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Publisher's version / Version de l'éditeur:
https://doi.org/10.1121/1.5109049
The Journal of the Acoustical Society of America, 145, 5, pp. EL435-EL441, 2019-05-23

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Citation: The Journal of the Acoustical Society of America **145**, EL435 (2019); doi: 10.1121/1.5109049
View online: https://doi.org/10.1121/1.5109049
View Table of Contents: https://asa.scitation.org/toc/jas/145/5
Published by the Acoustical Society of America

Relationship between the privacy index and the speech privacy class

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Abstract: It is regularly debated which metric to use for the assessment of architectural speech privacy. For open-plan offices, the Privacy Index, derived from the Articulation Index according to ASTM E1130 (2016), is usually used. For closed offices, the Speech Privacy Class is determined according to ASTM E2638 (2010). Disregarding the measurement method, and the fact that the metrics show different behavior regarding the Signal-to-Noise Ratio, both metrics are directly related and values of the Speech Privacy Class can thus be converted to Privacy Index values. The relationship is demonstrated and the result is validated with field and laboratory measurement data.

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Date Received: March 26, 2019 **Date Accepted:** May 4, 2019

1. Introduction

Speech communication and speech intelligibility are fundamentally related to the relationship between the signal energy arriving at the listeners' ears and the energy due to interfering noise from other sources.[1–3] Most metrics that have been devised to assess speech intelligibility reflect this fact.

In the context of office spaces, a lack of speech intelligibility (and thereby distraction) is usually desired. One metric that has been used primarily in open-plan offices is the Articulation Index (AI) (or rather its complementary metric, the Privacy Index, PI) determined according to ASTM E1130 (Ref. 4) from the Signal-to-Noise Ratio (SNR) at the receiver position. Following ASTM E1130, a pre-defined speech source sound pressure level (SPL) and spectrum must be used so that the only free parameters to be determined are the level difference (LD), or attenuation, in dB between the source reference SPL and the SPL at the receiver position, as well as the background noise SPL in dB at the receiver position. The measurement of the LD is carried out with a calibrated sound source so that the SPL at the source does not have to be measured. Recommended values of the PI for normal and confidential speech privacy that have been used historically are listed in the Appendix in ASTM E1130.

Another metric used for office space acoustics is the Speech Privacy Class (SPC) determined according to ASTM E2638.[5] The SPC was initially developed for speech security applications and is hence mostly used for closed office spaces. The intended use of the SPC is to determine the degree to which a conversation inside a closed office can be overheard at a receiver position outside of that office.[6] During the measurement, a sound source is operating inside the closed office while the SPL is measured both inside and outside the office to assess the LD provided by the surrounding partitions. While the SPC is, like the PI, in its core based on the SNR at the receiver position, a source reference SPL or spectrum is not included in the equation to calculate SPC. Opposed to the PI, the recommended criterion values of the SPC are based on a statistical evaluation of speech SPL measured in a large number of closed offices and meeting rooms.[7] Based on the statistical data, the criterion values for the SPC can be set depending on the degree of speech privacy that is desired. This approach leaves the LD and background noise SPL as the free parameters, which is the same type of data used for the PI.

Since the PI and the SPC are evaluated in very different architectural environments (open-plan and closed offices, respectively) the standardized ASTM methods of measurement are very different. However, due to the fact that both metrics rely on the same kind of data (LD and background noise SPL), it is to be expected that a fixed relationship exists between them. This paper will explore this idea and show that a

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simple mathematical relationship can be found between PI and SPC. The practical implication is that both metrics can, in principle, be used to assess speech privacy in offices, given the required acoustical data.

