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Acoustical capacity as a means of noise control in eating establishments

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Noise from many people speaking in eating establishments and other social gatherings is a well known and wide spread problem. The problem is particularly difficult to handle because the sound sources are individual and dynamic, i.e. the speech level increases when the ambient noise level goes up. However, a simple prediction model has been derived that allows estimating the ambient noise due to speech from a large group of people, the main uncertainty being the so-called group size, i.e. the average number of people per speaking person. As a measure of the acoustical quality is suggested the average signal-to-noise ratio when listening to a person speaking to you in a distance of 1 m and the ambient noise is that from other people speaking in the room. The Acoustical Capacity is defined as the number of people that would create a signal-to-noise ratio of -3 dB, which is considered the lower limit for “sufficient” quality of verbal communication under certain preconditions. The Acoustical Capacity is calculated from volume and reverberation time by a very simple equation. The acoustical quality of an eating establishment may be characterized by the ratio between the Acoustical Capacity and the total capacity.

1 Introduction

Noise from people speaking in restaurants and at social gatherings in closed environments is often a nuisance because it can be very loud, and a conversation may only be possible with a raised voice level and at a close distance. Because of the noise and the difficulties associated with a conversation the visitors may leave the place with a feeling of exhaustion, and people using hearing aids may find that verbal communication is impossible.

This is a well known and wide spread acoustical problem, but although a lot of research has been made, very little has been done to find solutions. A good overview of research on verbal communication in noise from speech is found in [1].

In many countries there is a growing awareness of the concept called universal design, which means accessibility for all in public buildings, and this is not limited to the physical access but includes also that the acoustical conditions should be suitable for the use of the building. Recently an investigation was made in Norway with the aim to throw some light on the problems due to the acoustical conditions in various kinds of rooms and spaces for people with reduced hearing or sight abilities [2]. It was found that particularly in canteens, restaurants and cafés the acoustical problems were very pronounced. In this kind of rooms 52% of the hearing impaired people were severely or much disturbed by the noise conditions, and 88% had difficulties with verbal communication, always or from time to time. The corresponding numbers for the other group of people with reduced sight abilities (and assumed normal hearing) were 13% and 51%, respectively.

2 METHOD

2.1 Vocal effort and the Lombard effect

The vocal effort is characterised by the equivalent continuous A-weighted sound pressure level of the direct sound in front of a speaker in a distance of 1 m from the mouth. A description of the vocal effort in steps of 6 dB is given in ISO 9921 [3], see Table 1. Thus normal vocal effort corresponds to a sound pressure level around 60 dB in the distance of 1 m. Speech at levels above 75 dB may be more difficult to understand than speech at lower vocal effort.

Table 1: Description of vocal effort at various speech levels, after ISO 9921 [3].

$L_{S,A,\,1m}$ dB	Vocal effort
54	Relaxed
60	Normal
66	Raised
72	Loud
78	Very loud

It is a well known phenomenon that many people speaking in a room can create a high sound level, because the ambient noise from the other persons speaking means that everyone raises the voice, which again leads to a higher ambient noise level. This effect is called the Lombard effect after the French otolaryngologist Étienne Lombard (1869 – 1920), who as early as 1909 was the first to observe and report that persons with normal hearing raised their voice when subjected to noise. The average relationship between speech level and ambient noise level is summarised in ISO 9921 [3].

The increase of the speech level as a function of the A-weighted ambient noise level is described by the rate *c* (the Lombard slope). Lazarus [4] made a review of a large number of investigations, and he found that the Lombard slope could vary in the range *c* = 0.5 to 0.7 dB/dB. The Lombard effect was found to start at an ambient noise level around 45 dB and a speech level of 55 dB. Assuming a linear relationship for noise levels above 45 dB, the speech level can be expressed in the equation:

$$L_{S,A,1m} = 55 + c \cdot (L_{N,A} - 45), \quad \text{(dB)} \tag{1}$$

where $L_{N,A}$ is the ambient noise level and *c* is the Lombard slope. The valid range for this relationship is limited to speech levels above 55 dB or noise levels above 45 dB.

2.2 Simplified theoretical model

Applying simple assumptions concerning sound radiation and a diffuse sound field in the room a calculation model for the ambient noise level was derived in [5]. By comparison with several independent cases of measured data covering a wide range of number of individuals present (ca. 50 – 540), it was found that only the Lombard slope *c* = 0.5 could make a reasonable agreement with the measured data. The same slope was found already in 1962 by Webster & Klumpp [6] and again by Gardner [7] in several cases including dining rooms and three cases of social-hour type of assembly, studying a wide range of number of individuals present in each facility.

