



**HAL**  
open science

# Parametric study for the development of a new indicator of the sound quality in open plan offices

Laurent Brocolini, Patrick Chevret

## ► To cite this version:

Laurent Brocolini, Patrick Chevret. Parametric study for the development of a new indicator of the sound quality in open plan offices. Forum Acusticum, Dec 2020, Lyon, France. pp.2187-2192, 10.48465/fa.2020.0216 . hal-03235225

**HAL Id: hal-03235225**

**<https://hal.science/hal-03235225>**

Submitted on 26 May 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

Laurent Brocolini<sup>1</sup>      Patrick Chevret<sup>1</sup>

<sup>1</sup> INRS, Rue du Morvan, CS 60027, 54519 Vandoeuvre-Lès-Nancy, France

laurent.brocolini@inrs.fr, patrick.chevret@inrs.fr

## 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  $\Delta T$  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.

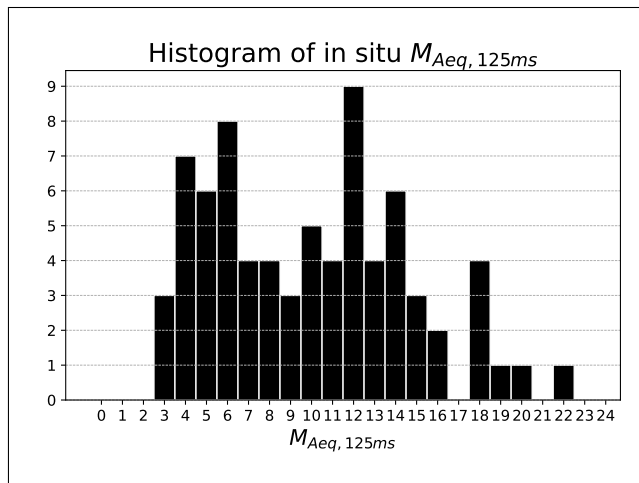


Figure 1. Histogram of in situ  $M_{Aeq,125ms}$ .

## 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?

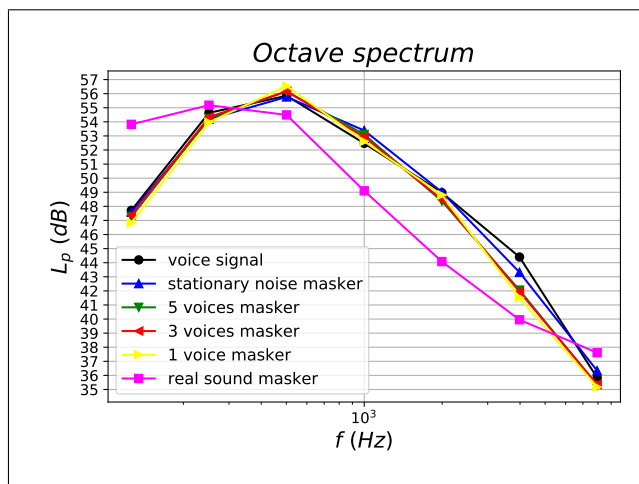
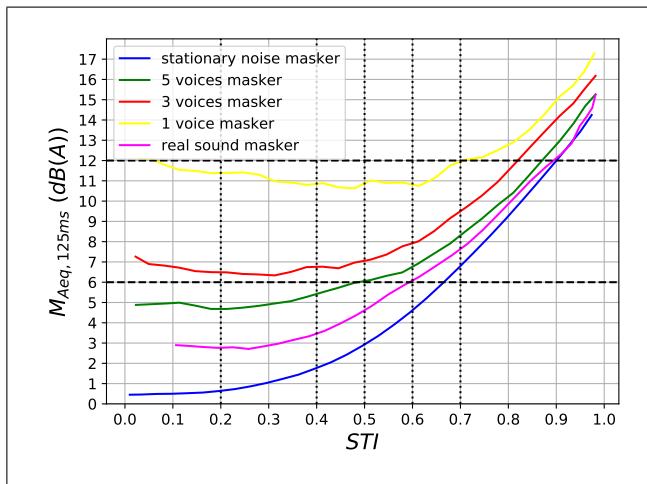


Figure 2. Octave spectrum.

