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Article

Restaurant acoustics – the science behind verbal communication in eating establishments

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Featured Application: The research results may be used for the acoustical design of restaurants and other rooms for social gathering.

Abstract: A well-known but also very complicated problem in room acoustics is the ambient noise when many people are gathered for a reception or in a restaurant, a bar, a canteen or a similar place. In such social gatherings, people want to speak with each other, but for the same reason the place can be very noisy, and verbal communication can be difficult or even impossible, especially for people with reduced hearing capacity. The noise depends on at least the following parameters; the volume, the reverberation time, the number of people, and the type gathering. Verbal communication in a noisy environment is a complicated feed-back situation, which implies two interesting phenomena; the Lombard effect and the cocktail-party effect. Solutions are presented both as a simplified model assuming a diffuse sound field and as an advanced computer simulation model. The concept 'Acoustic Capacity' of a facility is introduced, defined as the maximum number of persons in order to achieve a sufficient quality of verbal communication. In order to avoid poor acoustics in restaurants and similar places, it is necessary to design with bigger volume and more absorption material than usual in current building design practice.

Keywords: Verbal communication; Lombard effect; Cocktail party effect; Noise; Acoustic capacity; Universal design

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This paper is based on a plenary paper presented at the EuroNoise 2015 conference [1], but extended and with more figures and added discussion of possible applications. The organizing committee of EuroNoise 2015 has granted copyright permission for the reuse of this material.

1. Introduction

Noise from people speaking in restaurants and at social gatherings is often a nuisance because it can be very loud, and a conversation may only be possible with a raised voice level and in a short distance. Because of the noise and the difficulties associated with a conversation, the visitors may leave the place with a feeling of exhaustion or headache. Elderly people or those with reduced hearing ability may find verbal communication impossible.

In many countries, there is a growing awareness of the concept called universal design, which means accessibility for all in public buildings [2]. This is not limited to the physical access to a building, but includes also the acoustical conditions, which should be suitable for everybody. A recent investigation in Norway had the aim to throw light on the problems due to the acoustical conditions in various kinds of rooms and spaces for people with impaired hearing or vision [3]. It was found that the acoustical problems were particularly pronounced in canteens, restaurants and cafés and 52 % of people with impaired hearing were severely or much disturbed by noise in these places. The data in Table 1 show that 51 % of the people with impaired hearing report "often/always" difficulties having a conversation in these places. If "sometimes" is included, the percentage increases

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to 88 %. For the people with impaired vision (but normal hearing) the percentage having difficulties with conversations in the same kind of places "often/always" and "sometimes" is 51 %.

Table 1. Statistics of replies to the question: How often is it difficult to have a conversation in canteens, restaurants and cafés due to noise from speech? Data from [3].

	Hearing impaired		**Visually impaired**	
	Number	Percent	Number	Percent
Often / always	129	51 %	49	23 %
Sometimes	92	37 %	59	28 %
Seldom	22	9 %	34	16 %
Never	8	3 %	70	33 %
Total	251	100 %	212	100 %
No reply	20		38	
N	271		250	

In a noisy party, everyone raises the voice to be heard better, which again leads to a higher ambient noise level. This effect is the Lombard effect. The average relationship between speech level and ambient noise level (the Lombard slope) is mentioned in International Standard ISO 9921 [4] and the possible range of the slope is given in a graph. Lazarus [5, 6] made a review of a large number of investigations, and he found that the Lombard slope could vary in the range 0.5 to 0.7 (unit dB/dB). Already in 1962 Webster & Klumpp found that the Lombard slope was 0.5 [7]. The same result was reported in 1971 by Gardner [8] based on several cases of dining rooms and social-hour type of assembly. Bronkhorst [9] made a review paper and he confirmed the Lombard slope of 0.5 with reference to a study by Lane and Tranel [10].

MacLean [11] presented in 1959 a simple formula for the signal-to-noise ratio of conversation in a party with "well-mannered guests" (only one talker at any time in each group of people). Based on this he could show that there is a maximum number of guests compatible with a quiet party. When this number is exceeded the party becomes a loud one.