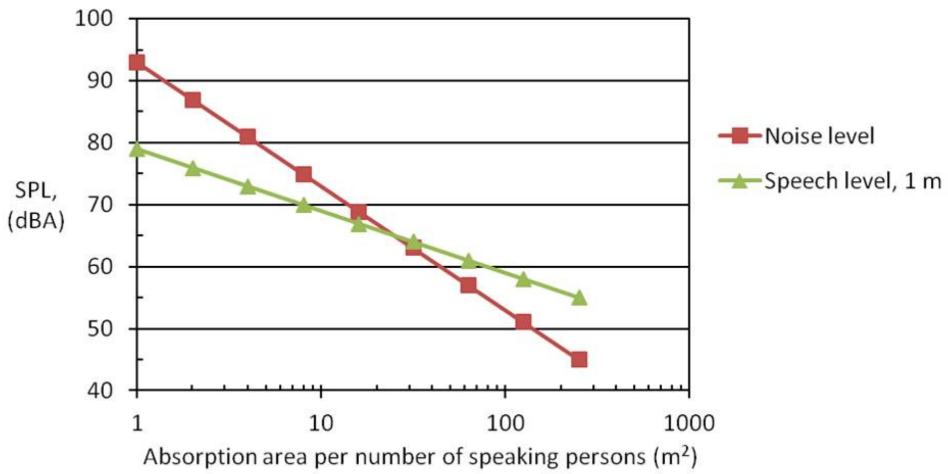

Figure 1: Ambient noise level and assumed speech level as functions of the absorption area per speaking person.

The suggested prediction model can be expressed in the equation:

$$L_{N,A} = 93 - 20\log\left(\frac{A}{N_S}\right) = 93 - 20\log\left(\frac{A \cdot g}{N}\right), \text{ (dB)} \tag{2}$$

where A is the equivalent absorption area (in m^2) of the room and N_S is the number of simultaneously speaking persons. Fig. 1 shows both the ambient noise level and the speech level as functions of the absorption area per speaking person. However, in general only the total number of people N present in the room is known, and thus it is convenient to introduce the group size, defined as the average number of people per speaking person, $g = N / N_S$.

The interesting consequence of (2) is that the ambient noise level increases by 6 dB for each doubling of number of individuals present. The same result was found be Gardner [7].

If the room has the volume V (m^3), the reverberation time in unoccupied state is T (s), and assuming a diffuse sound field, the Sabine equation gives the following estimate of the equivalent absorption area including the contribution from N persons:

$$A = \frac{0{,}16 \cdot V}{T} + A_p \cdot N, \quad (\mathrm{m}^2) \tag{3}$$

where A_p is the sound absorption per person in m^2. This depends on the clothing and typical values are from 0.2 to 0.5 m^2. However, the contribution of absorption from persons has been found to be of minor importance [5].

2.3 Verification of model

The prediction model was verified by comparison with measured data for a varying number of persons between 50 and 540 in two large foot courts and in a canteen [5, 8, 9]. The most important and difficult parameter is the group size, which was found to be between 2 and 4 in these cases. However, it is obvious that in general noise from speech cannot be predicted with a high accuracy, simply because there are unknown parameters related to individual differences and how much people actually want to talk. This may depend on the type of gathering, which can be more or less lively, how well people know each other, the age of the people, the consumption of alcohol, and other social circumstances.

As a test of the suggested prediction model, ten eating establishments reported by Hodgson et al. [10] were considered. The places belong to different categories; four cafeterias, three bistros, three restaurants, and two senior residence dining rooms. As input data was used the volume, the unoccupied reverberation time at mid frequencies (500 – 1000 Hz), and the number of seats, which is assumed to equal the number of people when fully occupied. The A-weighted sound pressure level was monitored over one day of normal operation, and the highest level in the reported range was used for comparison with the prediction model.

The range of seating capacity in these cases was from 40 to 126, and the measured noise levels were from 66 dB in one dining room to 82 dB in one bistro.

Good agreement with the prediction model could be obtained by adjusting the group size, which is the unknown parameter. For the bistros, cafeterias and restaurants the average group size was found to be around 4, with a minimum value of 2.5 for the noisy bistro. The results from the two senior residence dining rooms are very different from the other cases, being characterized by a group size as high as 8, i.e. not surprisingly the conversation here is not as lively as in the other eating establishments.

