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Statistical analysis of speech privacy based on the *SII*

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Abstract

Office designers have been concerned with speech privacy for decades. One way to define speech privacy is the capability of a listener to understand, or to be disturbed by, a conversation that is taking place somewhere else in the same, or in the adjacent, office. In the nineties, the study of speech privacy has mainly been carried out in terms of intelligibility, and the speech privacy index, *PI*, was defined as the complement of the intelligibility ($PI = 1 - I$). This work will focus on the speech privacy of enclosed offices. In that case the main parameters involved are the source speech, the transmission loss of the separating wall, and the background noise in the receiving room. A statistical model will be developed, based on the Speech Intelligibility Index, to analyse *PI* as a function of the above mentioned parameters in order to estimate the relative importance of each one of them to the privacy problem.

1. Introduction

In offices, the acoustical environment is closely related to the productivity of workers. The main acoustical problem in these environments is that the noise is made up of different components. Among them, the most important sources of noise may be office activity, imission from outside and conversation from other workers. Undesired speech has specific properties based on the information it carries that make this noise source much more disturbing than others. At present, and due to the modern architectural building techniques, this problem can be very important even for enclosed offices where conversational speech from adjoining rooms can propagate into the office with a level high enough to be heard. Another important issue is that of confidentiality; people producing speech may not want this to be understood outside the meeting room.I Information and consulting services might need a certain degree of speech privacy to suggest confidentiality to their clients.

Speech privacy was first studied in the sixties by Cavanaugh et al.[1]. In their work they stated that a speech privacy rating should depend on the background noise in the receiving room, the wall sound insulation, and the acoustical characteristics of both emitting and receiving rooms. Their work shows a strong relationship between the intelligibility, *I,* and the feeling of speech privacy. The most critical of the subjects began to feel a lack of privacy when the articulation index, *AI*, was *0.05*, which was thus described as confidential privacy.

Though from Cavanaugh's work it seems clear that an *AI* of *0.05* corresponds to confidential privacy, later studies point out that a direct relationship between changes in intelligibility and intelligibility indices for speech privacy is not quite straightforward [2]. In this way the Privacy Index, *PI*, (defined as *PI = 1 - I*) has been the objective of modern works, where the goal is to develop integrated design solutions to speech privacy, mainly by the use of signal to noise ratios [3].

2. Monte Carlo model

In enclosed offices with acoustic privacy problems, the intruding noise will be produced by speech in the emitting room and after being modified by room acoustics is transmitted through the wall to the receiving room where it will reach the listener after being, again, modified by the room acoustics. As a first approach both room acoustics effects will be neglected. Then, the quantities involved are the speech spectrum, the wall sound insulation, and the background noise in the receiving room.

The model will have to calculate the intelligibility in the receiving room once the speech has passed through the wall. As an estimate of intelligibility, the speech intelligibility index, *SII*, will be used [4]. All of these quantities are frequency dependent so that the dimension of the problem becomes large, a way to overcome that difficulty is the use of global ratings for the quantities involved; as there may exist several different members from the same element (speaker, wall, noise) with the same global rating the use of a set of samples becomes necessary.

Firstly, a sample of all possible walls will be created, and then the relationship arising from the model among the different quantities involved will be
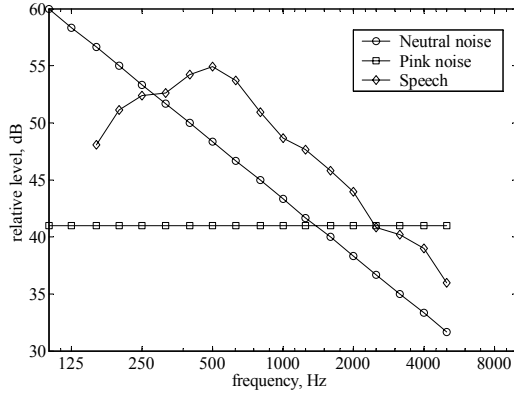
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Figure 1: Noise spectra used.

