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Harmonizing different metrics for speech privacy

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Abstract

It is regularly debated which metric to use for the assessment of speech privacy in open-office as well as closed-office environments. Metrics commonly used for this purpose include the Privacy Index (PI), which is derived from the Articulation Index (AI) determined according to ASTM E1130 as well as the Speech Privacy Class (SPC) determined according to ASTM E2638. Regardless of the method of determining these values, it has recently been shown that both metrics are mathematically related. In light of this information, it seems that the discussion might be better directed at different questions, for example what the recommended values should be for different environments (open-plan, closed or mixed). This paper will highlight the similarity between speech privacy metrics as well as the commonly recommended values for open-plan and closed offices and how they relate to each other. The analysis and discussion is based on data from extensive field measurements as well as measurements under laboratory conditions. The data of the field measurements is also compared to subjective responses to assess the perceived privacy.

Keywords: Speech privacy, Open-plan offices, Closed offices

1 INTRODUCTION

A major reason for complaints of workers in open-plan offices (and to some degree in closed offices) is the disturbance by speech from their co-workers causing distraction [1]. It is hence crucial for acoustic practitioners to be able to accurately predict and assess the perceived speech privacy in offices. Several metrics have been developed to asses speech privacy, all of which reflect the fact that speech intelligibility, which is an important factor influencing the amount of distraction caused by speech, is mostly determined by the ratio between the speech energy reaching the listener and the energy of the background noise at the listener position [2, 3].

This paper uses an extensive set of field and laboratory measurement data (Section 2) to examine three speech privacy metrics (Section 3) and to show that because of the similarity of the approaches, there is a clear relationship between all metrics (Section 4). This fact is used in analyzing the recommended values for the different metrics and in pointing out discrepancies between them (Section 5). In order to relate the findings to the actual perceived speech privacy, subjective data in the form of responses to questionnaires by the workers in open-plan offices are compared to the objective data (Section 6).

2 OBJECTIVE AND SUBJECTIVE DATA USED IN THIS STUDY

The data used in this paper to highlight the relationship between speech privacy metrics is from a large-scale study conducted by the National Research Council (NRC) of Canada from 2008 to 2013 in 24 buildings in North America [4, 5]. The study, called the “Post-occupancy evaluation of green and conventional buildings” and subsequently referred to in short as the GreenPOE study, involved objective measurements of indoor environment parameters, including acoustic measurements related to speech privacy, as well as an online questionnaire of the people working in the buildings where measurements were made. The questionnaire covered general questions about job satisfaction and stress as well as more specific questions related to the satisfaction with the indoor environment in the offices. For this paper, only the questionnaire items relating to speech privacy have been evaluated.

The objective data from the GreenPOE study yields almost 1300 datasets for open-plan offices with rather low speech privacy. To also include data representative of offices with higher speech privacy, such as closed offices, an additional 500 datasets from laboratory measurements at the NRC are used in this paper. The laboratory data was gathered from measurements made on different wall types together with artificially created background noise of varying sound pressure level (SPL).

3 SPEECH PRIVACY METRICS

In this section, the most common metrics used for assessing speech intelligibility and speech privacy in buildings are summarized. The metrics include the Privacy Index (PI), the Speech Intelligibility Index (SII) as well as the Speech Privacy Class (SPC).

3.1 Privacy Index (PI)

The Privacy Index (PI) is a measure of the speech privacy as it relates to a lack of intelligible speech, i. e. distraction, reaching the listener's ears. As such, the PI is defined as the complementary value of the Articulation Index (AI) [6, 7] as

$$PI = 100 \cdot (1 - AI)\,, \tag{1}$$

the AI itself being a measure of speech intelligibility with values between 0 and 1, so that the PI ranges between 0 and 100.

The factors involved in determining AI are the speech source reference SPL L_S, the level difference LD measured for a certain position of the sound source and the receiver, as well as the background noise SPL L_N. These values are used to determine the effective Signal-to-Noise Ratio (SNR) at the listener position. Following ASTM E1130, the speech source reference SPL for "normal" vocal effort has to be used, leaving LD and L_N as free variables. The variables of L_S, LD and L_N are all considered for the third-octave bands with center frequencies between 200 Hz and 5 kHz. As a single number rating, the AI (and thus PI) is then calculated as a weighted sum across frequency, with the frequency-weights specified in ASTM E1130.

