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PARAMETRIC STUDY FOR THE DEVELOPMENT OF A NEW INDICATOR OF THE SOUND QUALITY IN OPEN PLAN OFFICES

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ABSTRACT

Among the various sound sources present in open offices, intelligible speech is the one that has the greatest impact on the occupants of these spaces. Indeed, many field or laboratory studies have shown the effect of intelligible speech on annoyance or fatigue [1, 2]. For several years, INRS has been working on an indicator to evaluate the emergence of speech in noise, the M_{eq} [3]. This indicator, calculated as the difference between the equivalent level of ambient noise and the level exceeded 90% of the time ($L_{eq} - L_{90}$), has already shown convincing results in the evaluation of the effect of speech during laboratory experiments [4]. However, due — in part — to the simplicity of its definition, the link between this metric and sound perception in real conditions is still too weak. In this study, a parametric analysis (measurement time resolution, frequency weighting, background noise type effect) was conducted and compares the M_{eq} with various speech modulation indicators used to assess the acoustic quality of open offices (STI, Fluctuation strength, etc.).

1. INTRODUCTION

All studies agree that noise is one of the first, if not the first, factor of disturbance reported for people occupying open-plan offices. Noise is significantly correlated with absenteeism [5], work satisfaction, well-being, and a lack of privacy [6].

In open-plan offices, most of the noise is related to conversation, with the main disturbance reported by occupants being related to intelligible conversations [1]. The relationship between the perceived disturbance, or the cognitive overload linked to noise levels, has been actively studied by psychologists since the 1990's through laboratory-based experiments. The side effects of noise, named ISE (Irrelevant Sound Effect), are complex. For example, they depend on the type of noise and the task that workers are undertaking. Depending on the characteristics of the noise and the task, a cognitive overload can occur, leading to reduced performance.

In laboratory conditions, ISE can be measured with subjects by asking them to perform tasks requiring a cognitive effort in different sound conditions. The different conditions are characterized by physical or psychophysical indicators, often linked to the intelligibility of words in the background noise.

To assess the ISE, different indicators exist. The speech transmission index (STI), developed by Steeneken and Houtgast [7] is a commonly used indicator. Based on studies showing the link between intelligibility, Hongisto et al. proposed an empirical model of the decrease in performance (DP) [8], which could be used as a descriptor for the ISE, as a function of the STI. But, a first disadvantage of the STI is that it has been standardised for stationary background noises [9]. However, in real conditions in open-plan offices, ambient noise is generally composed of a mixture of more or less intelligible noises due to conversations. The acoustic level of the overall noise varies over time. So, the STI cannot be applied in these conditions because the ambient noise is not stationary. Another disadvantage is that STI was developed for a single voice source. Yet, in an open-plan office, there is often a mixture of many voices and other sound sources. In fact, STI can only be useful to assess the speech transmission quality from one to another point of open-plan office space and then only give information about the acoustic quality of it [9].

A better way to assess the fluctuations of ambient noise is to use the fluctuation strength. Fluctuation strength is a psychoacoustic indicator attempting to describe the perceived modulation of the sound-intensity of a signal around a frequency of 4 Hz. This indicator was initially developed by Zwicker and Fastl [10] and was further developed by Aures [11] then Daniel and Weber [12]. A study by Schlittmeier et al. [13] showed that the fluctuation strength is a relevant descriptor of the ISE. However, according to Liebl et al. [14] correlation between background noise and ISE is less clear. Moreover, it should be noted that the fluctuation strength presents the disadvantage of varying with the level of noise of the signal: the higher this level, the greater the fluctuation strength. So the choice of fluctuation strength as an index to assess the ISE is not obvious.

A simpler method than fluctuation strength to describe the speech modulation was recently developed by Chevret et al. [3]. This indicator, named M_{eq} for equivalent modulation index (see section 2) is defined in section 2, has already shown convincing results in the evaluation of the effect of speech during laboratory experiments [4]. However, due — in part — to the simplicity of its definition, the link between this metric and sound perception in real conditions is still too weak.

The aim of this paper is to deeper investigate the equivalent modulation index by analyzing the effect of time and

frequency weightings. The values of the parametric study are chosen in accordance with the frequency rate of the modulation transfer function and with the weighting factors used for the calculation of the STI. The underlying idea is to get a simpler indicator than STI and easier to measure in real conditions.