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

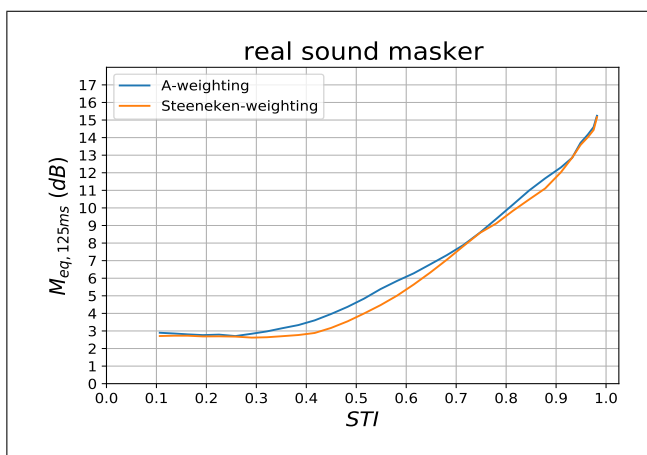
varied from -15 dB to +15 dB by increasing the target signal level. Figure 3 shows the evolution of  $M_{Aeq,125ms}$  as a function of STI for each masking sound. On this figure is also plotted typical  $M_{Aeq,125ms}$  values measured in the field (6 and 12 dB(A)) and different STI target values (0.2, 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.

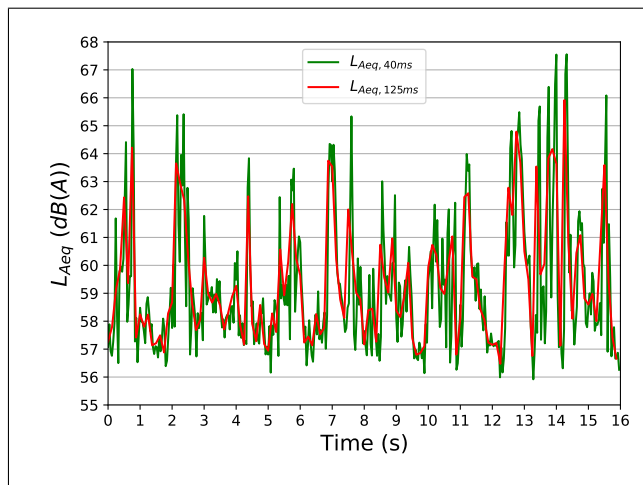


**Figure 4.** Frequency weighted  $M_{eq,125ms}$  as a function of STI for real sound masker.

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.