Recommended values of the PI for normal speech privacy in open-plan offices are listed in Appendix X2 of ASTM E1130 as 80 to 95. Values of PI above 95 are mentioned in the same Appendix as representing confidential speech privacy.

3.2 Speech Intelligibility Index (SII)

The Speech Intelligibility Index (SII) is a measure of speech intelligibility like the AI, and it has replaced the AI method in ANSI S3.5 [8]. While the basic input data and the frequency-weights for the SII are essentially the same as for the AI, the method for the SII additionally includes the psychoacoustic effect of frequency masking to determine the effective SNR at the listener's ears.

The SII has originally not been defined in terms of speech privacy, but in analogy to the PI the complementary value to the SII can be used. Recommended values for the SII in open-plan offices have been suggested for normal and confidential speech privacy as 0.2 and 0.1, respectively [9].

3.3 Speech Privacy Class (SPC)

As was mentioned above, the reasoning for using the PI as a measure of speech privacy is that it represents a lack of speech intelligibility, given that it is the complementary value to the AI. However, in situations with a low degree of speech intelligibility perceived speech privacy may not be as high as desired, as audible speech may still reach the listener [10].

To address this problem, the Speech Privacy Class (SPC) was developed for use especially in situations with low speech intelligibility, such as closed offices and meeting rooms. The SPC and the associated measurement method are defined in the standard ASTM E2638 [11]. The input data to determine the SPC is the measured level difference between the average SPL inside the closed room and the SPL at individual receiver positions outside of the room, as well as the background noise SPL at the receiver positions. The criterion values for the SPC are then chosen depending on the desired level of speech privacy [12].

In Appendix X2 of ASTM E2638, recommended values for the SPC are listed for different levels of speech privacy in closed rooms. For minimal and standard speech privacy the recommended values are 70 and 75, respectively.

4 RELATIONSHIP BETWEEN SPEECH PRIVACY METRICS

Since all of the commonly used speech privacy metrics are based on the effective SNR at the listener position, it is to be expected that there is a relationship between the metrics. Due to the fact that either a different frequency range is used or the frequency-weights differ between metrics, any relationship found will be an approximation. Nevertheless, it is shown below that relatively simple functions relating PI to SPC and SII can be found and that the agreement with experimental data is very good over the relevant range of values.

4.1 PI and SPC

The relationship between the PI and SPC has recently been demonstrated and validated with the data mentioned in Section 2 [13]. The following function to calculate the PI from the SPC was determined to give good accuracy over the entire range of SPC values ($R^2 = 0.992$):

$$PI \approx 100 \cdot \left[0.5 + 0.5 \cdot \mathrm{erf}\left(\frac{6.65}{100} \cdot SPC - 2.8\right)\right], \tag{2}$$

where erf is the error function. Fig. 1 shows the relationship between PI and SPC according to Eq. 2 together with the experimental data in open-plan and closed offices mentioned in Section 2. It can be seen that the agreement of Eq. 2 with experimental data is very good. The effect of limiting the SNR for the calculation of PI also becomes apparent for values of PI below 20 and above 80.

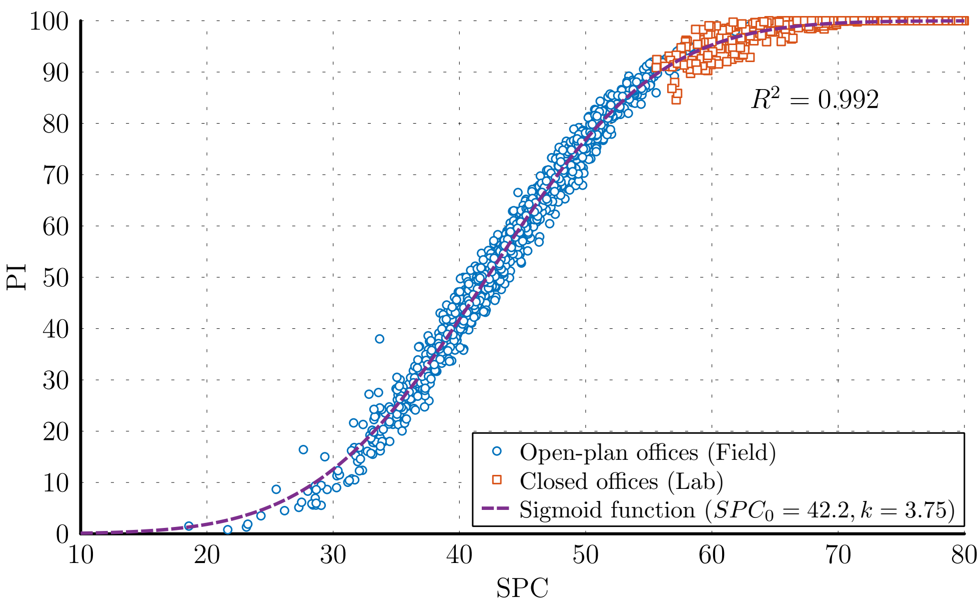

Figure 1. Relationship between SPC and PI for experimental data and according to Eq. 2