Figure 2: PI as a function of *TL* for a set of *T2* walls and 4 different pink noise levels.

shown. That set of walls will be used to study the influence of the global sound reduction index of the wall on the *SII* in the receiving room. The calculation of the sound pressure level in receiving room will be carried out by the mere subtraction of the wall sound insulation from the speech level. Lately, aural procedures have been developed to estimate the sound in the receiving room that are especially appropriate for subjective surveys [5].

The Monte Carlo model used in this work was firstly created by Moreno et al. [6] and is built up by 6 types of walls characterized by the number of straight segments that represent the main trends and by the position of the joint frequencies between segments (see *Table 1*).

Table 1: Wall classification types.

Wall type	Profile	Description
T1	/	One segment over all frequencies
T2	_/	Two segments, first flat
T3	/–	Two segments, second flat
T4	/–/	Three segments, central flat
T5	_/–	Three segments, central positive slope

3. Model analysis

The Monte Carlo model was generated with a basic sample with 100 elements per type, shifting them up and down as needed to get the required transmission loss, *TL*. The sound reduction index, A-weighted, was used due to its flexibility to take into account different spectral ranges. As speech spectrum, the one included in [4] for normal effort will be used, and three kinds of noise will be investigated, pink noise, neutral noise, and speech spectrum −see *Figure 1*−. The global sound pressure level was A-weighted, as well.
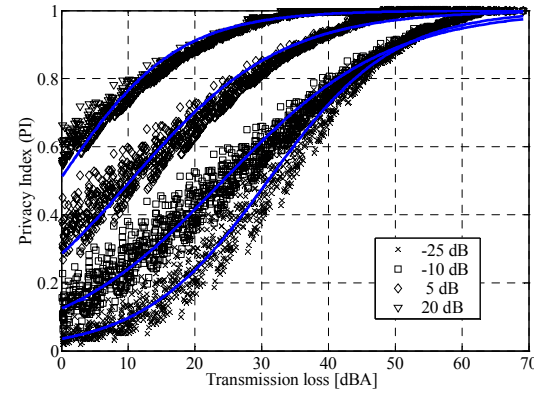
3.1. Dependence on *TL*, and noise sound pressure level

When *PI* is plotted as a function of *TL*, curves as the ones in *Figure 2*, the typical S shaped curves are obtained. In general, the results can be approximated by the equation:

$$PI = \frac{1}{1 + e^{-c_1 - c_2 SPL - c_3 TL}} \qquad (1)$$

where *SPL* is the noise level, *TL* the sound reduction index A-weighted. Constant c_3 was calculated to be about *0.1* for all of the cases studied. On the other hand, c_1 and c_2 depend on the kind of noise studied. *Figure 3* shows an example for pink noise. Both constants are so different for every case −noise and wall type pairs− that it is not possible to generalize their behaviour

3.2. Signal to Noise ratio dependence

When signal to noise ratios, *SN* are calculated, graphs like the one in *Figure 4* are found, and can be fitted by one expression similar to equation 1:

$$PI = \frac{1}{1 + e^{-b_1 - b_2 SN}} \qquad (2)$$

where b_1 and b_2 are a function of the wall and noise types. The scatter plot shows such a large spread that the variance of the fitting will be very high and the prediction may not be very accurate. On the other hand, the fitting of the upper part of the curve seems not to work quite as well. Presumably, experimental data would be smoother than these plots. In any case equation 2 is conservative.

In Figure 5 the results for b_1 and b_2 are shown. b_2, is related to the steepness of the curve, and is approximately constant for every wall type and every noise type. Differences are found for b_1. Wall types T1

and T2 are the same for a given noise, so they can be treated as a single case. The rest are close enough that the b_1 values can be substituted by a mean value −see Figure 5−. As a rule of thumb, greater b_1 values give higher PI curves. This means that the best privacy will be achieved for neutral noise and type T1 or T2 walls.

