# A simple sound metric for evaluating sound annoyance in open-plan offices

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### ABSTRACT

A major health issue in open-plan offices has emerged: noise; occupants of these new work spaces report sources of intelligible speech as the most irritating type of noise. Fluctuations in speech levels prevent people from completing some highly demanding tasks, thus inducing annoyance and fatigue. Many studies have attempted to identify a sound metric reflecting this Irrelevant Speech Effect. Hongisto et al. (2005) have shown that the Speech Transmission Effect can be used to assess disturbance due to a neighbour in the office. More recently, Schlittmeier et al. (2008) suggested that fluctuation strength could be used to assess how fluctuations in ambient noise levels affect task performance. This paper presents a new metric based on measurement of short-term temporal modulation of sound levels. Results indicate that this metric is as efficient as the Speech Transmission Index (STI) or FS, while being more suitable for in situ experiments and easier for health and safety practitioners to use.

## 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 [1], work satisfaction, well-being, and a sense of privacy [2].

In open-plan offices most noise is related to conversation, with the main disturbance reported by occupants being related to intelligible conversations [3]. The relationship between the perceived disturbance, or the cognitive overload linked to noise levels, has been actively studied by psychologists since the 1990s 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, cognitive processes can become saturated, 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 characterised by physical or psychophysical indicators, often linked to the intelligibility of words in the background noise.

The aim of this paper is to list and analyse the physical or psychophysical indicators through which ISE can be measured in laboratory conditions, and to assess their advantages and limitations when used in the field. Two types of indicators will be addressed: those used to assess the intelligibility of conversations in background noise, and those aiming to define a level of modulation of the ambient noise.

## INTELLIGIBILITY-BASED INDICATORS

Since intelligible conversations have been identified as the most problematic sources of noise for occupants of open-plan offices, indicators of intelligibility appear to be natural candidates for measuring the perceived discomfort. Several laboratory studies have investigated ISE based on the use of the *STI* (Speech Transmission Index) indicator. Measurement and calculation of the *STI* has been standardised for stationary background noises [4].

### STI with fixed-intensity ambient noise

The *STI* is calculated by assessing loss of modulation in the envelope of a signal. A signal which is fully intelligible (modulation equal to 1) at the source remains fully intelligible to the receiver when the loss of modulation is null; it becomes unintelligible when loss of modulation is equal to 1. From this description, it is possible to simply translate the effects of a transmission system (the work space in our case) for a signal which was initially fully intelligible. This approach was developed by Steeneken and Houtgast [5] and then adopted in the standard (IEC 60268-16, 2011). The general expression for the *STI* is:

$$STI = \sum_{k=1}^{n} W_k TI_k, \tag{1}$$

Where $W_k$ corresponds to weighting factors for each band and $TI_k$ is the index of transmission reflecting the quality of the transmission based on modulation of the target signal. This modulation is analysed over 14 one-third-octave bands, ranging from 0.63 Hz to 12.5 Hz. $TI_k$ is the mean modulation of transmissions over all these bands. The index of transmission for each octave band and each modulation frequency can be written as:

$$TI_{k,i} = \frac{SNR_{k,i}^{app} + 15}{30} \tag{2}$$

In this expression, $SNR_{k,i}^{app}$ is the “apparent” signal-to-noise ratio between the target signal and the interfering noise as received by the listener’s ear. Its value depends directly on the modulation transfer function, $m_{k,i}$, as seen in the following expression:

$$SNR_{k,i}^{app} = 10 \times \log_{10}\left(\frac{m_{k,i}}{1 - m_{k,i}}\right) \tag{3}$$

This equation implicitly contains all the factors contributing to the reduction in signal modulation for speech. If the signal is degraded by the presence of ambient noise and reverberation in the space, and by effects due to frequency masking, the transfer function for the modulation is written as the product of three partial modulation transfer functions, as follows:

$$m_{k,i} = m_k^1 \times m_k^2 \times m_{k,i}^3 \tag{4}$$

Experimental results from laboratory tests and observations in companies were recently compiled to assess how performance was affected for a task requiring working memory. From these data, Hongisto [6] proposed an empirical model of the decrease in performance (DP), which could be used as a descriptor for the ISE, as a function of the *STI*. This model produces a sigmoidal curve, and the author hypothesised that the DP is maximal at the inflection point of the intelligibility curve, which corresponds to the speech recognition threshold (SRT), i.e., at $STI = 0.4$ (figure 1). The general expression is:

$$DP = \frac{-7}{1 + \exp\left(\frac{STI - 0.4}{0.06}\right)} + 7 \ [\%] \qquad (5)$$

According to Hongisto, this curve is a “compromise” taking all of the data available in the literature into account. The shape of the sigmoid (height of the plateau and slope at the point of inflection) can be influenced by the type of task. The laboratory tests which were used to develop this model included a range of tasks: serial memory, text correction, *etc*. Observations in companies were based on perceived time wasted at work due to intelligibility of speech in various open-plan offices.