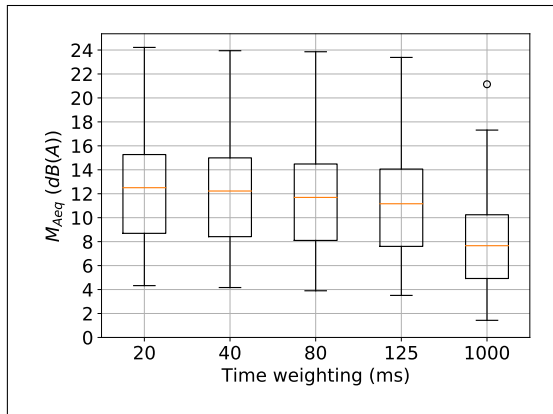
### 6.1 Recordings in real situations

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	***	***	***	***	-

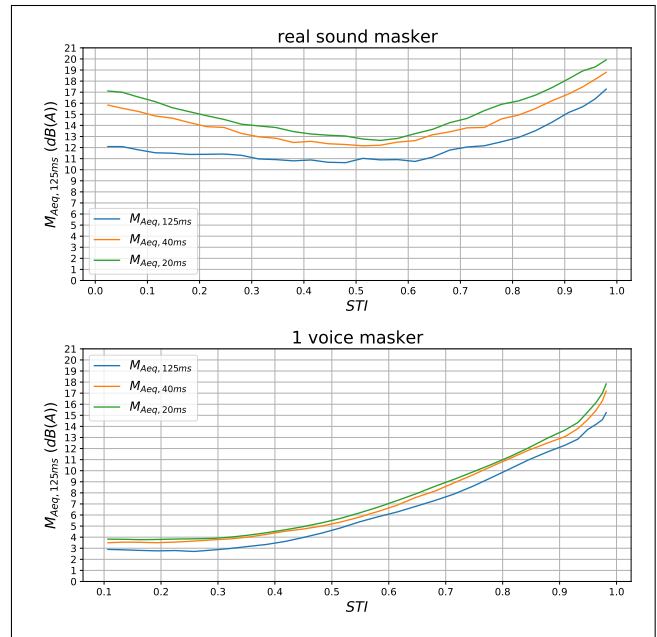
\*\*\*  $p < 0.001$

**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.

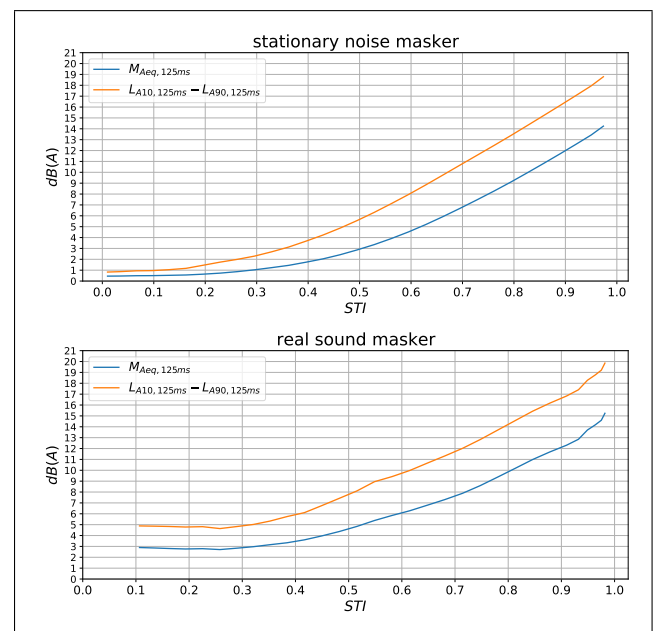
Figure 7 shows the  $M_{Aeq,20/40/125ms}$  as a function of the STI for 1 voice masker and real sound masker. Looking at the figure 7, as expected the temporal resolution has an effect mainly on the highest values of  $M_{Aeq}$ . Therefore, increasing the temporal resolution increases the dynamic scale 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

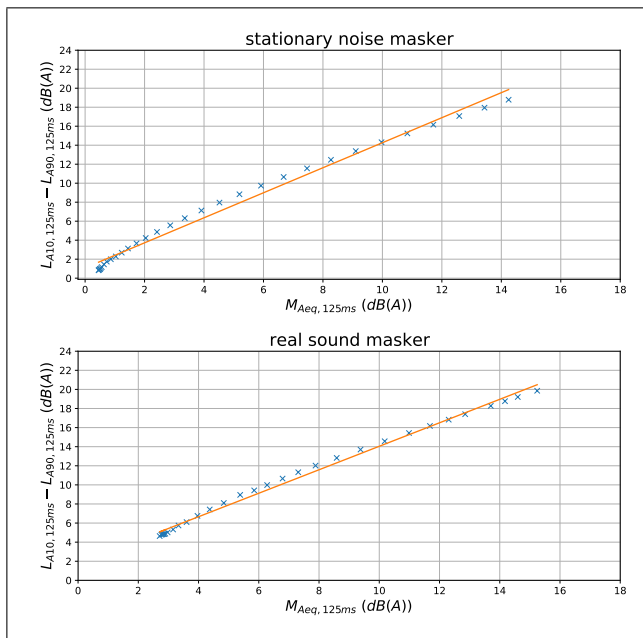
Recently, Renz et al. have proposed a very similar indicator to  $M_{Aeq}$  to assess the sound annoyance in open-plan office [19]. This indicator is calculated as the difference between the 10th and 90th percentile levels measured with a fast time weighting (125 ms):  $L_{A10,125ms} - L_{A90,125ms}$ . 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

This project was supported by the French National Research Program for Environmental and Occupational Health of ANSES (EST/2017/1/071).