2.4 Quality of verbal communication in a noisy environment

For the evaluation of acoustic quality of eating establishments it is suggested to consider the quality of verbal communication which can be related to the signal-to-noise ratio (SNR), see Lazarus [11]. Thus a SNR between 3 dB and 9 dB is characterized as “good”, and the range between 0 dB and 3 dB is called “satisfactory”. A SNR below -3 dB is characterized as “insufficient”.

A simple approach is suggested here, namely to define the signal-to-noise ratio as the level difference between the direct sound from a speaking person in a distance of 1 m and the ambient noise in the room. Thus, the SNR is the difference between the two curves shown in Fig. 1. By use of (1) and (2) the SNR can be expressed in terms of the absorption area per speaking person:

$$SNR = L_{S,A,1m} - L_{N,A} = -14 + 10\log\left(\frac{A \cdot g}{N}\right), \text{ (dB)} \tag{4}$$

This applies to A-weighted ambient noise levels between 45 dB and 85 dB, or a range of speech levels between 55 dB and 75 dB. The corresponding range of SNR is between +10 dB and -10 dB.

Table 2 shows how various labels for the quality of verbal communication relate to SNR, the corresponding speech levels and ambient noise levels. The corresponding required absorption areas per person are also calculated with assumed group sizes of 3 or 4. It follows that the quality of verbal communication is “insufficient” if SNR < -3 dB, or if the absorption area per person is less than 3-4 m^2, slightly dependent on what group size is assumed. “Satisfactory” verbal communication requires about 6-8 m^2 absorption area per person, and the double amount is required for “good” verbal communication.

Table 2: Quality of verbal communication and the relation to SNR (signal-to-noise ratio) as suggested by Lazarus [11].

Quality of verbal communication	SNR dB	$L_{S,A,1m}$ dB	L_{NA} dB	A/N m^2
Very good				
	9	56	47	(50 - 65)
Good				
	3	62	59	(12 - 16)
Satisfactory				
	0	65	65	(6 - 8)
Sufficient				
	-3	68	71	(3 - 4)
Insufficient				
	-9	74	83	(0.3 - 0.6)
Very bad				

While these considerations may be valid for normal hearing people, ISO 9921 [3] section 5.1 states that “People with a slight hearing disorder (in general the elderly) or non-native listeners require a higher signal-to-noise ratio (approximately 3 dB)”. This suggests that SNR > 0 dB should be applied to represent “sufficient” conditions for this group of people.

3 APPLICATIONS

3.1 Prediction of noise

With the suggested prediction model (2) it is possible to calculate the expected noise level from the volume, reverberation time and number of people gathered in the room. The uncertainty is mainly related to the group size, and from the cases that have been studied it appears that a group size of 3 to 4 is typical for most eating establishments and a value of g = 3.5 is recommended for the noise prediction.

The accuracy of the prediction depends on how close the assumed group size is to the actual group size. If the actual group size varies between 2.5 and 5, it means a total variation of 6 dB. This in turn means that the prediction method may have an uncertainty of ± 3 dB.

The prediction model is based on statistical conditions meaning that it should not be applied to small rooms with a capacity less than, say 50 persons. In small eating facilities like the restaurants studied in [12] the individual variations due to a very limited number of speaking people means that the uncertainty of the prediction is increased, so it may be unreliable.

Acoustical measurements were made May 2011 at the Technical University of Denmark on the occasion of the annual celebration with a lot of people dining in different rooms. Three rooms with very different acoustical conditions were monitored with sound level measurements during the evening, and the results were compared with the prediction method, see Table 3. The predicted noise levels in the three different halls are within ±1 dB of the measured noise levels. (Not published report by Dr. A.C. Gade). It should be noted, that in Hall A and Hall B the acoustically active volumes are not well defined, but have been estimated from the section of the rooms occupied by the dining people.

In cases like these where the volume is not well defined, it should be preferred to replace the simple prediction (2) by a computer simulation; this can lead to a surprisingly accurate estimate even in apparently complicated cases where a diffuse sound field cannot be assumed. Detailed information about this will be published in the near future, see [13].

Table 3: Results from measurements of noise in three dining rooms during the annual celebration at the Technical University of Denmark, May 2011.