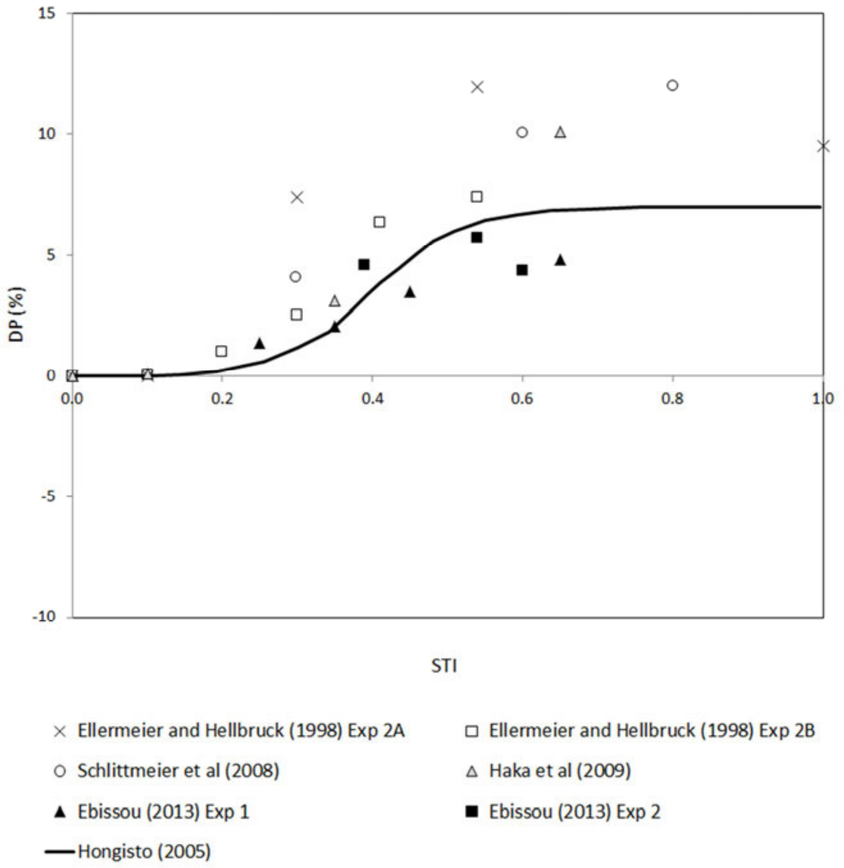


**Figure 1:** Decrease in performance as a function of *STI*. Data gathered from several publications. References for the legend: Ellermeier and Hellbruck (1998) [7], Schlittmeier et al. [8], Haka et al. (2009) [9], Ebissou (2013) [10]

### Fluctuating ambient noise

The *STI* can be used to assess intelligibility in the presence of stationary ambient noise. Recent laboratory experiments showed that the *STI* had a significant effect on the ISE (decreased performance and increased cognitive load). 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. The *STI* as presented above cannot be applied in these conditions because the ambient noise is not stationary.

Several studies have contributed to the development of an intelligibility index taking fluctuations in ambient noise levels into account. Work by Rhebergen et al. [11] followed by Brocolini et al. [12] developed the $SII_t$ and $STI_t$ indexes, respectively, using a sliding temporal window to calculate stationary indices, then averaging the values obtained for each position of the window. A second approach involving calculation of modulations to ambient noise was developed by Chevret [13]. This method can be used to calculate an $STI_m$ index based on the increase in speech-related noise modulation due to reduced modulation of ambient noise. Work is ongoing at INRS to establish the link between the ISE and these indices. The results of this work will be presented during this conference.