Tang et al. [12] suggested a prediction model for noise in an occupied room with repeated iterations by assuming a raised voice level due to the ambient noise, which again increases due to the raised voice level. Measurements in a canteen were also reported, with number of occupants varying from very few and up to around 300 while the measured A-weighted sound pressure level (SPL) varied from 57 dB to 75 dB. They applied the absorption of 0.44 m^2 per person, but the absorption per person was found to have very little influence on the predicted noise level.

Kang [13] used a computer model and the radiosity method to predict sound pressure levels in dining spaces. A constant sound power from all speakers was assumed. A parametric study was carried out to examine the basic characteristics of conversation intelligibility in dining spaces and to study the effect of increasing sound absorption, area per person, ceiling height etc.

Navarro & Pimentel [14] reported the relationship between number of people and the measured sound pressure level due to the noise from speech in two large food courts. In one foot court the measured A-weighted SPL was up to 74 dB with around 345 people. In the other foot court with around 540 people was measured up to 80 dB. Attempts to explain the results by a simplified analytical model showed some similarities with the measured results assuming raised vocal effort and an average group size of either 2 or 4 people per talker.

Hodgson et al. [15] measured noise levels in ten eating establishments and reported A-weighted SPL between 45 dB and 82 dB. They also described an iterative model for predicting the noise levels including the Lombard effect. Using an optimization technique they found the best estimates for some unknown parameters in the model, e.g. that sound absorption per person varied between 0.1 m^2 and 1 m^2, the Lombard slope was on average 0.69, and the group size was around 3.

Astolfi & Filippi [16] reported measurements in four Italian restaurants with volumes between 99 m^3 and 191 m^3 and seating capacity between 29 and 88. Measured A-weighted SPL was between

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67 dB and 76 dB, depending on the number of persons in the restaurant. Attempts were made to evaluate speech intelligibility and speech privacy.

To & Chung [17] did measurements of noise levels in twelve Hong Kong restaurants having volumes from 455 m^3 to 12 000 m^3. They found that the main parameter for the noise level was the occupancy density, and an empirical model for the noise level was suggested. The mean values of measured A-weighted SPL were 68.9 dB, 72.7 dB and 76.5 dB for low, medium, and high occupancy density, respectively.

Rindel [18] derived a simple theoretical model for the ambient noise level taking the Lombard effect into account. The main parameters were volume per person, reverberation time and group size. By validation with measured data, he confirmed the Lombard slope of 0.5 and the group size between 3 and 4 for typical restaurants. Based on this model, Rindel suggested the acoustic capacity of a room as a simple measure of the acoustical properties [19].

de Ruiter [20] looked at the noise level as function of sound absorption per person in several eating establishments and showed good agreement with Rindel's formula [18]. He suggested the required amount of sound absorption in a restaurant to be minimum 3.5 m^2 per person.

Nielsen et al [21] investigated the relation between objective acoustic parameters and subjective evaluation of acoustical comfort in five restaurants. A very high correlation was found between the difficulty to hear and understand other guests at the table and the seating density (number of people per square meter). An equally high correlated parameter was the number of people divided by the calculated acoustic capacity of the space.

2. Speaking in noise, the Lombard effect

The vocal effort is characterized by the A-weighted SPL of the direct sound in front of a speaker in a distance of 1 m from the mouth. Vocal effort is ranged and labelled in steps of 6 dB, see Table 2. Thus normal vocal effort corresponds to a SPL around 60 dB in the distance of 1 m. Speech at very high vocal effort, i.e. levels above 75 dB, may be more difficult to understand than speech at lower vocal effort. The dynamic range of the human voice is remarkable. By shouting, the SPL can reach 84 dB to 90 dB, and in private communication (whispering or soft speech) typical levels are 35 dB to 50 dB.

Table 2. Description of vocal effort at various speech levels (A-weighted SPL in a distance of 1 m in front of the mouth). Adapted from Lazarus [5] Table 3.

$L_{SA,1m}$ dB	**Vocal effort**
36	Whispering
42	Soft
48	Relaxed
54	Relaxed, normal
60	Normal, raised
66	Raised
72	Loud
78	Very loud
84	Shouting
90	Maximal shout
96	Maximal shout (individual)

The Lombard effect is named after the French otolaryngologist Étienne Lombard (1869 – 1920), see Figure 1. He was the first one to observe and report that persons with normal hearing raised their voice when subjected to noise [22]. However, the Lombard effect is not particular for humans, but has also been found in other mammals and birds [23].