2. PI

The PI is typically obtained for open-plan office scenarios, and it is determined from the AI as

$$\mathrm{PI} = 100\,(1\text{–}\mathrm{AI}), \tag{1}$$

where the AI is a value between 0 and 1. The AI itself is a weighted sum of the SNR at the receiver position, $R(f)$. With the frequency weights $w_{\mathrm{AI}}(f)$ defined in ASTM E1130,

$$\mathrm{AI} = \sum_{f=200\,\mathrm{Hz}}^{5\,\mathrm{kHz}} w_{\mathrm{AI}}(f) R(f) \tag{2}$$

$$= \mathbf{w}_{AI}^{T}\mathbf{R}, \tag{3}$$

where Eq. (3) expresses the weighted sum as a vector dot product, with the vector of frequency-weights $\mathbf{w}_{\mathrm{AI}}$ and the vector of SNR values $\mathbf{R}$. In all following derivations, the frequency-dependent variables will be represented by vectors.

The receiver SNR is determined from the selected source reference SPL $\mathbf{L}_S$ and measurements with a loudspeaker that has been calibrated at a distance of 1 m. While the loudspeaker is operating at the source position with a calibrated SPL, the SPL at the receiver position is measured and the LD is obtained as the difference between the calibrated SPL and the SPL at the receiver position. Together with the background noise SPL $\mathbf{L}_N$ measured at the receiver position, the SNR is calculated as

$$\mathbf{R} = \mathbf{L}_S - \mathbf{LD} - \mathbf{L}_N. \tag{4}$$

According to ASTM E1130, the values of the SNR have to be limited in range between $R_{\min} = 0\,\mathrm{dB}$ and $R_{\max} = 30\,\mathrm{dB}$.

Inserting Eqs. (3) and (4) into Eq. (1) results in the following equation for the PI:

$$\mathrm{PI} = 100 - 100 \cdot \mathbf{w}_{\mathrm{AI}}^{T}(\mathbf{L}_S - \mathbf{LD} - \mathbf{L}_N), \tag{5}$$

where the value-limitation of the SNR is not explicitly expressed in Eq. (5). The effect of the limitation of the SNR values will be explored in Sec. 5. To comply with ASTM E1130, at least one of the reported values for AI (and thus PI) has to be calculated with the given source reference SPL for "normal" vocal effort. This means that the weighted sum $\mathbf{w}_{\mathrm{AI}}^{T}\mathbf{L}_S$ in Eq. (5) is a constant, giving for the PI the following expression:

$$\mathrm{PI} = 100 - 100 \cdot \mathbf{w}_{\mathrm{AI}}^{T}\mathbf{L}_S + 100 \cdot \mathbf{w}_{\mathrm{AI}}^{T}(\mathbf{LD} + \mathbf{L}_N) \tag{6}$$

$$= 100 \cdot \mathbf{w}_{\mathrm{AI}}^{T}(\mathbf{LD} + \mathbf{L}_N) - C, \tag{7}$$

where the constant value C depends on the chosen source reference SPL. The value for normal vocal effort is $C = 100 \cdot \mathbf{w}_{\mathrm{AI}}^{T}\mathbf{L}_{S,\mathrm{normal}} = 87$.

3. SPC

The SPC was developed initially for closed office scenarios, where the SNR can be expected to be low and thus privacy is usually higher than in open-plan offices. Measurements are carried out with a loudspeaker operating inside a closed office, while the SPL is measured both inside (source SPL) and outside (receiver SPL) of that office, with the outside measurement positions made at a distance of 0.25 m from each surface considered relevant for the receiving space. From this data, the SPC is determined according to ASTM E2638 as a frequency-average of the sum of the LD, LD(f), between the source and receiver SPL and the background noise SPL $L_N(f)$ as

$$\mathrm{SPC} = \frac{1}{16}\sum_{f=160\,\mathrm{Hz}}^{5\,\mathrm{kHz}} [\mathrm{LD}(f) + L_N(f)] \tag{8}$$

$$= \mathbf{w}_{\mathrm{SPC}}^{T}(\mathbf{LD} + \mathbf{L}_N), \tag{9}$$

where the vector of frequency weights $\mathbf{w}_{\mathrm{SPC}}$ is a 16-element vector with all entries being equal to 1/16. Note that the frequency range for the SPC includes the 160 Hz third-octave band in addition to the third-octave bands from 200 Hz to 5 kHz used for the PI calculation.