2. EQUIVALENT MODULATION (SHORT M_{EQ})

The equivalent modulation index is based on calculation of the continuous equivalent noise level, L_{eq} [15]. By choosing the duration of the integration, the events or phenomena to be identified from this signal can be determined. From the L_{eq} the equivalent modulation index M_{eq} is calculated as the difference between the short equivalent level of ambient noise calculated every ΔT ms (time weighting) and the 90th percentile level. As the equivalent modulation index is based on the short equivalent level, it is possible to add a frequency weighting to the calculation of the indicator, such as an A-weighting.

So far, the various studies carried out on the equivalent modulation index [2, 3] have been carried out with a frequency A-weighting and a fast time weighting ($\Delta T = 125ms$). Thus, a time resolution of 125 ms can reveal events with a frequency of appearance of less than 4 Hz which is characteristic of the syllabic rate in speech. These two parameters are generally easy to use given their implementation in sound level meters.

Equation 1 present the calculation of the M_{eq} with an A-weighting and a fast time weighting (125 ms). L_{Aeq} is measured over a representative period (from a few minutes to several hours) and taking into account only in the 7 frequency octave bands from 125 Hz to 8 kHz.

$$M_{Aeq,125ms} = L_{Aeq} - L_{A90,125ms} \text{ dB(A)}$$

$$\text{with } L_{Aeq} = 10 \log\left(\sum_{k=1}^7 10^{L_{Aeq,k}/10}\right) \quad (1)$$

3. OVERVIEW OF THE M_{AEQ} IN FIELD

To have a global view of the equivalent modulation index, the M_{Aeq} , as defined in equation 1, was measured in 20 open spaces (in different areas of the open space) during a long time (more than 1 hour). Figure 1 shows an histogram of these measurements.

As it can be seen on the figure 1, M_{Aeq} values are mainly located around 12 dB(A) and between 4 and 6 dB(A). In this situation, the higher the M_{Aeq} , the more intelligible it reflects. For example, when the M_{Aeq} is 12 dB(A), the noise environment is likely to be more annoying than when it is 5 dB(A). However, it is not possible at this stage to establish a target value of M_{Aeq} to be achieved in order to determine whether a noise environment is annoying.

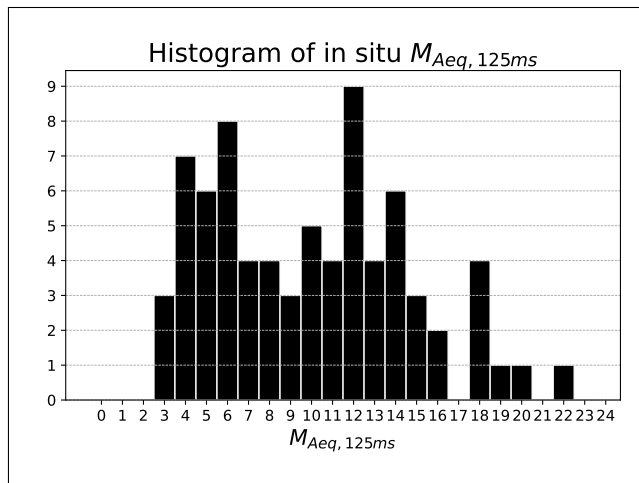


Figure 1. Histogram of in situ $M_{Aeq,125ms}$.

4. THE SPEECH TRANSMISSION INDEX

According to the IEC 60268-16 [9] the calculation of STI allows to define several target values like 0.2: Privacy distance; 0.4: Beginning of the increasing slope of the sigmoid curve of Hongisto's model [8]; 0.5: Distraction distance 0.6: Beginning of the plateau of the sigmoid curve [8]; 0.7: High intelligibility. Based on those results, the question that may arise is: how much is the M_{eq} for these different STI values?

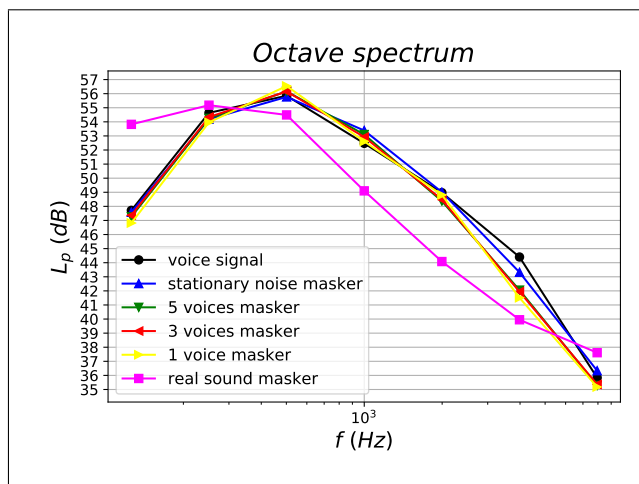


Figure 2. Octave spectrum.