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Figure 1. Etienne Lombard (1869 – 1920). The discoverer of the Lombard effect (Photo, Paul Berger).

The Lombard effect starts at a noise level around 45 dB and a speech level of 55 dB [6, 7]. In more quiet surroundings, the vocal effort is not influenced by the ambient noise. The increase of the speech level as a function of the ambient noise level is described by the rate *c*. Assuming a linear relationship for noise levels above 45 dB, the speech level in a distance of 1 m can be expressed in the equation:

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

where $L_{\mathrm{N,A}}$ is the A-weighted SPL and *c* is the Lombard slope. The frequency spectrum of speech depends on the vocal effort [24]. As seen in Figure 2, the spectrum becomes more dominated by high frequencies when vocal effort increases.

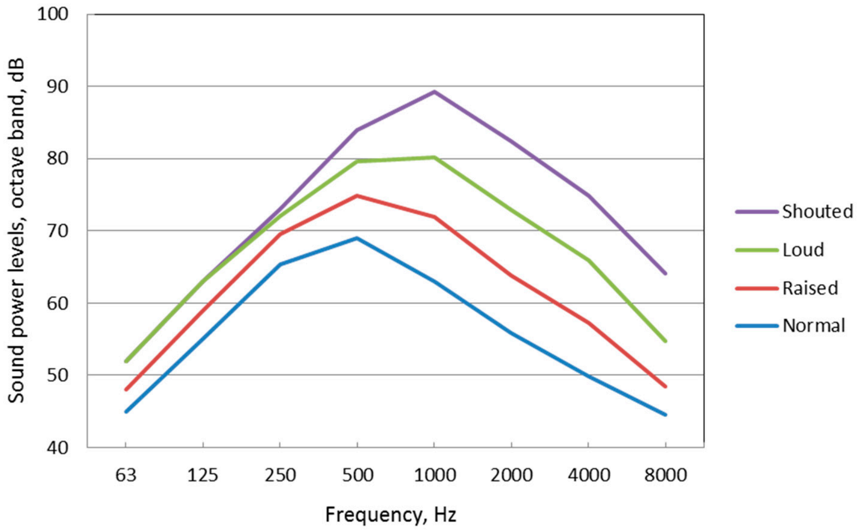

Figure 2. Speech spectra for different levels of vocal effort. Values at 250 Hz to 8 kHz are calculated from ANSI 3.5 [24]. Values at 63 Hz and 125 Hz from [27].

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3. Hearing in noise, the cocktail party effect

Listening to voices at a social gathering is a very interesting situation that challenges our hearing system. Due to the ability of a normal hearing person to localize a sound source in the surrounding 3D space, it is possible to focus on one out of many voices, and to catch what one person says, while the other voices are suppressed as background noise.

This so-called "cocktail party effect" was first reported 1953 by Cherry [25] as a result of laboratory experiments. The test subjects had two different messages applied to the two ears through headphones, and he reported no difficulty in listening to either speech at will and "rejecting" the unwanted one. The phenomenon was further analyzed by MacLean [11]. An overview of later research in the cocktail party effect is found in the review paper by Bronkhorst [9].

4. Prediction models

4.1. A simple prediction model for the speech noise level

A calculation model for the ambient noise level was derived by Rindel [13] applying simple assumptions concerning sound radiation and a diffuse sound field in the room. 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 [14, 15]. In the comparison with these data it became clear that the Lombard slope *c* had to be 0.5; this was the only value that made a reasonable good fit between the experimental data and the simple prediction model. The suggested prediction model can be expressed in the equation:

$$L_{\mathrm{N,A}} = 93 - 20\,\mathrm{lg}\left(\frac{A}{N_{\mathrm{S}}}\right) = 93 - 20\,\mathrm{lg}\left(\frac{A \cdot g}{N}\right), \text{ (dB)} \quad (2)$$

where A is the equivalent absorption area (in m^2) and N_S is the number of simultaneously speaking persons. This is shown in Figure 3. The group size g is introduced in the second equation. Since only the total number of people N present in the room is known, 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 formula 2 is that the ambient noise level increases by 6 dB for each doubling of number of individuals present. The same result was found by Gardner [8].