## INDICES BASED ON MODULATION OF AMBIENT NOISE

In the context of an open-plan office, indices of intelligibility are mainly used to determine the disturbance caused by a source of noise placed in a particular position in the layout relative to a receiver placed in another position. This scenario provides information on the quality of acoustic transmission between the source and the receiver, accounting for effects due to separators of office spaces, high cubicle separators, and, to a lesser extent, the acoustic quality of the workspace. The disadvantage is that it cannot directly characterise the quality of the ambient noise in the work space, unless the number of receivers is increased and measurements of ambient noise are included in the assessment.

### Fluctuation strength

Fluctuation strength is a psychoacoustic indicator attempting to describe the modulation of the sound-intensity of a signal around a frequency of 4 Hz. This indicator was initially developed by Zwicker and Fastl [14] and was further developed by Aures [15] and Daniel and Weber [16]. It can be expressed by the following relation:

$$f_s = \frac{\int_0^{24\,Barks} \Delta L\,(z) dz}{\frac{4\text{ Hz}}{f_{mod}} + \frac{f_{mod}}{4\text{ Hz}}}\ \text{[vacils]} \tag{6}$$

Where $\Delta$L is the perceived depth of modulation and $f_{mod}$ is the modulation frequency. The flucutation strength is maximal at 4 Hz.

This frequency corresponds to the mean speaking rate for a constraint-free discussion. Recent works (Schlittmeier et al. [17], Liebl et al. [18]) showed that the fluctuation strength is a relevant descriptor of the ISE, base on the following relation:

$$ISE = DP(f_s) = \frac{ISE^{\max}}{f_s^{\max}} \times\ f_s. \tag{7}$$

In this expression, the DP is determined relative to the condition with no ambient noise (i.e., silence). The values of ${f_s}^{\max}$ and $ISE^{\max}$ are directly experimentally-determined. They depend on the test conditions, in particular the difficulty of the task to be performed. Thus, in Schlittmeier et al. [17], these parameters are 0.68 vacils and 7.5%, respectively, for the maximal DP. In these conditions, the slope for DP as a function of the fluctuation strength was 11.03. In Liebl et al. [18], the values were 0.278 vacils and 19.27% for the DP, which gives a slope of 69.3. These different results indicate that the tasks required of the subjects were more difficult in the second case.

The results presented in [17] were produced using a set of 70 different background noises, such as samples of classical music, animal noises, conversations, or repeated monosyllables, and appear to indicate that the strength of fluctuation is a good descriptor of the ISE. This correlation between background noise and ISE is less clear in [18]. Indeed, the results presented fail to clearly distinguish speech in a stationary background noise with a signal-to-noise ratio of -6 dB(A) or 0 dB(A), respectively. However, it is difficult to draw definitive conclusions from this study as the values for the fluctuation strength obtained for signals at 55 dB(A) (SNR = 0 dB(A)) were unexpectedly low (2.6 cV); expected values for these noise levels would be around 40 cV (see figure 2).

In parallel to this discussion, it should be noted that the fluctuation strength presents several disadvantages when attempting to determine the ISE. The most important disadvantage is the fact that it varies with the level of noise of the signal: the higher this level, the greater the fluctuation strength. This is illustrated in figure 2 for several extracts of conversation with different signal-to-noise ratios (various *STI*). However, results in [8, 19, 20] showed that the degree of perturbation is independent of the noise intensity for fixed-intensity noises, at least over the 48 to 76 dB(A) range. This appears to contradict the choice of fluctuation strength as an index to assess the ISE. This point should therefore be discussed between researchers working on the subject.