4. Comparison of frequency weights and calculations for PI and SPC

Due to the fact that the weighted sums in Eqs. (7) and (9) for the PI and SPC, respectively, have different frequency weights, no exact algebraic relationship between the two metrics can be determined, e.g., by solving Eq. (9) for the common term in both equations, $\mathbf{LD} + \mathbf{L}_N$, and inserting it into Eq. (7).

However, an approximate mathematical relationship between PI and SPC can be established by analyzing the weights used in each case. As seen from Eq. (5), the weights for PI are the AI weights scaled by a factor of 100. To obtain the same result for the weighted sum, $\mathbf{w}_{\mathrm{SPC}}^T(\mathbf{LD} + \mathbf{L}_N)$ for input data that is constant across frequency, the SPC weights have to be scaled. For unit input data [i.e., $\mathrm{LD}(f) + L_N(f) = 1$ for all frequencies], the result for PI is proportional to $100 \cdot \sum \mathbf{w}_{\mathrm{AI}} = 333/100$. Compensating for the fact that the SPC weights cover an additional frequency band (16 third-octave bands from 160 Hz to 5 kHz for SPC instead of 15 third-octave bands for AI from 200 Hz to 5 kHz), the scaling factor is obtained from this value as $333/100 \cdot 16/15 = 444/125 \approx 32/9$. This establishes the following relationship between the frequency-weights:

$$100 \cdot \sum \mathbf{w}_{\mathrm{AI}} \approx \frac{32}{9} \cdot \sum \mathbf{w}_{\mathrm{SPC}} \,. \tag{10}$$

The scaled frequency-weights for both metrics are shown in Fig. 1. The relationship in Eq. (10) will be used below to determine the approximate relationship between PI and SPC.

Obviously, even with the scaled weights a difference in the two metrics may be observed because of a difference in the frequency-weighting of the data. However, the spectral shape of the background noise SPL does not vary a lot between open-plan and closed offices, and even though the attenuation provided by open-plan office furniture and closed rooms is different, the general spectral shape (more attenuation at high frequencies) is still similar. It will be shown in Sec. 6 that this leads to a clear trend when comparing the results of PI and SPC.

Using Eq. (10) and comparing Eq. (7) with Eq. (9), an approximate relationship between PI and SPC can be derived as

$$\mathrm{PI} \approx \frac{32}{9} \cdot \mathrm{SPC} - X \,. \tag{11}$$

The parameter X depends on the choice of source reference SPL for PI and, as will be shown below, it is influenced by the different frequency weights for PI and SPC. The relationship in Eq. (11) and the value of X will be analyzed in Sec. 6 by comparing PI and SPC results of field and laboratory measurements.

5. Modeling the effect of SNR limitation

As mentioned in Sec. 2, the SNR for the PI is limited for each frequency band between 0 and 30 dB. This results in a deviation from the linear relationship in Eq. (11) because of PI values that gradually approach 0 or 100 in a non-linear way as the SNR reaches the limits. When comparing the PI with the SPC, this is observed as a relationship that can be represented by a sigmoid function.

In the context of this work, the scaled and shifted error function erf(x) will be used to model PI values as a function of SPC values, including the effect of limiting

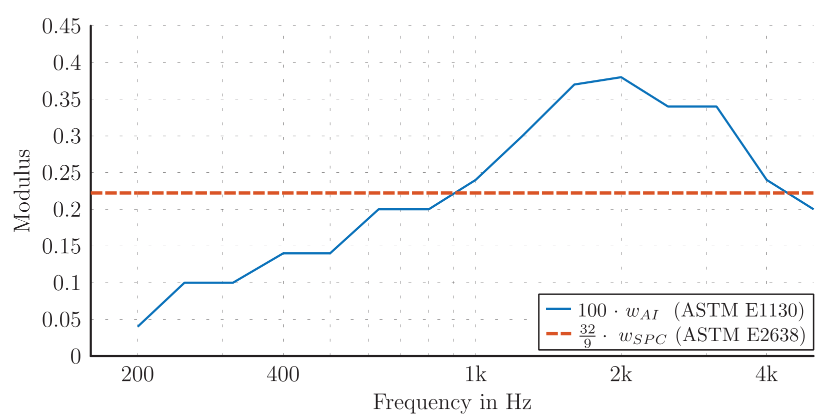

Fig. 1. (Color online) Comparison of (scaled) frequency weights for PI and SPC calculations.