Room	Volume	RT	No. of seats	Measured L_{Aeq}, 19:30 - 22:00	Calculated $L_{N,A}$, (g = 3.5)
	m^3	s		dB(A)	dB(A)
Hall A	2485	2,5	480	87	88
Hall B	2495	0,8	530	82	81
Hall C	1605	1,0	380	83	83

3.2 Guidelines for sufficient acoustical conditions

As suggested above the minimum absorption area per person should be 4 m^2 for sufficient acoustical quality, and preferably the double absorption area for a satisfactory quality. It would be natural that the acoustic design is based on the maximum capacity, i.e. a full restaurant; all seats occupied. In that case the amount of absorption area required for good acoustical quality is obviously very difficult to reach, especially in a room with a low ceiling and a dense location of tables and chairs. Acoustical treatment with sound absorbing ceiling is not sufficient, and it may be necessary to include parts of the walls for sound absorbing treatment. A thick carpet on the floor would also contribute to the sound absorption.

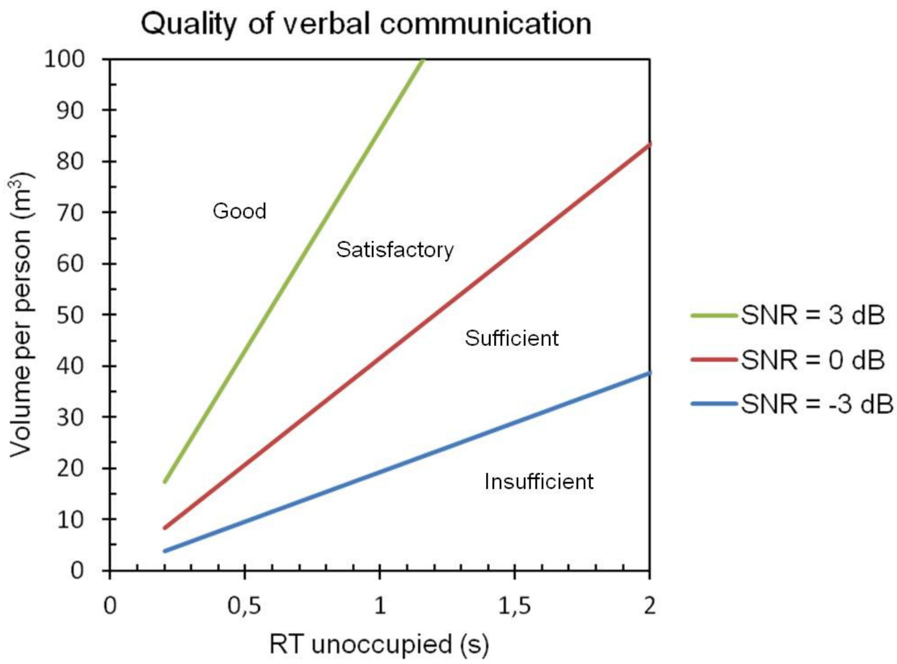

Figure 2: The minimum volume per person required for a certain quality of verbal communication as a function of the reverberation time in unoccupied state. A group size of 3.5 is assumed.

A high ceiling will help to achieve the goal, especially if parts of the walls are made sound absorbing. Figure 2 shows the influence of volume per person and reverberation time on the quality of verbal communication. It is clear, that a sufficient big volume and a short reverberation time are both very important. So, a simple rule-of-thumb for the design of eating establishments is that volume per person should be at least $T \cdot 20$ m^3, where T is the reverberation time. If the reverberation time is 0.5 s the required minimum volume per person is 10 m^3 for sufficient acoustical quality, and the double for satisfactory quality.

3.3 Recommended "Acoustical Capacity" in restaurants

The above findings can also be used for a room with known absorption area to estimate the maximum number of persons in order to keep a certain quality of verbal communication. So, it is suggested to introduce the concept of "Acoustical Capacity" for an eating facility, defined as

the maximum number of persons allowed in the room for"Sufficient" quality of verbal communication.

Sufficient quality of verbal communication requires that the SNR is better than -3 dB, or that the ambient noise level is below 71 dB, see Table 2. A simplified approximation to the results in Figure 2 yields that the number of persons in the room should be limited to:

$$N_{\max} \cong \frac{V}{20 \cdot T} \tag{5}$$

where V is the volume in m^3 and T is the reverberation time in seconds in furnished but unoccupied state at mid frequencies (500 – 1000 Hz). $N_{\max}$ is the suggested Acoustical Capacity for an eating establishment.