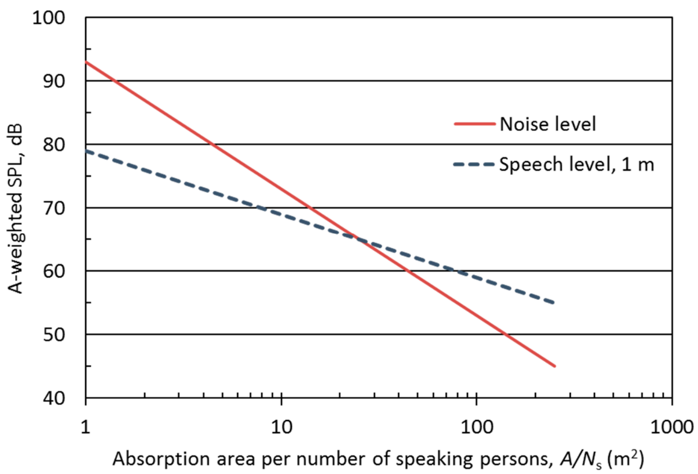

Figure 3. A-weighted SPL of ambient noise and of speech in a distance of 1 m in front of the mouth, both as functions of the sound absorption area per speaking person. (Figure courtesy of Euronoise 2015, Rindel [1]).

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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 to the absorption 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 m^2 to 0.5 m^2. The contribution of absorption from persons is negligible if the ambient noise level is sufficiently low. Below 73 dB, it follows from formula 2 that the room has a total absorption area per person around $10/g$, i.e. approximately 3 m^2 with a typical group size of 3.5. Thus, the absorption from the persons' clothing should be taken into account when the noise exceeds 73 dB.

It is obvious that noise from speech where many people are gathered 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, age of the people, consumption of alcohol, and other social circumstances.

With the suggested prediction model (formula 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 in restaurants.

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 may not apply to small rooms with a capacity less than, say 50 persons.

4.2. A prediction model for the quality of vocal communication

The quality of vocal communication is related to the signal-to-noise ratio, defined as the difference between the A-weighted SPL of the direct sound from a speaking person in a certain distance r and the ambient noise in the room. Thus, the SNR in the distance of 1 m is the difference between the two curves shown in Figure 3.

The signal-to noise ratio is not influenced by the Lombard effect, because we can assume that on average all speaking persons in the room use the same vocal effort. The increase in vocal effort due to ambient noise is the same for the speaker we are listening to and for all the other speaking persons in the room. The signal-to-noise ratio in the distance r can be calculated from the absorption area per person (A/N) and the group size g:

$$\mathrm{SNR} = L_{\mathrm{S,A}} - L_{\mathrm{N,A}} = 10\lg\left(\frac{Q \cdot A \cdot g}{16\pi \cdot r^2 \cdot N}\right), \ (\mathrm{dB}) \tag{4}$$

where Q is the directivity of a speaking person (Q = 2 is assumed in front of the mouth). This formula 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 SNR range is from – 10 dB to +10 dB.

A result very similar to Equation 4 was derived by Pierce [26] pp 276-277. He assumed that people were grouped as shown in Figure 4, and that one and only one person was speaking in each group. The distance between the groups was assumed sufficiently large, so sound from other groups could be considered in a reverberant sound field.

For the evaluation of the acoustics, we can apply the quality of verbal communication, which is related to SNR, see Lazarus [6]. Thus a SNR between 3 dB and 9 dB is characterized as "good", the range between 0 dB and 3 dB is "satisfactory", and SNR below -3 dB is "insufficient", see Table 3. It is suggested to focus on the border between sufficient and insufficient, i.e. SNR = -3 dB, as a minimum

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requirement for acoustical design of restaurants. Figure 5 shows how the SNR in a distance of 1 m depends on the volume and reverberation time, and the importance of sufficient volume per person is obvious.