To look at the evolution of the M_{Aeq} with the STI, several signals have been synthesized. These signals, lasting 16 seconds, correspond to a target signal (1 male voice) and 4 masking signals: a stationary noise, a mix of 5 voices, a mix of 3 voices and 1 single voice (male). All these signals have been normalized to a LTASS spectrum. In addition, a 5th masking signal was created from a real office recording (see section 6.1). The octave band spectrum (125Hz – 8kHz) of the different signals is shown in Figure 2. On this figure, it can be seen that the real office signal is not LTASS-equalized.

Then, the voice signal (target) was superimposed to each masking signal and the signal-to-noise ratio have been

varied from -15 dB to +15 dB by increasing the target signal level. Figure 3 shows the evolution of $M_{Aeq,125ms}$ as a function of STI for each masking sound. On this figure is also plotted typical $M_{Aeq,125ms}$ values measured in the field (6 and 12 dB(A)) and different STI target values (0.2, 0.4, 0.5, 0.6 and 0.7). As it can be seen, depending on the situation a $M_{Aeq,125ms}$ value is equal to several STI values and vice versa.

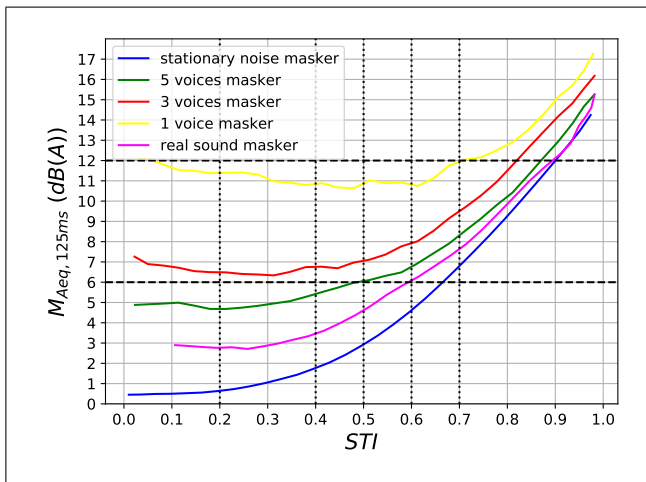


Figure 3. $M_{Aeq,125ms}$ for each masking sound as a function of STI.

5. FREQUENCY WEIGHTING EFFECT

So far, the frequency weighting for the calculation of the equivalent modulation index has been an A-weighting. However, in the calculation of the STI given by the IEC 60268-16 standard [9], the frequency weighting is that proposed by Steeneken et al. [16–18]. These frequency weighting factors have been determined with the objective to a better prediction of the speech intelligibility. In this study, the M_{eq} with the Steeneken octave-band weighting factors was calculated for the 5 target signal + masking sound compositions by varying the signal-to-noise ratio from -15 to +15 dB and with a time weighting of 125 ms.

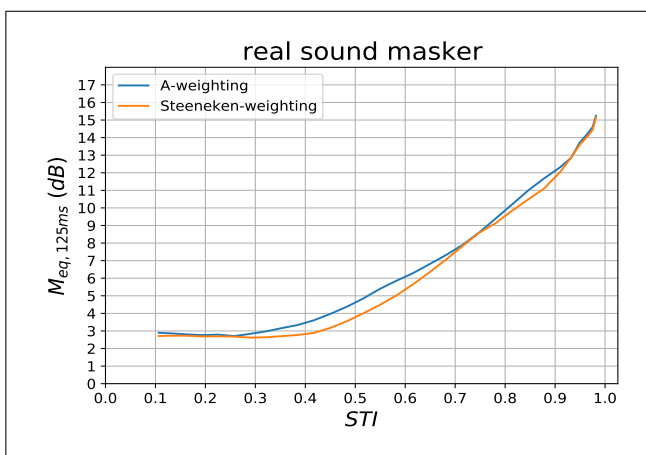


Figure 4. Frequency weighted $M_{eq,125ms}$ as a function of STI for real sound masker.