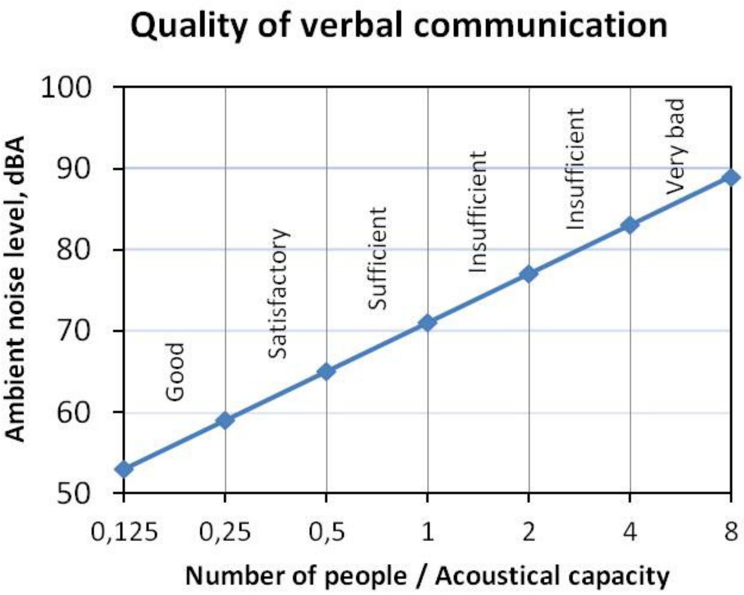

Figure 3: Ambient noise level and quality of verbal communication as functions of the number of people relative to the Acoustical Capacity.

If the number of people does not exceed the Acoustical Capacity, it is possible to have verbal communication in a distance of 1 m using a raised voice, i.e. it is possible to have a conversation across a 1 m wide table. However, when the number of people exceeds this limit, e.g. to the double, the expected ambient noise level is raised by 6 dB to around 77 dB and the SNR is decreased to -6 dB for communication in a distance of 1 m. This means that verbal communication requires a closer distance, i.e. it is still possible to have a conversation with the person sitting next to you in a distance of 0.5 m or less, but across the table it is very difficult.

The above considerations are related to normal-hearing people. Hearing-impaired people may still have problems, even when the suggested design guidelines are followed. However, with the present knowledge it is not possible to give precise guidelines that would be sufficient for the acoustical needs of hearing-impaired people in eating establishments. An example of a strengthened criterion could be if the limit for sufficient conditions for hearing impaired people is SNR

= 0 dB, i.e. 3 dB better than assumed above for normal hearing people; this corresponds to a maximum ambient noise level of 65 dB. According to the suggested prediction model this condition can be expected when the number of individuals in the facility does not exceed 0.5 times the Acoustical Capacity.

4 Discussion

Among the 16 restaurants and other eating facilities studied so far, none have good acoustical conditions when fully occupied, see Table 4. The noise problems may vary from moderate to extreme, but it must be realised that there are no easy solutions, except limiting the number of people. The Acoustical Capacity is suggested as a guideline, but all the cases have a higher total capacity; the acoustically best five of the 16 cases have a total capacity less than twice the Acoustical Capacity (shown in green colour in Table 4), whereas the remaining cases have a higher capacity and thus the potential of severe noise problems.

Table 4: 16 eating establishments, their Acoustical Capacity and the ratio between total number of seats and Acoustical Capacity. Colour code in the last column indicates a range from best (green) to worst (red).

EE	Volume	RT unocc.	No. of seats	Ac. Capacity	Ratio
	m^3	s			
C1	619	0,5	120	62	1,9
C2	412	1,0	100	21	4,9
B1	692	1,5	72	23	3,1
B2	384	1,2	46	16	2,9
B3	333	0,9	70	19	3,8
R1	176	0,9	40	10	4,1
R2	180	0,5	54	18	3,0
R3	960	0,8	126	60	2,1
S1	297	0,5	56	30	1,9
S2	1176	0,8	106	74	1,4
Food Court J	7228	1,3	350	278	1,3
Food Court L	3133	0,9	550	174	3,2
Canteen	1235	0,5	250	131	1,9
Hall A	2485	2,5	480	50	9,7
Hall B	2495	0,8	530	156	3,4
Hall C	1605	1,0	380	80	4,7

Searching for solutions to the acoustical problems in restaurants, the results from the noise prediction model are analysed from the point of view of the restaurant owner. There are three parameters to look at; volume, reverberation time and number of seats.

It is important that the volume is big, but increasing the ceiling height in an existing building is expensive and may be technically difficult. So, this is mainly a parameter to be considered for the design of new facilities.

A short reverberation time is essential, and the possibility to increase the area with efficient sound absorbing materials should be analysed together with an architect. Ceiling, walls, curtains, floor, tables, free standing screens; all surfaces should be analysed for the possibility for sound absorbing treatment. Changes may have moderate costs and can be carried through within a short time.