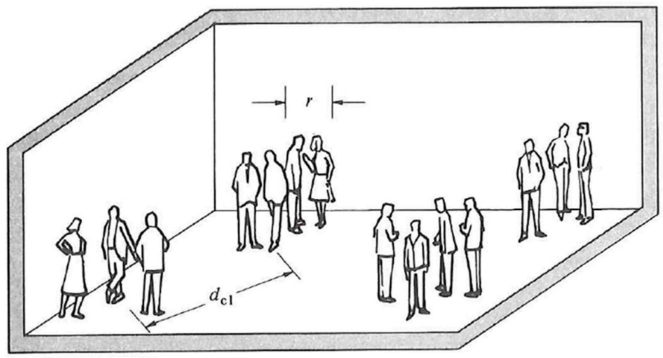

Figure 4. Social gathering. People have conversations in groups, and *r* is the distance between speaker and listener. Reproduced from A.D. Pierce: Acoustics, 1989 [26] p. 277 with permission from the Acoustical Society of America.

Table 3. Quality of verbal communication, dependent on the signal-to-noise ratio. Adapted from Lazarus [6] Table 2.

Quality of verbal communication	**SNR** dB
Very bad	< -9
Insufficient	(-9; -3)
Sufficient	(-3; 0)
Satisfactory	(0; 3)
Good	(3; 9)
Very good	> 9

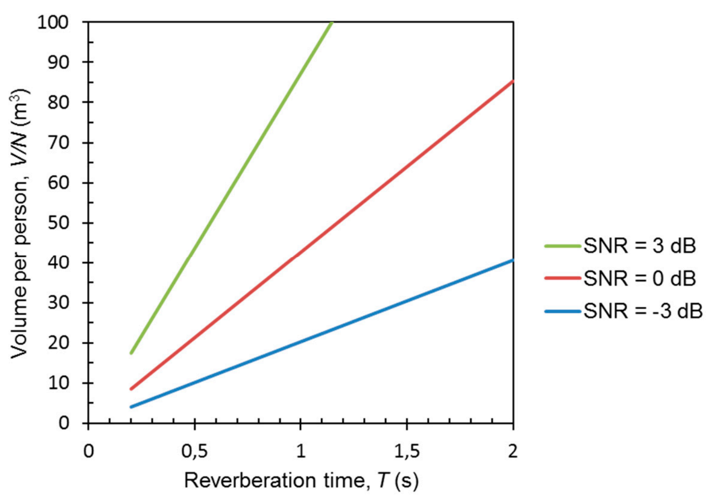

Figure 5. Quality of verbal communication as function of room volume per person and reverberation time. (Figure courtesy of Euronoise 2015, Rindel [1]).

These considerations may be valid for normal hearing people. However, ISO 9921 [4] 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 improvement is relative to that

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required for normal hearing listeners, and thus for this group of people a SNR ≥ 0 dB should be applied to represent "sufficient" conditions, and SNR ≥ 3 dB to represent "satisfactory" conditions.

The SNR and thus the quality of communication can be improved if the listener can come closer to the speaking person. Reducing the distance from 1 m to 0.7 m means a 3 dB better SNR, and coming as close as 0.5 m yields another 3 dB improvement. So, this is the obvious solution for maintaining communication in a too noisy environment, but it doesn't change the noise level.

4.3 A computer model for arbitrary spaces

In some cases the space is highly irregular and volume is not well defined. Then it may be necessary to replace the simple prediction (Formula 2) by a computer simulation. Instead of assumptions of the room volume and reverberation time, the room geometry is modelled and appropriate absorption data are assigned to the surfaces according to the materials.

The relation between the sound power level of a point source and the SPL in a receiver point is the transfer function of the room. The principle in the computer model is to calculate a transfer function from a surface source that covers the total area with speaking persons to a receiver grid covering the same area. The calculations are made in eight frequency bands from 63 Hz to 8 kHz and the surface source should have the spectrum of speech, preferably corresponding to the vocal effort that is assumed, see Figure 2. The median value of the A-weighted SPL in the receiver grid is used together with the total sound power emitted from the surface source to calculate the surface transfer function. This is the response of the room to the speech noise with the chosen location of the sources and receivers. The surface transfer function is independent of the level of sound power of the source. Assuming a certain number of people and a group size (e.g. 3.5), the ambient noise can be calculated. For further details about this method are found in [27].