The inverse relationship of Eq. 2 was found in [13] as follows:

$$SPC \approx \frac{100}{6.65} \cdot \mathrm{erf}^{-1}\left(\frac{PI}{50} - 1\right) + 42.2, \tag{3}$$

where erf^{-1} is the inverse error function. It has to be mentioned that the inverse relationship in Eq. 3 is not reliable for PI values below 5 or above 95, as the inverse error function tends towards negative and positive infinity, respectively, beyond these values. This represents the effect of limiting the SNR range in the calculation of the PI, which effectively leads to a loss of information.

4.2 PI and SII

From the raw data mentioned in Section 2, the SII was calculated in addition to the PI and SPC. This allows to compare the values of PI and SII and establish the relationship between these two metrics. It was found that a simple second order polynomial function describes SII as a function of AI very well ($R^2 = 0.998$), which gives the following function:

$$SII \approx 0.28 \cdot AI^2 + 0.69 \cdot AI\,. \tag{4}$$

By replacing AI in Eq. 4 according to Eq. 1 as $AI = 1 - {}^{PI}\!/_{100}$, an expression of SII as a function of PI is obtained:

$$SII \approx 0.28 \cdot \left(\frac{PI}{100}\right)^2 - 1.25 \cdot \frac{PI}{100} + 0.97\,. \tag{5}$$

The relationship between PI and the complementary values of SII (i. e. $1 - SII$) is shown in Fig. 2 for the experimental data and according to Eq. 5. The good agreement of the calculated values with experimental data can be verified in the graph. While the agreement is slightly worse as PI tends toward zero, the agreement for higher values of PI, which are most relevant for the assessment of speech privacy, is very good. Overall, for 99 % of the data there is a deviation of less than 0.03 between the measured values of SII and the values calculated from PI according to Eq. 5.

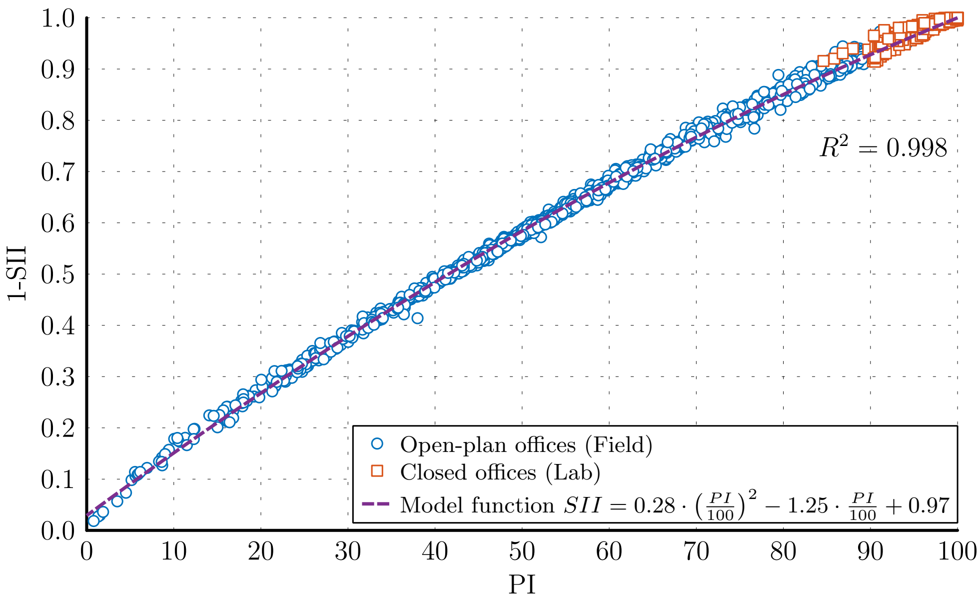

Figure 2. Relationship between PI and SII for experimental data and according to Eq. 5

The relationship between PI and SII can be inverted (as was done for Eq. 2 and Eq. 3), to give the following expression to calculate PI from SII:

$$PI \approx 100 \cdot \left(2.23 - \sqrt{\frac{SII}{0.28} + 1.52}\right)\,. \tag{6}$$

5 DISCREPANCIES BETWEEN RECOMMENDED VALUES OF SPEECH PRIVACY METRICS

Given the relationship between the speech privacy metrics detailed above, it should be ensured that the recommended values for all metrics are in alignment, so that no conflicting results are obtained depending on which metric was chosen to evaluate speech privacy.