the SNR. The error function belongs to the family of sigmoid functions often used to represent data sets where saturation or limitation of the values occurs. In previous works, the logistic function (also referred to as Boltzmann function, see, e.g., Ref. 3) has been used, but the error function is a better representation in the critical range of SNR values where the SNR limitation begins to have an effect.

Values of the error function range from −1 to 1, and the mid-point (a value of 0) occurs at $x = 0$. Hence, for the application in the context of PI values, the error function was scaled to cover the range from 0 to 100 and a shift parameter SPC_0 was introduced to align the mid-point of the PI (i.e., PI = 50) with the corresponding SPC value. Including the scale and shift of the error function leads to the following model function to relate PI values to SPC values:

$$\mathrm{PI(SPC)} = 100 \cdot \left[0.5 + 0.5 \cdot \mathrm{erf}\left(\frac{\sqrt{\pi}}{100} \cdot k \cdot (\mathrm{SPC{-}SPC_0})\right)\right]. \tag{12}$$

The value of SPC_0 will be determined in Sec. 6 during the validation with the measured data. The scaling of $\sqrt{\pi}/100$ in Eq. (12) ensures that the slope of the model function at the mid-point is equal to k. From Eq. (11) the theoretical value is $k = 32/9$. The goodness of fit of the model function in Eq. (12) to experimental data will be analyzed in Secs. 6.1 and 6.2.

6. Validation with field and laboratory measurements

In this section, results of extensive field and laboratory measurements will be used to validate the relationship between PI and SPC described above. The field measurements were made in open-plan offices in a total of 24 buildings in North America, yielding almost 1300 data sets.[8] All measurements were carried out with a calibrated sound source and fulfilled all requirements of ASTM E1130. The laboratory measurements to represent closed offices were performed under controlled conditions at the National Research Council Canada. In the laboratory, measurements were carried out for a number of different partition types and with artificially created background noise of varying SPL, giving an additional 500 data sets for scenarios of high speech privacy. All laboratory measurements were carried out according to ASTM E2638.

For the 1800 combined data sets for open-plan and closed offices the raw data for **LD** and background noise SPL $\mathbf{L}_N$ as a function of frequency was extracted so that both PI as well as SPC could be calculated for further analysis. In the following, all values presented for PI have been calculated with the source reference SPL for normal vocal effort according to ASTM E1130.

6.1 Determining the parameters for the sigmoid model function

As was mentioned in Sec. 5, the sigmoid model function in Eq. (12) depends on two parameters: the shift value SPC_0 for the mid-point and the slope k at the mid-point. In this section, the slope parameter is determined to best represent the influence of the limitation of the SNR values for the PI. To focus solely on the SNR limitation, the difference in the frequency-weights between PI and SPC was eliminated by re-calculating the SPC values based on the raw measurement data for **LD** and $\mathbf{L}_N$, where the weights $\mathbf{w}_{\mathrm{SPC}}$ in Eq. (9) were replaced according to the relationship in Eq. (10) as $\mathbf{w}_{\mathrm{SPC}} \approx 100 \cdot 9/32 \cdot \mathbf{w}_{\mathrm{AI}}$.

To determine the slope parameter, the theoretical value for the shift parameter SPC_0 was determined for the mid-point of the PI (PI = 50) according to Eq. (11) (with $X = 87$) as $\mathrm{SPC}_0 = (50 + 87) \cdot 9/32 = 38.5$ [compare Eqs. (7) and (9) for equal weights and normal source reference SPL]. This value of SPC_0 was kept fixed and the parameter k was varied, starting with the theoretical value of $32/9 \approx 3.56$. The optimized value was determined as $k = 3.75$, which is only 5% higher than the theoretical value. This optimized value for k was found to best represent the effect of the SNR limitation at low and high values of the SNR (squared correlation value for all data sets of $R^2 = 0.998$) and it will be used for all further analysis in Sec. 6.2.