5. Cases

5.1. Canteen

This case is based on measured data reported by Tang et al. [12]. The following text has previously been published in [18] and is reused with permission from Elsevier (License number 4238680339894). The noise level was measured continuously in a canteen for 2.5 h during lunch time, where the number of people increased in the first hour from nil to around 250 (Measurement A in Fig. 6).

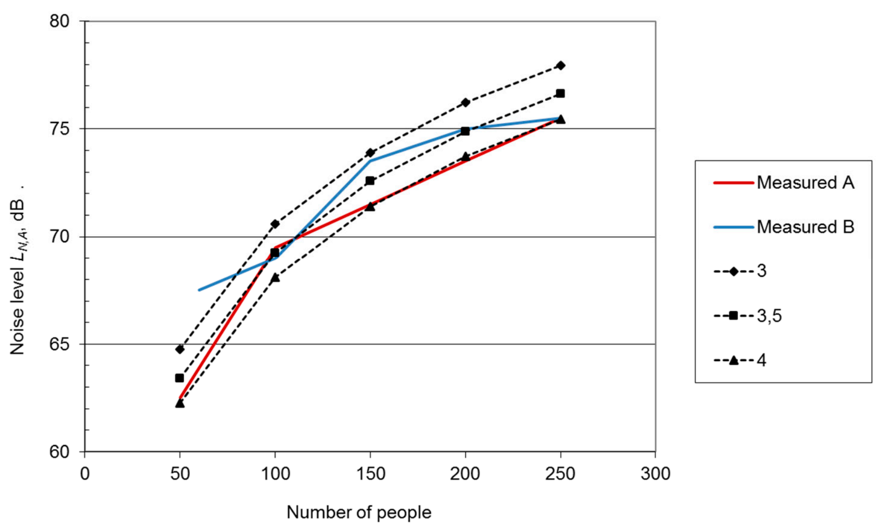

Figure 6. Measured and predicted noise level for a canteen as a function of the number of people present. Measurement A: first period with increasing number of people; Measurement B: second period with decreasing number of people. Measured data from Tang et al. [12]. The parameter on the predicted curves is the group size, *g*. (Adapted from Rindel [18] Figure 3).

In the later 1.5 h the number of people gradually decreased, but the noise level did not decrease as much as could be expected, and at the end of the measurements around 50 people were left, but the noise level was about 5 dB higher than with the same number of people at the beginning. The canteen had a volume of 1 235 m^3 and the unoccupied reverberation time 0.47 s at mid frequencies. The measured results are compared with the prediction model (Equation 2) using the sound absorption per person $A_P = 0.2$ m^2, and different values of the group size g. The best overall agreement with the prediction model is obtained with a group size of 3.5. However, in Measurement A between 150 and 250 people, a very good agreement is obtained with a group size of 4, indicating that people are not talking so much in the beginning of the lunch, whereas the later part of the lunch represented by Measurement B matches better with a group size of 3, i.e. more people talking. Thus it is clear that the group size g should not be considered constant, but varies according to the social character of the gathering.

5.2.Reception at a conference

In connection with an acoustical meeting in Krakow, September 2014, a welcome party and a farewell reception were held in the main building of AGH University of Science and Technology. The main foyer is a high room with volume approximately above 8000 m^3 and reverberation time around 4 s at mid frequencies, see Figure 7A. At the welcome party, the room was crowded and very noisy due to speech from several hundreds of people and additional background music (voice and piano). It was extremely difficult to have a conversation during this gathering. The SPL was not measured at that time, but at the farewell reception in the same room, the sound level was measured, and within a period of 15 minutes the $L_{A,eq}$ was 77 dB. Just before the reception there was a closing ceremony with 260 participants, so it is assumed that the number of people attending the farewell party was around 250, or a little less, see Figure 7B. Using equation (2) and (3) with A_p = 0.35 m^2 yields 78 dB, i.e. very close to the measured level. With the same equation, and estimating the number of people at the welcome party to be between 500 and 1000, the SPL would have been around 82 dB to 85 dB, see Table 4.

