowledge of the auditory filter shapes at high sound levels should allow to bring the calculated data nearer to the subjective data for Moore's model.

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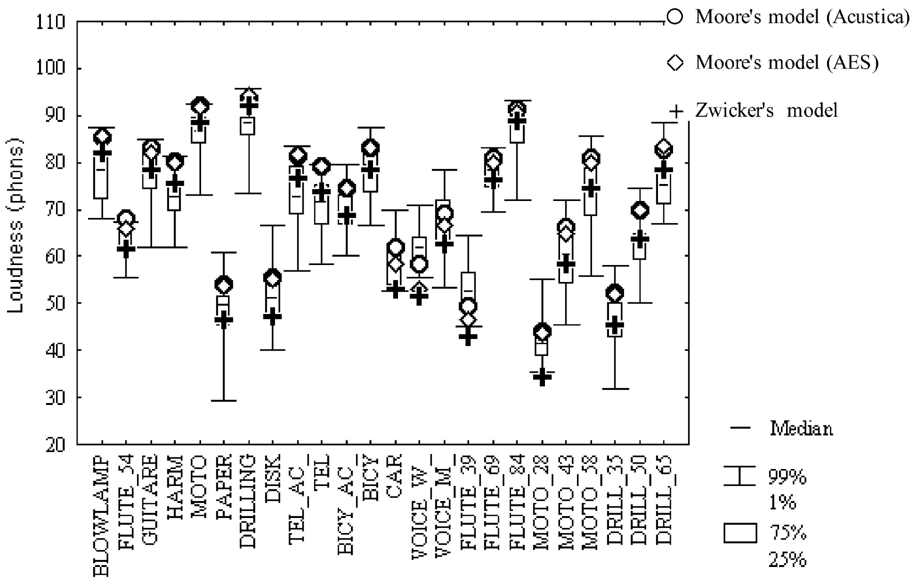

Figure 3: Adjusted loudness of each of the twenty-four environmental sounds; the Box Whiskers places a box around the median (horizontal line) which represents the 75th percentile and whisker outside of the box represent the 99th percentile; the symbols are the prediction of the three models, as indicated next to the figure.

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