Measurement uncertainty and unicity of acoustic single number quantities in open-plan offices

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Abstract
The ISO 3382-3 standard defines indicators of the propagation of speech (spatial decay - D_{2S}, level at 4 m - L_{pAS4m} and comfort distance – r_C) and that of its intelligibility (distraction distance – r_D) to assess the acoustic quality of open plan offices. However, it has the limitation of not dealing with measurement uncertainties. This is one of the reasons for the recent revision of the standard. The objective of this work is to evaluate these uncertainties using numerical simulations based on a stochastic approach. This paper describes the simulated offices and the Monte-Carlo approach to take into account both the positioning error of the instrumentation and its measurement uncertainties. Finally, the estimated uncertainties is compared to the literature and the implications for the standard of the conclusions are highlighted.

Keywords: ISO 3382-3; Measurement uncertainty; Room acoustics; Open-plan office.

1 Introduction

Noise constitutes a major source of annoyance in open-plan offices. Among all noise sources in this type of work environment, conversational noise is the most detrimental, especially when speech is intelligible [1]. Therefore, the question of the propagation of speech noise is a major aspect of the acoustic quality of open-plan offices. The ability of an office (including layout and furnishings) to limit this propagation of speech is estimated according to the ISO 3382-3 measurement standard [2]. This estimation is made thanks to single number quantities (SNQs) which consist in the aggregation of octave band values from 125 Hz to 8 kHz. The ISO 3382-3 standard defines SNQs reflecting two different philosophies with regard to the acoustic quality of open-plan offices. The first one is based on the description of the spatial decay of the A-weighted sound pressure level (SPL) of a signal presenting a speech spectrum, while the second approach focuses on the spatial decay of speech intelligibility. Four SNQs are defined:

- The decrease of the A-weighted SPL of speech by doubling the distance to the source: D_{2S},
- The A-weighted SPL of speech at a distance of 4 m from the source: L_{pAS4m},
- The distance from the source where the A-weighted SPL of speech falls below 45 dB(A), called distraction distance and noted r_C,
- The distance from the source at which the intelligibility of speech is sufficiently low that speech is not a source of annoyance. This corresponds to the distance, noted r_D, where the STI falls below 0.5.

In the field, the measurement procedure consists in measuring the SPL along a virtual line from one workstation to another. This measurement path must be as straight as possible, but small deviations are allowed if the configuration of the workplace does not allow drawing a perfect line. During the measurement, an omnidirectional loudspeaker is placed at one end of the path. The distance from the source and the speech level or the STI, depending on the measured SNQ, are measured at each workstation along the path. D_{2S}, L_{pAS4m} and r_C are derived from the linear regression of the A-weighted SPL of speech as a function of the base-2 logarithm of the distance to the source, while the distraction distance r_D is derived from the linear regression of the STI as a function of the distance to the source (see Figure 1).

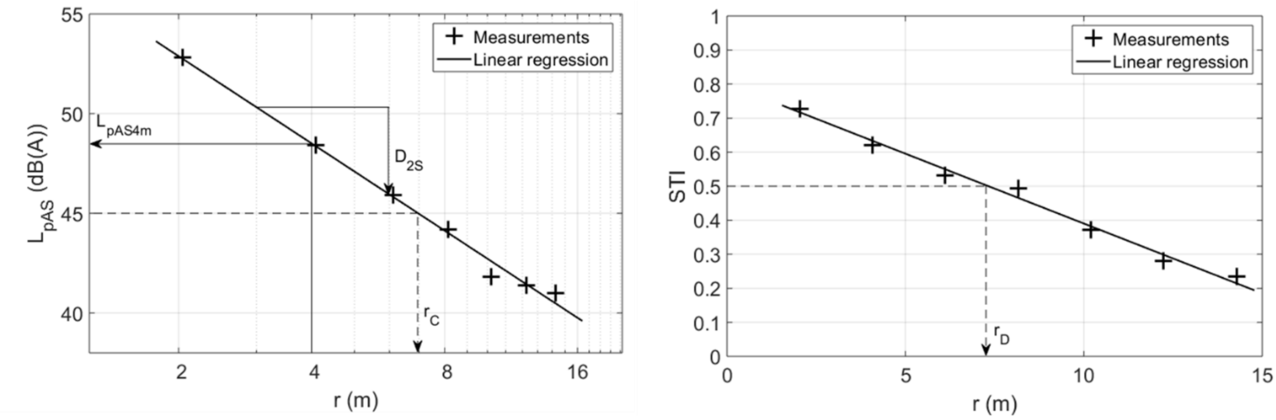

Figure 1 – Evaluation of the SNQs according to ISO 3382-3 standard.