Since the target signal and the first 4 masking sounds considered (noise, 5 voices, 3 voices and 1 voice) are normalized with the same spectrum, there is no difference between the A-weighting and those proposed by Steeneken et al. as it could be expected. For the "real masking sound", the difference of M_{eq} between the two weightings remains very small ($max(\Delta M_{eq}) \simeq 0.9dB$) as it can be seen on Figure 4, although the spectrum of the mask is different from the spectrum of the target signal.

6. TIME WEIGHTING EFFECT

Second parameter studied was the time weighting of L_{Aeq} . Indeed, a faster acquisition rate allows to highlight more events as can be seen on figure 5 which shows an example of the L_{Aeq} along time for a signal composed of a target signal and a masking stationary noise (signal-to-noise ratio = 0 dB), calculated with 125 ms time weighting and 40 ms time weighting.

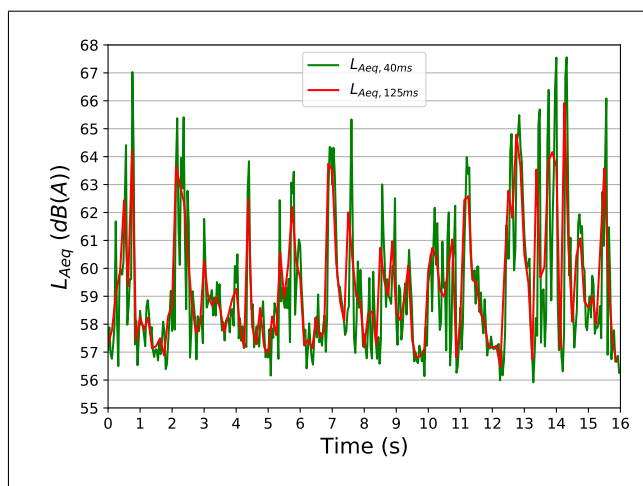


Figure 5. L_{Aeq} evolution for a composition of target signal and stationary masker at the same A-level.

6.1 Recordings in real situations

To study the effect of time weighting, the M_{Aeq} was calculated from 257 audio recordings from open-plan offices (recording duration varies from 10s to 3min, the majority of the signals having a duration of 30s). The M_{Aeq} was calculated with the following time weighting: 20 ms, 40 ms, 80 ms, 125 ms and 1 s. Table 1 and figure 6 show a description and a boxplot of the M_{Aeq} data from the 257 real situations.

time weighting (ms)	20	40	80	125	1000
mean	12.3	11.9	11.5	11.0	7.9
std	4.2	4.2	4.2	4.1	3.6
min	4.3	4.2	3.9	3.5	1.4
max	24.2	23.9	23.9	23.4	21.1

Table 1. Description of M_{Aeq} in 257 open spaces.

While the mean values of M_{Aeq} do not appear to vary

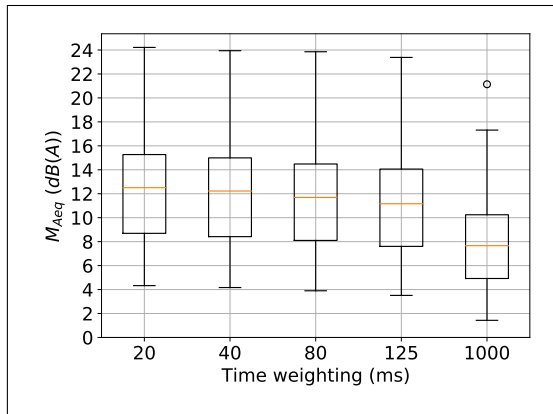


Figure 6. Boxplot of 257 in situ offices M_{Aeq} .

much with the time weighting, a repeated measures analyses of variance (RM-ANOVA) with time weighting (5) as within-subjects factor shows that there is a statistical difference between the values of M_{Aeq} ($F(1.2, 297.1) = 1168.9^{***}$, $MSE = 2.33$, $p < .0001$, $\eta_p^2 = 0.82$). Post-hoc analysis shows that M_{Aeq} mean values are statistically different whatever the time weighting (see Table 2).

time weighting (ms)	20	40	80	125	1000
20	-	***	***	***	***
40	***	-	***	***	***
80	***	***	-	***	***
125	***	***	***	-	***
1000	***	***	***	***	-

*** $p < 0.001$

Table 2. Bonferroni corrected probability values for the difference in M_{Aeq} between the five time resolution conditions.