3.3. Variation of Speech Intelligibility Index Resolution Threshold (*SIIRT*) with *TL*

The *SIIRT* is defined as the presentation level necessary for a listener to recognize the speech material correctly a specified percent of the time. Defined this way, the *SIIRT* agrees well with the concept of the degree of privacy, and it can be useful to asses this for a maximum speech level for which a minimum degree of privacy will never be exceeded. *Figure 6* shows a plot of *SIIRT* (20%) as a function of *TL*, it can be observed that for a given noise level the plot graphs straight lines. There is a certain noise level below which the lines are superimposed; higher noise levels give higher lines.

This same kind of graph is found for every wall type and every kind of background noise, thus a linear fitting seems to be appropriate:

$$SIIRT_{Pd} = p_1 TL + p_2 \qquad (3)$$

where the subscript *Pd* states the degree of privacy assessed, defined as the maximum *SII*, expressed as a percentage, that can be obtained for the level indicated by *SIIRT*. In doing so, plots similar to the one in *Figure 7* are obtained for a 20% privacy degree. In all of them the value of the slope (p_1) is one. Curves for p_2 have a first constant interval, with a limit around *25 dBA*, and they depend on the kind of noise. The reason is that, according to the *SII* model used, for lower noise levels, ear internal noise becomes dominant, and the influence of the external noise is negligible.

For higher noise levels p_2 shows a linear behavior with noise levels. Furthermore, for a given noise level p_2 values do not differ more than *3 dB* among wall types. Thus p_2 can be expressed as a linear function of noise levels:

$$p_2 = c_1 \, SPL + c_2 \qquad (4)$$

where c_1 and c_2 are coefficients to be fitted. Again, c_2 is always one and the square of the correlation coefficient for the fitting defined through equation 3 is always greater than *0.97*. Thus equation 3 becomes:

$$SIIRT_{Pd} = TL + SPL + c_2 \qquad (5)$$

where c_2 depends on the noise type and on the privacy degree chosen. From *Figure 8*, where p_2 for a *Pd* of *20 %* is shown, it is apparent that p_2 as a function of the *A-weighted SPL* of noise and does not depend on the kind of noise. Thus, only one expression can be used where the independent term c_2 is a function of *Pd*.
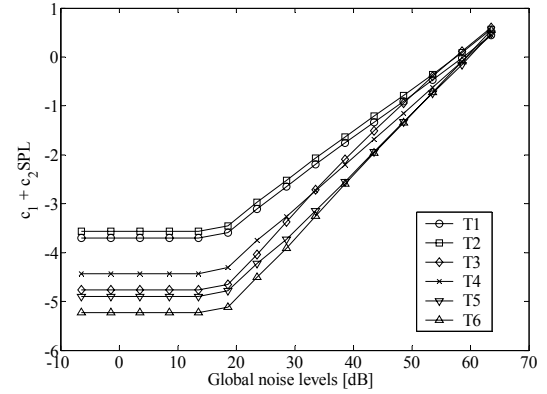

Figure 3: Behaviour of fitting constants from equation 1 for all the wall types and pink noise.
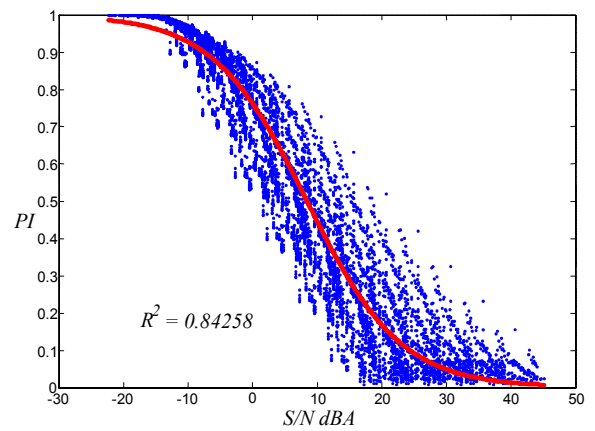