The current version of the ISO 3382-3 standard is undergoing revision and does not mention measurement uncertainties, an essential aspect of the evaluation. The lack of consideration of measurement uncertainties makes it impossible to assess the relevance of target values set by national and international standards.

Very few studies in the literature address the issue of the measurement uncertainties of the SNQs recommended in ISO 3382-3. Haapakangas et al. [3], who studied the relation between various quantities and the perceived disturbance by noise, reported that the measurement uncertainties of D_{2S} and L_{pAS4m} are 1 dB(A) and 1.5 dB(A), respectively. These values are based on ‘‘the experience and unpublished data of the authors”. Later, Yadav and colleagues [4] conducted an experimental study of the repeatability of the metrics of ISO 3382-3. Based on 36 measurements, the study concluded that the measurement uncertainty of D_{2S} and L_{pAS4m} are 0.6 dB(A) and 1.0 dB(A), respectively. Hongisto et al. [5] conducted a round-robin test, evaluating the reproducibility of the metrics of ISO 3382-3 (2012). The test took part in an office of rather low acoustic quality (D_{2S}, L_{pAS4m} and r_C of about 3.8 dB (A), 52.5 dB(A) and 17 m). For a single measurement path, the obtained measurement uncertainty ranged from 0.2 to 0.5 dB(A) for D_{2S}, from 0.9 to 1.3 for L_{pAS4m} and from 2.4 to 5.5 m for r_C. Finally, Schneider et al. [6] estimated the measurement uncertainties of D_{2S} and L_{pAS4m} by applying a Monte-Carlo approach on 44 measurements realized in 17 offices of various acoustic quality (D_{2S} between 3.0 and 8.8 dB(A) and L_{pAS4m} between 43.5 and 54.9 dB(A)). The authors reported an uncertainty ranging from 0.6 to 0.7 dB(A) for D_{2S} and from 0.2 to 0.9 dB(A) for L_{pAS4m}.
The standard also lacks precision, or justification, regarding the unicity of the SNQs within an acoustic area (i.e. a space where both the ceiling and furniture design are homogeneous). The standard requires that the SNQs be evaluated on at least two measurement paths in an acoustic area. The current version of the standard requires the results of each path to be reported, while the revised version intends to report only the average SNQs measured within an acoustic area. This change is still under debate because it lacks justifications.

The aim of this study is to provide useful additional information on the SNQs, and more particularly on their measurement uncertainties and their unicity within acoustic areas. The study is based on simulations and a Monte-Carlo approach as recommended by the International Bureau of Weights and Measures [7].
The simulated offices and the Monte-Carlo approach will be described. Then, the estimated uncertainties will be compared to the literature and the implications of the conclusions for the standard will be highlighted.

2 Methods

2.1 The simulations

The simulations used for this study were performed using the RayPlus v8.1.0 software. This software is based on a ray tracing method. It takes into account reflections by surfaces, the transmission loss of partitions and diffractions by edges [8]–[10]. Results are given in octave bands between 125 Hz and 8000 Hz. For the simulations presented hereafter, the receivers (microphones) are spherical cells 5 cm in diameter and, in order to obtain the convergence of the calculated levels to within less than 0.1 dB, 10 million rays are traced for each source.
The office designed for the simulations has a simple geometrical layout and is intended to be representative of call centres. In this type of office, people have a predominantly individual activity, mainly on the phone. They do not need to communicate with each other. This is why the layout is homogeneous with partitions installed between the workstations facing each other. The office is 13.6 m by 8.5 m and accommodates 32 workstations. The workstations are laid out in four rows separated by a 2 m wide centre aisle (see Figure 2). The two sidewalls present windows along their entire length. The office constitutes a single acoustic area, according to the ISO 3382-3 standard, since both the acoustic treatment and the layout are similar throughout the office. The layout of the office suggests four straightforward measurement paths, numbered from P1 to P4 on Figure 2.