6.2 Comparison to measured data

In this section, the linear [Eq. (11)] and sigmoid [Eq. (12)] model functions, which relate PI and SPC values, will be validated with the combined 1800 datasets for open-plan and closed offices mentioned in the introduction to this section.

In Fig. 2, the results for PI are plotted against the SPC values. Both metrics have been determined from the raw measured data for **LD** and $\mathbf{L}_N$ according to the respective ASTM standard. The field data for open-plan offices is represented by circles and the laboratory data for closed offices is shown as squares.

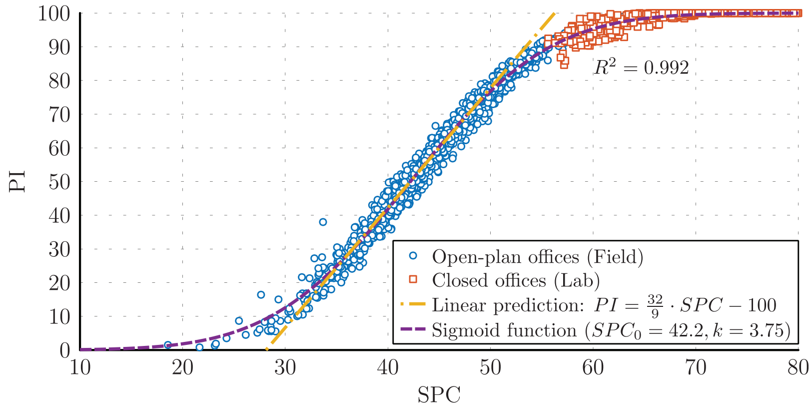

Fig. 2. (Color online) Comparison of PI and SPC values for experimental data together with linear [Eq. (11), $X = 100$] and sigmoid [Eq. (12), $\mathrm{SPC}_0 = 42.2$, $k = 3.75$] model function.

For the linear model function in Eq. (11), the offset value has been determined to be $X = 100$ by analyzing the weighted sum of $\mathbf{LD} + \mathbf{L}_N$ for the open-plan office data sets. This offset value reflects the choice of normal source reference SPL as well as the effect of the different frequency weights for PI and SPC that was mentioned in Sec. 4. With this offset value X, the linear relationship between PI and SPC becomes

$$\mathrm{PI} \approx \frac{32}{9} \cdot \mathrm{SPC} - 100\,. \qquad (13)$$

With the linear function in Eq. (13), which has additionally been plotted as a dashed-dotted line in Fig. 2, very good agreement can be observed for SPC values between 33 and 51, or PI values between 20 and 80. This covers the range of PI values typically encountered in open-plan offices.

Equation (13) can be used to establish the shift value SPC_0 that is a parameter of the sigmoid model function in Eq. (12). SPC_0 corresponds to the mid-point value $\mathrm{PI} = 50$. With an offset value of $X = 100$, Eq. (13) can be solved for the SPC value corresponding to $\mathrm{PI} = 50$ as $\mathrm{SPC}_0 = (50 + 100) \cdot 9/32 = 42.2$. The other parameter k affecting the slope of the sigmoid model function has been determined in Sec. 6.1. The optimized value of $k = 3.75$ can be used in general, as the effect of the SNR limitation is not changed by the difference in frequency-weights.

As is seen in Fig. 2, the sigmoid function with the parameter values of $\mathrm{SPC}_0 = 42.2$ and $k = 3.75$ (dashed line) achieves a very good agreement with the measured data over the entire range of PI and SPC values. The squared correlation value is $R^2 = 0.992$, meaning that the sigmoid model can account for 99.2% of the data variance. In fact, for the prediction of PI values from SPC values with the sigmoid function, about 80% of the results give deviations of less than ± 2.5 points, and more than 95% of the predicted values yield deviations of less than ± 5 points.