The possible revision of the furnishing plan for the restaurant should be considered. In stead of maximising the number of seats, which is apparently often the case, the noise problems can be efficiently reduced by changing to a less crowded seating plan. As a guideline the total number of seats should be as close as possible to the “Acoustical Capacity”, and preferably no more than twice this number. This measure is inexpensive and may be done over night.

5 Conclusion

A simple prediction model for the ambient noise due to speech in eating establishments is presented. The model takes the Lombard effect into account, and it has been verified for several test cases. The main uncertainty in the prediction model is connected to the parameter called group size which is the average number of people per speaking person. For noise predictions in typical restaurants and similar places a group size of 3.5 is recommended.

For the characterisation of the acoustical conditions the quality of verbal communication is applied, using the signal-to-noise ratio for a speaker in a distance of 1 m as an objective parameter. A signal-to-noise ratio of -3 dB is suggested as a realistic basis for design criteria. This leads to a combined requirement for the reverberation time and the volume; the reverberation time should be as short as possible, but in addition a large volume is necessary. The volume per person should be at least $T \cdot 20\ m^3$, where T is the reverberation time.

It is obvious that the acoustical problems depend strongly on the number of people present in the room. So, in addition to the design guide for the acoustical treatment of rooms, it is suggested to introduce the Acoustical Capacity of a room as a way to label, what number of persons should be accepted in the room in order to obtain sufficient quality of verbal communication. In other words, if the number of people in the room exceeds the labelled Acoustical Capacity, the ambient noise level may exceed 71 dB and the quality of verbal communication is characterised as insufficient.

For hearing impaired people and non-native speakers the acoustical needs are stronger and a better SNR is needed for an acceptable quality of verbal communication. An example of such a strengthened criterion could be that the ambient noise level may not exceed 65 dB, corresponding to a maximum of people that is only half the Acoustical Capacity of the facility. A similar strengthened criterion may be valid for non-native speakers.

References

[1] A.W. Bronkhorst, The Cocktail Party Phenomenon: A Review of Research on Speech Intelligibility in Multiple-Talker Conditions. *Acta Acustica united with Acustica* 86, 2000, 117-128.

[2] L. Knudsen, *Syns-og hørselshemmedes opplevelse av lydforhold i rom og arealer*. (In Norwegian). NIBR-notat 2011:102. Norwegian Institute for Urban and Regional Research. Oslo, Norway, 2011.

[3] ISO 9921. *Ergonomics – Assessment of speech communication*. Geneva, 2003.

[4] H. Lazarus, Prediction of Verbal Communication in Noise - A Review: Part 1. *Applied Acoustics* 19, 1986, 439-464.

[5] J.H. Rindel, Verbal communication and noise in eating establishments. *Applied Acoustics* 71, 2010, 1156-1161.

[6] J.C. Webster, R.G. Klumpp, Effects of Ambient Noise and Nearby Talkers on a Face-to-Face Communication Task. *J. Acoust. Soc. Am.* 34, 1962, 936-941.

[7] M.B. Gardner, Factors Affecting Individual and Group Levels in Verbal Communication. *J. Audio. Eng. Soc.* 19, 1971, 560-569.

[8] M.P.N. Navarro, R.L. Pimentel, Speech interference in food courts of shopping centres. *Appl. Acoustics* 68, 2007, 364-375.

[9] S.K. Tang, D.W.T. Chan, K.C. Chan, Prediction of sound-pressure level in an occupied enclosure. *J. Acoust. Soc. Am.* 101, 1997, 2990-2993.

[10] M. Hodgson, G. Steiniger, Z. Razavi, Measurement and prediction of speech and noise levels and the Lombard effect in eating establishments. *J. Acoust. Soc. Am.* 121, 2007, 2023-2033.

[11] H. Lazarus, Prediction of Verbal Communication in Noise - A Development of Generalized SIL Curves and the Quality of Communication (Part 2). *Applied Acoustics* 20, 1987, 245-261.

[12] A. Astolfi, M. Filippi, Good Acoustical Quality in Restaurants: a Compromise between Speech Intelligibility and Privacy. *Proc. of ICA*, Kyoto, Japan, 2004.

[13] J.H. Rindel, C.L. Christensen, A.C. Gade, Dynamic sound source for simulating the Lombard effect in room acoustic modeling software. *Proc. of Inter Noise*, New York, USA 2012.