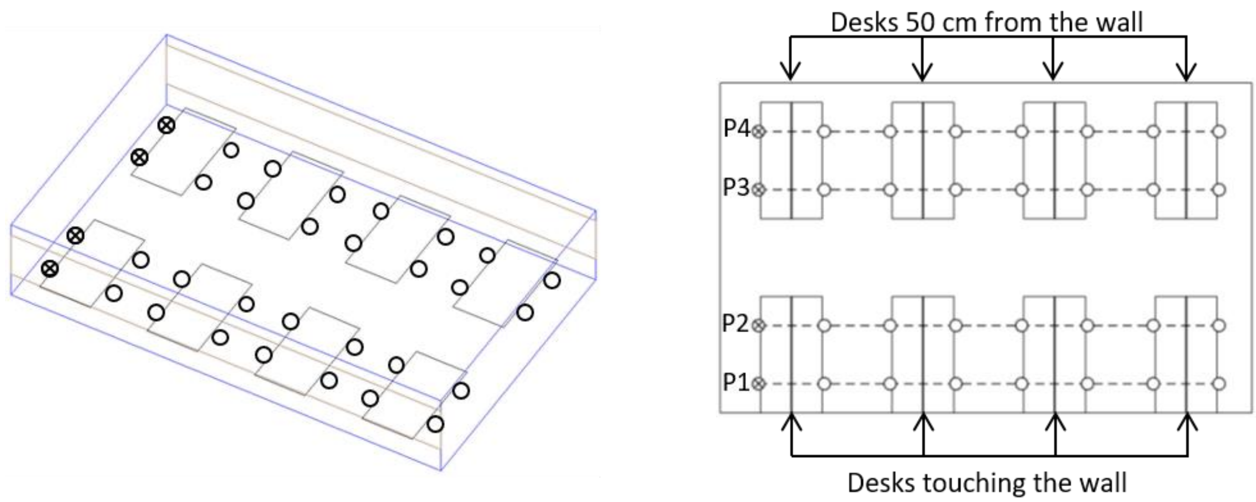

Figure 2 – Layout of the simulated office with 32 workstations and the four measurement paths (dashed lines) numbered from P1 to P4. (Circles: microphones, Crossed circles: sources)

In the simulations, 16 furniture configurations were defined including different acoustic properties of the ceiling, different heights and acoustic properties of the screens. For the ceiling, two classes of material were considered: class A ($\alpha_w \geq 0.9$) and class C ($0.6 \leq \alpha_w \leq 0.9$) according to the ISO 11654 (1997) standard [11]. The screen height was set to four different values: 190 cm, 150 cm, 130 cm and 110 cm.

2.2 The Monte-Carlo approach

The Monte-Carlo methods takes into account both positioning error of the apparatus and the uncertainties intrinsic to the measuring instruments. The calculation process is represented on Figure 2.

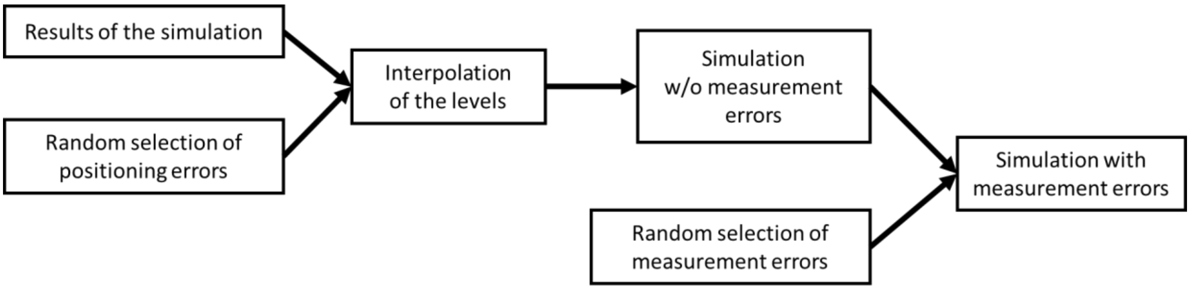

Figure 3 – Process of the Monte-Carlo approach.