Figure 4: Speech privacy as a function of signal-to-noise ratio. Wall type: *T1*, background noise: speech spectrum.
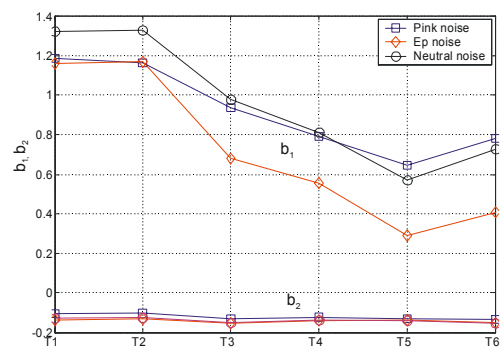

Figure 5: Fitting constants from equation 2.

4. Conclusions

A Monte Carlo model has been developed for speech privacy of enclosed offices based on the *SII* descriptor of the intelligibility. From that model it has been shown that a system based on global ratings of background levels inside the room and *TL* of the separating wall are not adequate.

Nevertheless, models based on signal to noise ratios could be appropriate; the model shows a great spread in the data that might be overcome by the use of some kind of function −the weighting functions used in the *AI* calculation could be an example to follow−.

To finish, the use of resolution thresholds has been investigated. This approximation to the privacy problem seems to be the most promising and the most accurate. Furthermore, as noted in Cavanaugh's work [1], a given privacy level is found for a fixed *AI* (i.e. there exists a direct relationship between *AI* and *SII*), and in the *SIIRT* study this value is kept constant. Therefore, it is expected that their results would agree well with experimental data. Though, how these quantities can to be measured at such low values, is an open issue currently.

5. References

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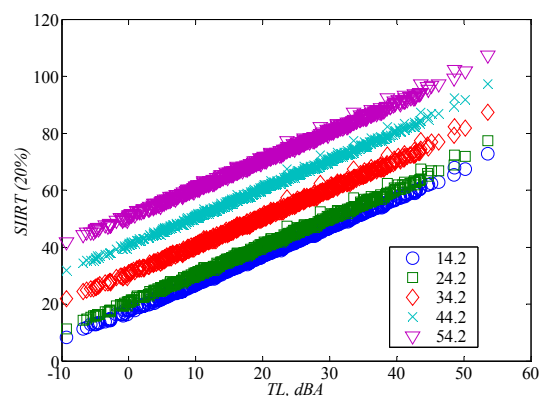
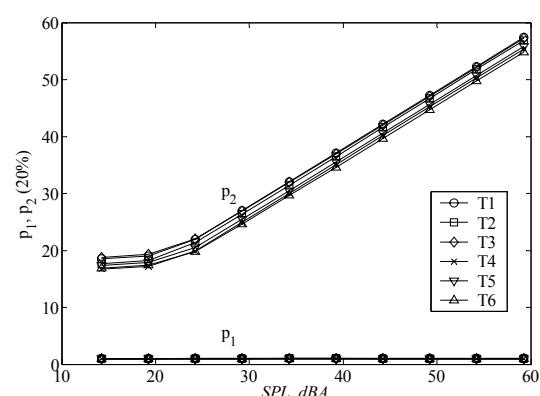*Figure 6: SIIRT* as a function of *TL* for different *A-weighted SPL* and a speech spectrum as background noise.
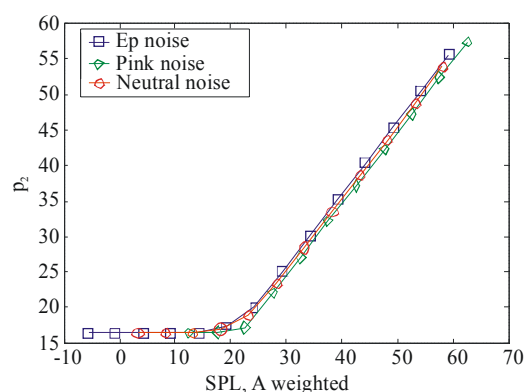

Figure 7: Fitting constants for equation 3

Figure 8: Equation 4 plot for different noise types.