6.2 Virtual situations in laboratory

To confirm the effect of time weighting on M_{Aeq} , an analysis was conducted with synthesized signals. The procedure used was the same as the one presented previously (see section 4), i.e. superimposing a target signal (1 voice) and a masking sound by varying the signal-to-noise ratio. Then the M_{Aeq} level of mixtures was calculated with the following time weighting: 20 ms, 40 ms, 80 ms, 125 ms and 1 s.

Figure 7 shows the $M_{Aeq,20/40/125ms}$ as a function of the STI for 1 voice masker and real sound masker. Looking at the figure 7, as expected the temporal resolution has an effect mainly on the highest values of M_{Aeq} . Therefore, increasing the temporal resolution increases the dynamic scale of M_{Aeq} and consequently could be beneficial to a M_{Aeq} evaluation based method. 20 ms is close to 40 ms which could finally be a good compromise because it corresponds to a sampling frequency of 25 Hz which is twice the maximum frequency range of the STI's transfer function modulation [7,9].

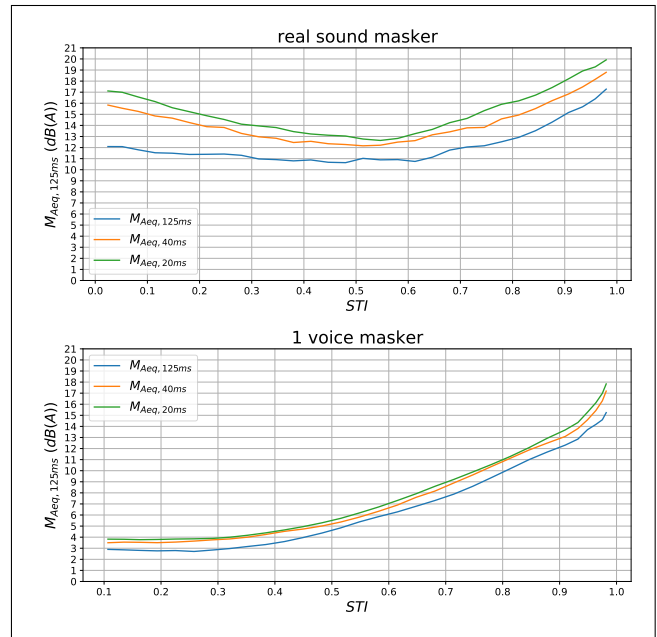


Figure 7. $M_{Aeq,20/40/125ms}$ as a function of STI for 1 voice and real sound maskers.

7. COMPARISON WITH A NEW GERMAN INDICATOR

Recently, Renz et al. have proposed a very similar indicator to M_{Aeq} to assess the sound annoyance in open-plan office [19]. This indicator is calculated as the difference between the 10th and 90th percentile levels measured with a fast time weighting (125 ms) : $L_{A10,125ms} - L_{A90,125ms}$. The main goal of this indicator is to assess the sound annoyance in open-plan office in more objective way than with the rating level L_r defined in the German standard DIN 45545-2 [20].

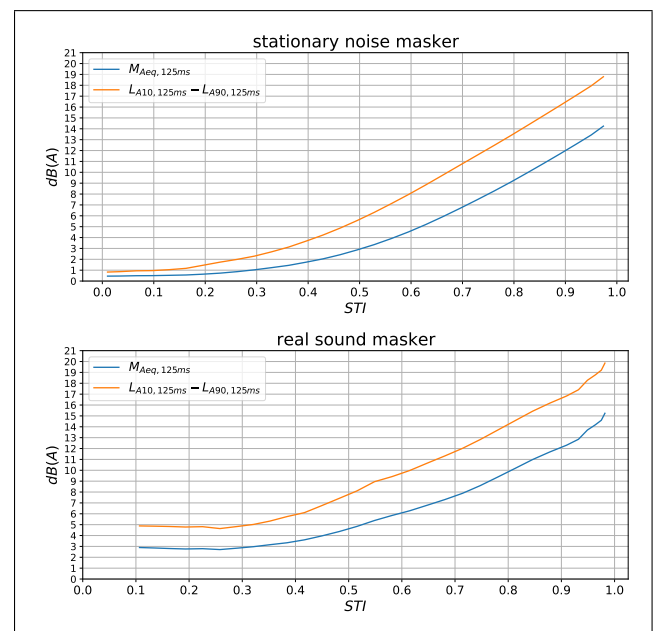


Figure 8. $M_{Aeq,125ms}$ and Renz et al. indicator as a function of STI for stationary noise and real sound maskers.