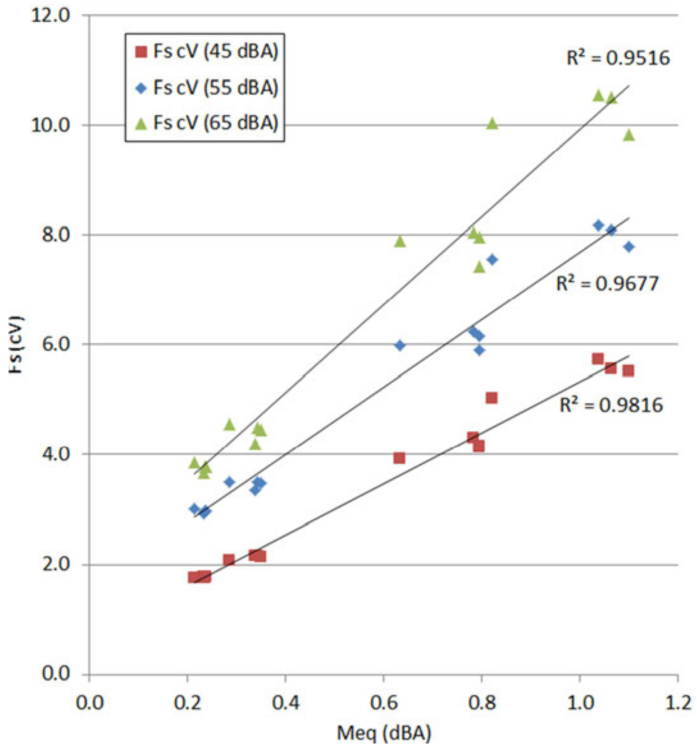


**Figure 2:** Fluctuation strength as a function of *STI* for extracts of conversation in the presence of fixed-intensity ambient noise (various SNR).

### Equivalent Modulation (short Meq)

A simpler method than fluctuation strength was recently developed by Kostallari et al. [21]. This method is based on calculation of the continuous equivalent noise level, $L_{eq}$ [22], also known as the short $L_{eq}$, which can be defined as follows:

$$L_{eq}(t_1, t_2) = 10 \times \log_{10} \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{p^2(t)}{p_0^2} \, dt \qquad (8)$$

This indicator simply translates the noise level over a given recording duration (equal to $\Delta T = t_2 - t_1$). By choosing the duration of the integration, the events or phenomena to be identified from this signal can be determined. The example of a 20-s conversation, illustrated in figure 3, shows that the duration of integration has a significant effect on how the $L_{eq}$ changes over time. This is particularly visible when comparing integration durations of 1 s and 125 ms (see figure). Comparison of integration durations of 125 ms and 40 ms also revealed differences, but they were less marked. Nevertheless, the profiles remained relatively similar. The duration of integration is inversely proportional to the bandwidth of the signal modulation. Thus, an $L_{eq}$ of 125 ms reveals events with a frequency of appearance of less than 4 Hz.