To enable the emulation of the positioning errors, nine positions of the apparatus were defined at each workstation within the simulation. The nine positions were set on a 3-by-3 20-cm wide square horizontal grid centred on the position of the workstation (head of the person). The simulations compute octave-band SPL for each pair of source and microphone of every measurement position.

The first step of the Monte-Carlo process consists in randomly selecting the positioning error of each measurement device. This error follows a bivariate normal distribution so that the instrumentation is positioned, in 95% of the cases, in a 20-cm square centred on the theoretical position. The levels estimated for the selected positions of the source and microphones are interpolated from the results of the simulations.

The second step of the process consists in randomly selecting the measurement error of the apparatus. The distance measurement error follows a normal distribution whose standard deviation is equal to 0.05 m (95% of the distance measurement errors are less than 0.1 m). The measurement error of octave-band SPL follows a uniform law in the interval $[-u_{oct}\sqrt{3}, u_{oct}\sqrt{3}]$, where u_{oct} are derived from the Class 1 sound level meters specifications of the IEC 61672-1 (2003) standard (see Table 1). Lastly, the evaluation of the STI also require the measurement of the reverberation time, whose measurement uncertainty is described in the ISO 3382-2 standard. Therefore, the measurement error of the reverberation time follows a uniform law on an interval defined by this standard.

Table 1 – Measurement uncertainty of octave-band SPLs derived from the IEC 61672-1 (2003) standard.

fc (Hz)	125	250	500	1000	2000	4000	8000
u_{oct} (dB)	1.3	1.3	1.2	1.2	1.3	1.7	2.6

The process emulate errors for a single measurement. Therefore, it is repeated several times in order to provide the measurement uncertainties. The number of repetitions was gradually increased until convergence of the results, i.e. until the magnitude of the uncertainties estimated by two consecutive runs were within 0.01 dB for D_{2S} and L_{pAS4m} and within 0.01 m for r_C and r_D. This criterion was fulfilled with 10,000 repetitions.

3 Results

The simulations are representative of a wide variety of acoustic qualities since the mean values of the SNQs from the simulations spans:

- From 3.4 to 7.5 dB(A) for D_{2S},
- From 40.6 to 51.9 dB(A) for L_{pAS4m},
- From 2.5 to 14.7 m for r_C,
- From 3.4 to 14 m for r_D.

3.1 Measurement uncertainties

The mean values of the SNQs, together with the 95% confidence intervals, are represented Figure 3. For D_{2S}, the measurement uncertainty is equal to 0.4 dB(A). The measurement uncertainty of L_{pAS4m} varies between 0.4 and 0.6 dB(A). Those of r_C and r_D range respectively from 0.2 to 1.5 m and from 0.2 to 0.9 m.

Due to the fact that the values reported by Haapakangas and colleagues [3] are derived from unpublished data, the only possible comment is that the order of magnitude are similar even if our are about half of those reported by Haapakangas *et al*.
Yadav and colleagues [4] performed measurements on 36 paths distributed in 21 offices. The measurement paths were composed of 5 to 8 workstations. For each of the paths, the authors performed two measurements of the SNQs and the reported uncertainties (0.61 dB(A) for D_{2S} and 1.04 dB(A) for L_{pAS4m}) are extracted from these measurement. The measured SNQs ranged from 3.2 and 8.5 dB(A) for D_{2S} and from 46.1 to 55.6 dB(A) for L_{pAS4m}. The simulations gave values very close to those reported by Yadav et al.. For L_{pAS4m}, the results of the simulations are about half of the uncertainty reported by the authors.
Hongisto and colleagues [5] performed a round-robin test on two measurement paths in an office with two configurations (the height of the acoustic screens was adjustable). For both configurations, the SNQs measured were about 3.8 dB(A), 52.5 dB(A), 17 m and 15 m respectively for D_{2S}, L_{pAS4m}, r_C and r_D. These values correspond in our study to the configuration with 110-cm-high class C screens and class C ceiling. In this configuration, the simulations gave an uncertainty of 0.4 dB(A) for D_{2S}, 0.4 for L_{pAS4m}, between 0.7 and 1.5 m for r_C and between 0.7 and 1.0 m for r_D. Hongisto *et al.* reported un uncertainty varying between 0.2 and 0.5 dB(A) for D_{2S}, between 0.9 and 1.3 dB(A) for L_{pAS4m}, from 2.4 to 5.5 m for r_C and from 1.2 to 2.7 m for r_D. Therefore, the results of the simulations are similar to those reported by Hongisto *et al*. but the uncertainty of L_{pAS4m}, r_C and r_D estimated by the simulations are about half of those obtained with the round robin test.
Schneider and colleagues [6] estimated the uncertainty of D_{2S} and L_{pAS4m} on 44 paths composed of 4 to 6 measurement points. They report magnitudes ranging from 0.6 to 0.7 dB(A) for D_{2S} and from 0.2 to 0.9 dB(A) for L_{pAS4m}. Those results are slightly higher than those of the present study.