In the following, three tables are provided which list the recommended values for each speech privacy metric and the converted values for the other two metrics according to the relationships presented above. Table 1 lists the recommended values for PI, Table 2 lists the recommended values for SII and Table 3 lists the recommended values for SPC. In each of the tables, the original recommended values are underlined.

Table 1. Recommended values for PI in open-plan offices (underlined) according to ASTM E1130, and corresponding values for SPC and SII, converted according to Eq. 3 and Eq. 5, respectively.

Level of Speech Privacy	<u>PI</u>	SPC	SII
Normal	<u>80–95</u>	51–60	0.15
Confidential	<u>95–100</u>	> 60	0.035

Table 2. Recommended values for SII in open-plan offices (underlined), and corresponding values for PI and SPC, converted according to Eq. 6 and Eq. 2, respectively.

Level of Speech Privacy	<u>SII</u>	PI	SPC
Normal	<u>0.2</u>	74	49
Confidential	<u>0.1</u>	86	54

Table 3. Recommended values for SPC in closed offices (underlined) according to ASTM E2638, and corresponding values for PI and SII, converted according to Eq. 2 and Eq. 5, respectively.

Level of Speech Privacy	<u>SPC</u>	PI	SII
Minimal	<u>70</u>	100	0
Standard	<u>75</u>	100	0

An important conclusion that can be drawn from the data in Tables 1 and 2 for open-plan offices is that the recommended values of SII do not agree well with the recommended values for PI. Converting the values for PI from ASTM E1130 to SII using Eq. 5 yields substantially lower values than the recommended values for SII. This shows that depending on the metric used to assess speech privacy in an open-plan office, different results may be achieved.

For closed office spaces, the data in Table 3 shows that no meaningful distinction between minimal and standard speech privacy (or higher levels of speech privacy) can be assessed by PI and SII, as the values for PI are all equal to 100 and the values for SII are all equal to zero, whereas SPC values are increasing according to the level of privacy. This indicates that the speech intelligibility may be zero but speech sounds may still be audible.

It can thus be concluded that there is a need to harmonize the recommended values of speech privacy metrics, and that the SPC is the only metric which can be used in scenarios of high speech privacy, whereas all metrics (PI, SII and SPC) can be used for lower speech privacy.

6 SUBJECTIVE SPEECH PRIVACY

Given that the existing metrics and the associated recommendations may not lead to consistent results, it is important to also consider the subjective speech privacy perceived by the people working in offices. As was mentioned in Section 2, the GreenPOE study, which yielded the objective measurement data used above, also included a questionnaire to obtain subjective responses from the people working in the offices where the data was measured. In the questionnaire, workers were asked to rate the agreement with general statements about their work satisfaction, and to respond to more detailed questions related to different aspects of the indoor environment, such as lighting, air quality, and acoustics.

For the data presented in this paper, the subjective ratings to the questions related to the office acoustics were evaluated and compared to the results for the objective metrics. In all questions, a 7-point rating scale was used, with categories either corresponding to a degree of satisfaction or to the agreement with a statement or question, from "Not at all" (1) to "Very" (7). Since it was not always possible to link the survey data to the objective measurements at individual workstations, average results for each building will be used both for the objective as well as the subjective data.

In general, significant correlation ($p < 0.01$) between the subjective ratings and the objective results for the three speech privacy metrics (PI, SII and SPC) was found. The degree of correlation was very similar between all metrics, so here only the example for the PI will be shown. In Fig. 3 the average subjective ratings for the question "At your workstation, how understandable are overheard conversations and phone calls from others in your building?" are shown for all 24 buildings as a function of the average PI in each building. The 95 % confidence interval for each average subjective rating is indicated by the error bars. The correlation between PI and the responses for this question ($R^2 = 0.65$) was highly significant ($p < 0.0001$). The linear regression line is also plotted in Fig. 3.