With the parameter values determined above, the final equation for the PI as a function of SPC is

$$\mathrm{PI}(\mathrm{SPC}) \approx 50 + 50 \cdot \mathrm{erf}\left(\frac{6.65}{100} \cdot \mathrm{SPC} - 2.8\right), \qquad (14)$$

or for the inverse relationship using the inverse error function erf^{-1},

$$\mathrm{SPC}(\mathrm{PI}) \approx \frac{100}{6.65} \cdot \mathrm{erf}^{-1}\left(\frac{\mathrm{PI}}{50} - 1\right) + 42.2\,. \qquad (15)$$

Given the good agreement of the sigmoid model function with a total of 1800 measured data sets, it can be confidently said that there is a clear relationship between PI and SPC and that hence, in principle, both metrics can be used to assess speech privacy as long as the same type of measured data are available.

It has to be mentioned at this point that the data for open-plan offices used for the validation was all acquired in North American offices. The model functions presented here, which have shown very good agreement with the data, are hence only valid for the type of office furniture typically used in North America and comparisons to measurements made in other parts of the world remain to be carried out in the future to establish the general applicability.

Table 1. Table of recommended PI values (ASTM E1130) and SPC values (ASTM E2638) for speech privacy in open-plan and closed offices, respectively, together with the converted SPC and PI values according to Eqs. (15) and (14), respectively. Original values from the standards are underlined.

Level of Speech Privacy	PI	SPC	Open-plan/closed	Reference
Normal	80–95	51–60	Open-plan	E1130
Confidential	95–100	>60	Open-plan	E1130
Minimal	100	70	Closed	E2638
Standard	100	75	Closed	E2638

As a first application of the relationship established in this paper, Table 1 lists recommended values of PI for open-office speech privacy as mentioned in Appendix X2 of ASTM E1130 and the converted SPC values according to Eq. (15). In addition, the recommended SPC values for speech privacy in closed rooms from Appendix X2 of ASTM E2638 with the converted values for PI according to Eq. (14) are listed.

7. Conclusion

The calculation of the PI and SPC has been reviewed and compared. It has been shown, both mathematically as well as through comparisons with empirical data, that a clear relationship between the two metrics exists.

The linear function to relate PI values to SPC values [Eq. (13)] was found to give a very good agreement in the range of PI values between 20 and 80, or SPC values between 33 and 51. This is the range of values typically encountered in open-plan offices and hence a simple relationship, which can easily be inverted, is applicable in these cases.

For the higher SPC and PI values usually measured in closed offices, the sigmoid function [Eq. (14) and its inverse in Eq. (15)] can be used to relate the two metrics with a high degree of accuracy. It should be noted that the sigmoid model function is applicable in both types of office scenarios, open-plan and closed.

The relationship between PI and SPC shows that fundamentally both metrics are useful for assessing speech privacy in offices. Especially for open-plan office scenarios with low to medium speech privacy, both metrics can be employed as the PI and SPC are linked by a simple linear relationship. The fact that the PI and SPC are closely related does of course not negate the problem of PI values being saturated in situations where speech privacy is relatively high. This suggests that only the SPC can be used in closed offices, whereas both PI and SPC can be used in open-plan offices.

The results presented in this paper may help to harmonize acceptable values for the two metrics so that the change from open-plan to closed offices does not yield contradicting recommendations.

Acknowledgments

The authors gratefully acknowledge the support by Chantal Arsenault who provided the raw field measurement data. The original research (GreenPOE study) from which the field data were taken was generously supported by the National Research Council Canada; the Natural Resources Canada Program of Energy Research and Development (PERD); the Public Works and Government Services Canada; the governments of Alberta, Manitoba, Nova Scotia, New Brunswick, Ontario, and Saskatchewan; BC Hydro; the Fonds en efficacité énergétique de Gaz Métro; Haworth; the Jim H. McClung Lighting Research Foundation, Inc.; and the University of Idaho—Integrated Design Lab.

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