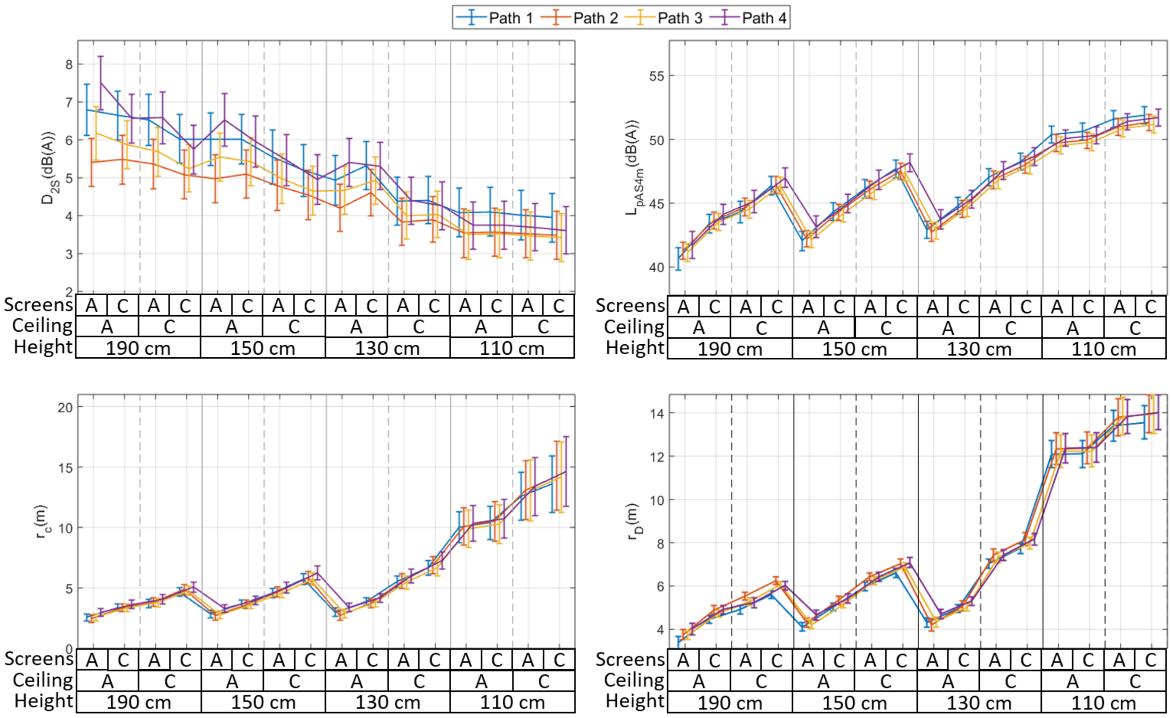

Figure 4 – Mean values and 95% confidence interval of the SNQs of ISO 3382-3 for the four measurement paths in each of the 16 acoustic configurations

This overall underestimation of the measurement uncertainties may be explained by the fact that the measurement uncertainties of the SNQs are highly dependent on the number of measurement points used for their evaluation. Furthermore, the measurement uncertainties might depend on the layout of the office.