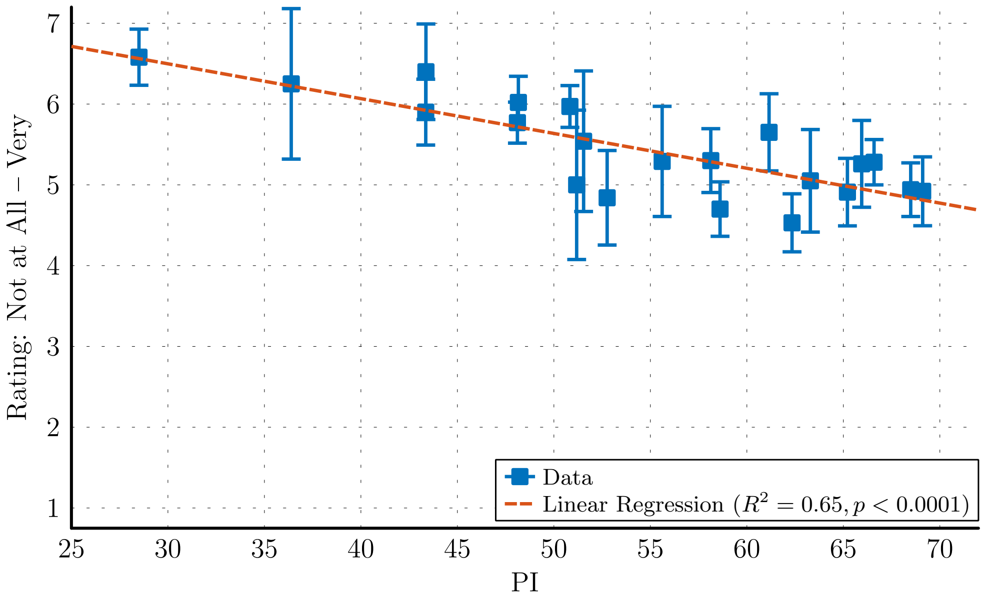

Figure 3. Relationship between average PI and average subjective response per building to the question "At your workstation, how understandable are overheard conversations and phone calls from others in your building?". The 95 % confidence interval for each average subjective rating is indicated by the error bars.

Given that the recommended values for the speech privacy metrics mentioned in Section 5 were reached at almost none of the measured workspaces (see data in Figs. 1 and 2), it was to be expected that the perceived speech privacy would be unsatisfactory. This is supported by the subjective responses in Fig. 3, where none of the data points correspond to a positive perception of the speech privacy, which in this case would be represented by low scores (conversations not understandable). However, the significant correlation between objective and subjective data shows that the perceived speech privacy can be assessed with the objective metrics, where higher values of the objective metrics correspond to a higher subjective rating of speech privacy.

7 CONCLUSIONS

The three common metrics to assess speech privacy in offices — PI, SII and SPC — have been examined in this paper and a relationship between all three metrics has been established based on an extensive set of measurement data from the field and the laboratory. In addition, the relationship between objective results and the perceived level of speech privacy by office workers has been demonstrated using responses from surveys performed in the same buildings where the objective measurements were carried out.

It was shown that a clear relationship between PI, SII and SPC exists and that values of one metric can thus be converted into values of the other metrics with a high degree of confidence. Using the established relationship, it was pointed out that the values typically recommended to achieve a certain level of speech privacy are not consistent between the three metrics. This is problematic since it is then possible that the actual perceived speech privacy in an office will depend on which metric was used to predict and assess the speech privacy during the design phase. The conclusion is that the decision which metric to use for the assessment of speech privacy in open-plan offices is typically not relevant. It is far more important to ensure that the recommendations for target values of the metrics are consistent and yield the desired level of perceived speech privacy.

It was also shown that only the SPC is useful in assessing high levels of speech privacy, because the other metrics impose an artificial limit on the receiver SNR which leads to a loss of information. This means that the PI and SII are not valid metrics for closed offices and meeting rooms, where speech privacy is typically higher.

The evaluation of the subjective responses regarding speech privacy has shown that there is a significant correlation between the objective and the subjective data, which confirms that the speech privacy metrics are useful for assessing the perceived performance. In agreement with the objective data, the subjective responses have shown that office workers in open-plan offices are not satisfied with the level of speech privacy. However, given that worker satisfaction does improve with an increase of the objective values, it should be possible to design open-office workplaces that perform better in terms of speech privacy. One of the first steps toward that goal will be to harmonize and verify the recommended values for the speech privacy metrics so that designers have a reliable framework to work with.

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