## 10. REFERENCES

- [1] M. Pierrette, E. Parizet, P. Chevret, and J. Chatillon, "Noise effect on comfort in open-space offices: development of an assessment questionnaire," *Ergonomics*, vol. 58, no. 1, pp. 96–106, 2015.
- [2] K. Kostallari, E. Parizet, and P. Chevret, "Indicateurs de confort acoustique dans les bureaux ouverts," *13ème Congrès Français d'Acoustique, Le Mans*.
- [3] P. Chevret, E. Parizet, and K. Kostallari, "A simple sound metric for evaluating sound annoyance in open-plan offices," *ICBEN, Zurich*, 2017.
- [4] K. Kostallari, E. Parizet, L. Brocolini, N. Judon, and P. Chevret, "Compared effects of overall level and speech intelligibility on self-reported fatigue in open-plan offices : a laboratory study," *Forum Acusticum 2020, Lyon*.
- [5] Y. Fried, S. Melamed, and H. A. Ben-David, "The joint effects of noise, job complexity, and gender on employee sickness absence: An exploratory study across 21 organizations—the cordis study," *Journal of Occupational and Organizational Psychology*, vol. 75, no. 2, pp. 131–144, 2002.

- [6] E. De Croon, J. Sluiter, P. P. Kuijer, and M. Frings-Dresen, "The effect of office concepts on worker health and performance: a systematic review of the literature," *Ergonomics*, vol. 48, no. 2, pp. 119–134, 2005.
- [7] H. J. Steeneken and T. Houtgast, "A physical method for measuring speech-transmission quality," *J. Acoust. Soc. Am.*, vol. 67, no. 1, pp. 318–326, 1980.
- [8] V. Hongisto, "A model predicting the effect of speech of varying intelligibility on work performance," *Indoor Air*, vol. 15, pp. 458–468, dec 2005.
- [9] IEC-60268-16 *Sound System Equipment – Part 16: Objective rating of speech intelligibility by speech transmission index*, 2011.
- [10] H. Fastl, E. Zwicker, H. Fastl, and E. Zwicker, "Fluctuation Strength," in *Psychoacoustics*, pp. 247–256, Springer Berlin Heidelberg, 2007.
- [11] v. W. Aures, "A procedure for calculating auditory roughness," *Acustica*, vol. 58, pp. 268–281, 1985.
- [12] P. Daniel and R. Weber, "Psychoacoustical roughness: Implementation of an optimized model," *Acta Acustica united with Acustica*, vol. 83, no. 1, pp. 113–123, 1997.
- [13] S. J. Schlittmeier, T. Weißgerber, S. Kerber, H. Fastl, and J. Hellbrück, "Algorithmic modeling of the irrelevant sound effect (ISE) by the hearing sensation fluctuation strength," *Attention, Perception, Psychophys.*, vol. 74, no. 1, pp. 194–203, 2012.
- [14] A. Liebl, A. Assfalg, and S. J. Schlittmeier, "The effects of speech intelligibility and temporal-spectral variability on performance and annoyance ratings," *Appl. Acoust.*, vol. 110, pp. 170–175, sep 2016.
- [15] P. Luquet, "Method for the objective description of an acoustic environment based on short leq values," *Applied Acoustics*, vol. 15, no. 2, pp. 147–156, 1982.
- [16] H. J. Steeneken and T. Houtgast, "Mutual dependence of the octave-band weights in predicting speech intelligibility," *Speech communication*, vol. 28, no. 2, pp. 109–123, 1999.
- [17] H. J. Steeneken and T. Houtgast, "Phoneme-group specific octave-band weights in predicting speech intelligibility," *Speech Communication*, vol. 38, no. 3-4, pp. 399–411, 2002.
- [18] H. J. Steeneken and T. Houtgast, "Validation of the revised stir method," *Speech Communication*, vol. 38, no. 3-4, pp. 413–425, 2002.
- [19] T. Renz, P. Leistner, and A. Liebl, "Use of energy-equivalent sound pressure levels and percentile level differences to assess the impact of speech on cognitive performance and annoyance perception," *Appl. Acoust.*, vol. 153, pp. 71–77, oct 2019.
- [20] DIN-45645-2 *Ermittlung von Beurteilungspegeln aus Messungen – Teil 2: Ermittlung des Beurteilungspegels am Arbeitsplatz bei Tätigkeiten unterhalb des Pegelbereiches der Gehörgefährdung (Determination of rating levels from measurement data – Part 2: Determination of the noise rating level for occupational activities at the work place for the level range underneath the given risk of hearing damage)*. DIN Deutsches Institut für Normung e.V., Berlin (Germany), 2012.
- [21] T. Renz, P. Leistner, and A. Liebl, "A simple model to predict the cognitive performance in distracting background speech," in *Euronoise. Crete (Greece)*, pp. 1891–1896, 2018.