3.2 Unicity of the SNQs

The revision of the ISO 3382-3 standard raised the question of the description of an office using a unique value of the SNQs. The simulations enable to explore this question. If the office is described by a unique value, the mean values and confidence intervals of the SNQs must be evaluated without differentiating the measurement paths. Figure 4 shows the mean value and 95% confidence interval for each SNQ considering that it is possible to describe an entire office with a unique value. On this figure, it appears that the consideration of a unique value of L_{pAS4m}, r_C and r_D does not have any major consequences. However, it seems that D_{2S} loses its discriminatory nature in the process: the measurement uncertainty of the unique value of D_{2S} ranges from 0.4 to 0.9 dB(A) which corresponds to a 95% confidence interval of up to ±1.8 dB(A).
It seems therefore problematic to consider that an office is described by a unique value of D_{2S} that is independent for the measurement path.

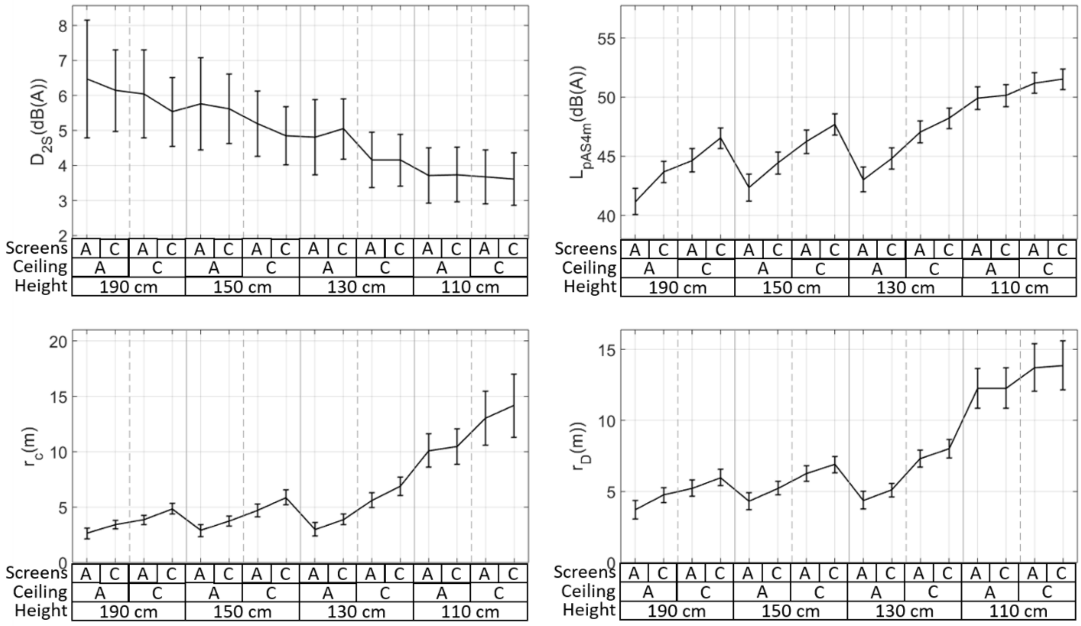

Figure 5 – Mean values and 95% confidence interval for each of the 16 acoustic configurations considering that the office is described by a unique value for each SNQ.

4 Conclusions

This study investigated the measurement uncertainties of the SNQs defined in the ISO 3382-3 standard (and in its revised version), namely D_{2S}, L_{pAS4m}, r_C and r_D. This analysis relies on simulations based on a stochastic approach. The office was representative of a wide range of acoustic qualities.
The estimated uncertainties were of the same order of magnitudes as the values presented in the literature even if an underestimation is to be noted in some cases. This can be explained by two observations: firstly, the uncertainty of the SNQs is greatly dependent on the number of measurement points used for their evaluation and secondly that it might depends on the layout of the office.

The magnitude of the measurement uncertainties confirms the ability of the SNQs to differentiate offices of various acoustic qualities.
However, concerning the question of the description of an office using a unique value of the SNQs, the simulations seems to highlight an issue with respect to D_{2S}. Indeed, it seems that describing an office with a unique value of D_{2S} makes it impossible to differentiate different office acoustic qualities based on the measure of D_{2S}.

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