Indeed, the rating level is based on A-weighted equivalent continuous to which penalties are added (penalty for impulsiveness KI (pulse adjustment), and penalty for tonality and informational constituents KT (surcharge of tonality and information incorporation)). But these penalties are depending on the subjective assessment.

Figure 8 shows $M_{Aeq,125ms}$ and the indicator of Renz et al. as a function of the STI for two synthesized signals (target signal + stationary noise and real sound maskers). As it can be seen, the evolution of $M_{Aeq,125ms}$ and Renz et al. indicator with the STI is very similar. The only difference is the absolute value of the indicator, higher for the German one. This difference is due to the presence of L_{A10} which reflects uncommon events in the office that are not necessarily related to speech. The similarity of these two indicators is confirmed with regard to figure 9 on which is plotted the values of the Renz et al. indicator as a function of the $M_{Aeq,125ms}$ for different signal-to-noise ratios and for the stationary noise and real sound maskers.

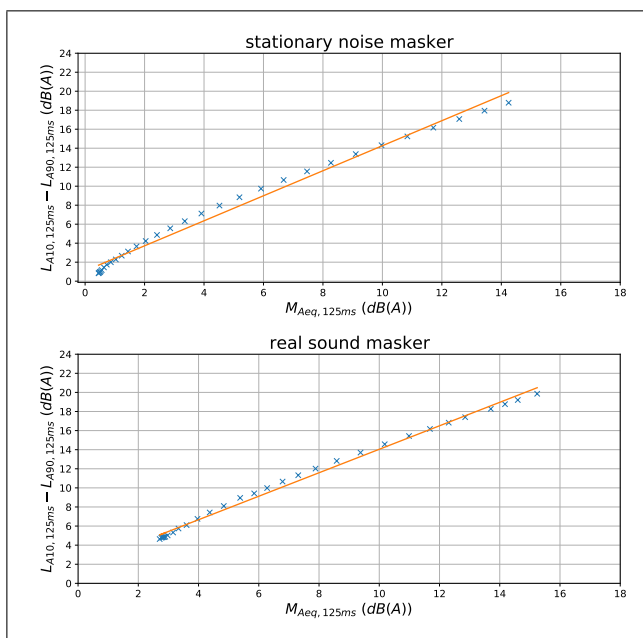


Figure 9. Renz et al. indicator as a function of $M_{Aeq,125ms}$.

In Renz et al. paper [19], authors show that the suggested metric $L_{A10,125ms} - L_{A90,125ms}$ correlates significantly with both working memory performance and perceived annoyance. Given the very strong correlation between this metric and the M_{Aeq} (see Figure 9), it is reasonable to assume that the M_{Aeq} should also correlate well with performance and annoyance as measured in the laboratory.

8. DISCUSSION

The aim of this paper was to study the effect of two parameters (frequency weighting and time weighting) on the modulation index $M_{eq} (L_{eq} - L_{90})$ in order to see whether a calculation method closer to the one used for the STI

would allow predicting intelligibility as well as the latter without compromising the simplicity of calculation and measurement.

While the frequency weighting (other than the A-weighting usually used) does not significantly change the M_{eq} values, the time weighting has a non-negligible effect. Indeed, the M_{eq} is sensitive to time weighting. The shorter the time constant, the higher the M_{eq} (up to 5 dB(A) difference between a time weighting of 40 ms and 125 ms depending on the sound condition). A more advanced study on the link between M_{eq} and performance / annoyance / fatigue is necessary to validate the optimal time weighting.

In field, the advantage of a speech modulation indicator such as the M_{eq} for measuring ISE is undeniable as the measurement of this indicator is simple to implement in an occupied environment (compared to a STI measurement, as example). In Germany, Renz et al. [19] suggest using an indicator very similar to the M_{eq} to measure acoustic conditions in occupied offices. This indicator, calculated as the difference between 10th and 90th percentile levels correlates well with performance and annoyance, and a model has already been established [21].

In the future, it will be interesting to continue investigations on this kind of indicator with the aim of defining limit values related to annoyance.

9. ACKNOWLEDGMENT

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