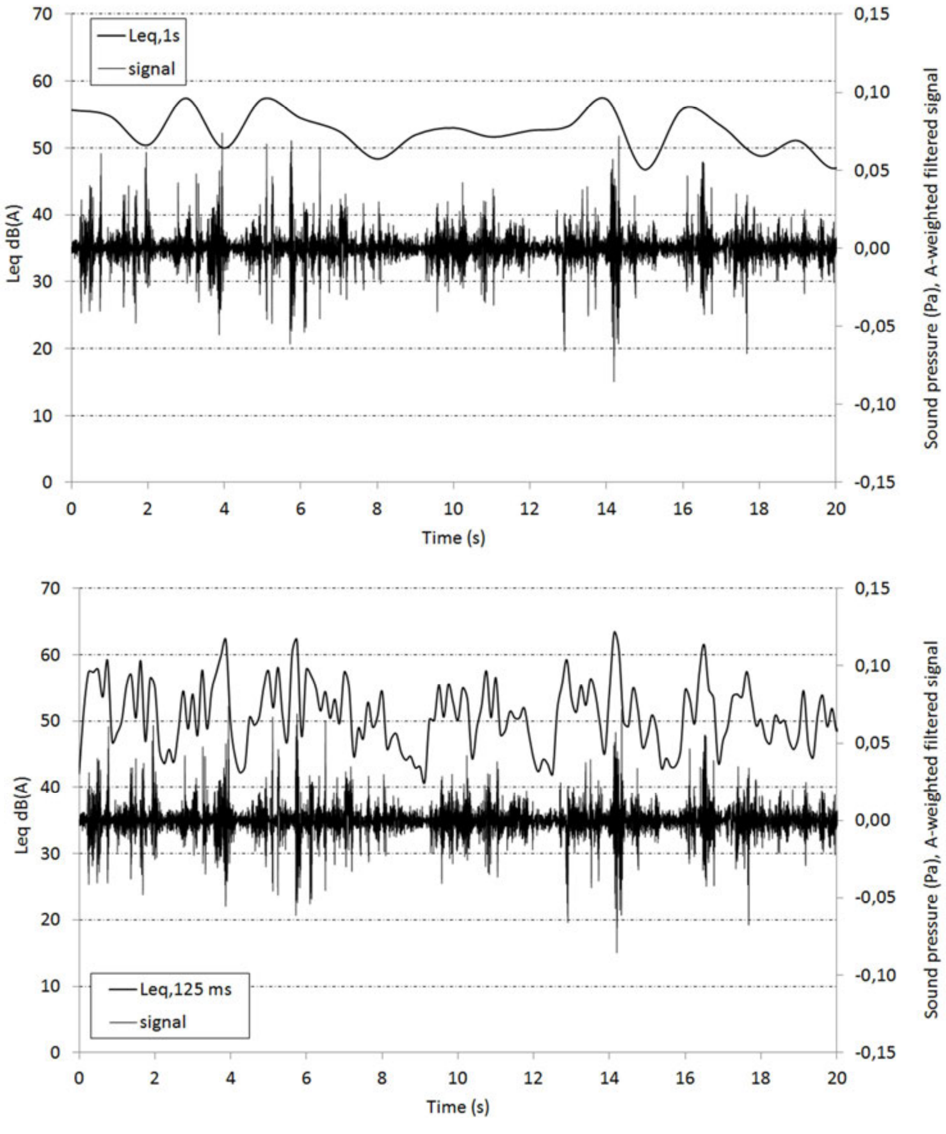


**Figure 3:** A-weighted $L_{eq}$ for a speech signals with different integration durations (top) $\Delta T = 1\ s$ (bottom) $\Delta T = 125\ ms$

Recent measurements in companies and results of laboratory tests run by INSA and INRS identified a novel indicator of the rate of modulation with a simpler definition than fluctuation strength. This indicator, called $M_{eq}$, can be determined by calculating the depth of modulation of a signal by subtracting A-weighted $L_{eq}$ from the LA90 index.

Figure 4 represents the $M_{eq}$ as a function of the $STI_t$ for a target voice masked by different mixtures of more or less intelligible speech-related noises. The $STI_t$ and $M_{eq}$ values were obtained by varying the signal-to-noise ratio between the target signal and the masking signal. The curves have a parabolic shape, with the minimum corresponding to a situation for which the target signal is as "intelligible" as the masking signal. For an $STI_t$ below this minimum point, the background noise predominates. The target signal therefore loses intelligibility but the overall intelligibility of the mixture increases. The parabolic shape is more marked with more intelligible masking signals.

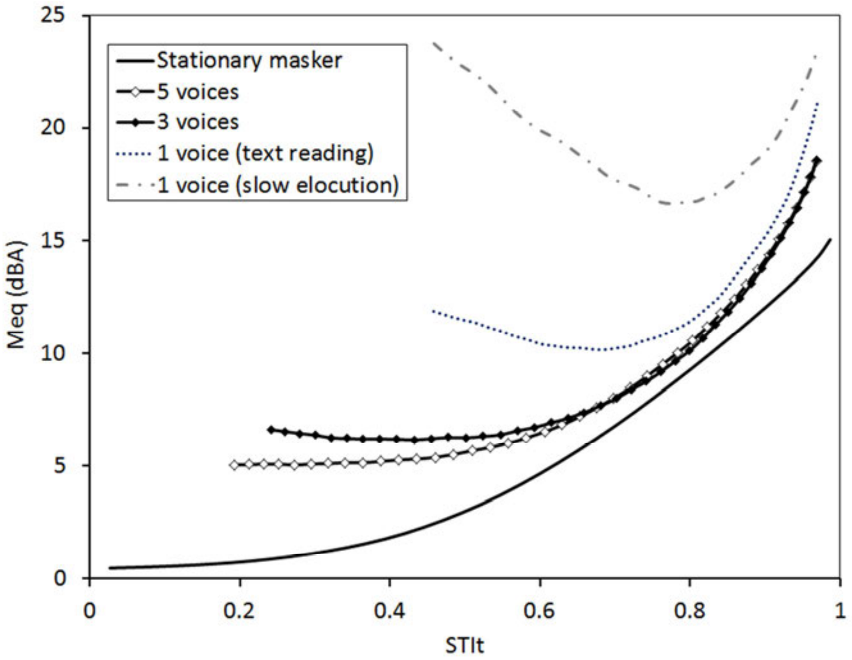


**Figure 4:** $MA_{eq}$ as a function of the $STI_t$ for different masking noises made up of mixtures of speech noises. The target voice is a conversation with slow elocution.

Laboratory tests were performed to determine the potential link between the $M_{eq}$ and the *ISE*. The results of these tests will be presented during this conference.

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