Table 4. Calculated and measured ambient noise during social gatherings in the AGH hall.

Volume V, m^3		8 265	
Reverberation time, T, s		3.9	
Number of people N	250	500	1000
Calculated $L_{N,A}$, dB	78	82	85
Measured $L_{A,eq,15\,min}$, dB	77	-	-

(a) (b)

Figure 7. The hall in the main building of AGH University of Science and Technology, Krakow. (**a**) The empty hall; (**b**) A photo from the farewell reception.

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5.3 Banquet in several large rooms

A banquet was held May 2011 at the Technical University of Denmark on the annual celebration with hundreds of people dining in several, separate rooms. During the evening, the sound level was monitored in three rooms with very different acoustical conditions. The results were compared with those obtained with the prediction method using a computer model, see Table 5.

Table 5. Measured and calculated ambient noise during a banquet in three halls.

	Hall A	Hall B	Hall C
Volume *V*, m^3	N/A	N/A	1 605
Reverberation time, s	2.5	0.8	1.0
Number of people *N*	480	530	380
Measured $L_{A,eq,2\,h}$, dB	87	83	83
Calculated (simulation) $L_{N,A}$, dB	88	83	83
Calculated (simple) $L_{N,A}$, dB	-	-	82

The number of seats in the three halls was 480, 530 and 360, respectively. Hall A was a very long, wide corridor with ceiling height 3.6 m. The surfaces are stone, concrete and glass and the mid-frequency reverberation time (with tables, but without people) was 2.5 s. Only a part of this hall was used for the banquet. Hall B was a canteen with ceiling height 3.0 m and mid-frequency reverberation time 0.8 s. The geometry was complicated and the volume not well defined. Hall C was a nearly square hall with glass walls, the ceiling height is 4.35 m and mid-frequency reverberation time 1.0 s. Photos from the latter is seen in Figure 8.

The sound was monitored between 19:00 and 22:00, using three measurement positions under the ceiling in each hall. During the first half hour, the noise increases significantly (15 dB to 20 dB) but after that the level is relatively stable for several hours. An example from Hall C is seen in Figure 9. The results in Table 5 are averaged over two hours between 20:00 and 22:00. The predicted noise levels in the three different halls deviate 1 dB or less from the measured noise levels. Assumed group size was 3.5.

(a) (b)

Figure 8. Hall C used for the banquet at the Technical University of Denmark. (**a**) The hall with tables and chairs before the banquet; (**b**) Same hall during the banquet.

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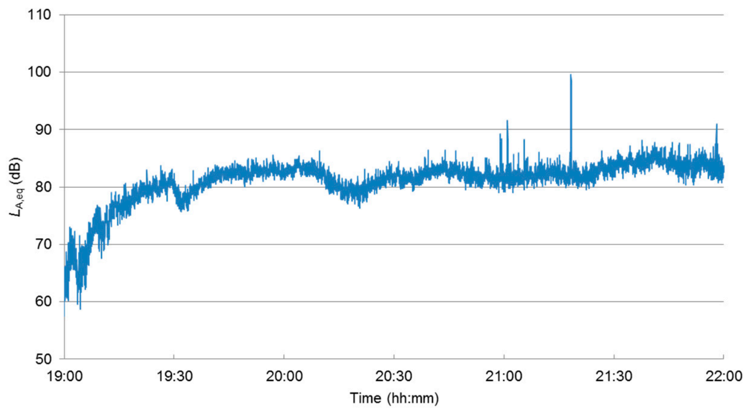

Figure 9. Measured A-weighted SPL in Hall C during the banquet.

6. Acoustic capacity and quality of verbal communication

6.1 The concept of acoustic capacity

The above findings can 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 acoustic capacity for an eating establishment, defined as the maximum number of persons in a room allowing sufficient quality of verbal communication between persons (in a distance of 1 m).

Sufficient quality of verbal communication requires that the ambient noise level is no more than 71 dB, which means that the average SNR in a distance of 1 m is at least -3 dB, see Table 3. A simplified approximation derived from Equation 2 yields that the number of persons corresponding to 71 dB, i.e. the acoustic capacity:

$$N_{\max} \cong \frac{V}{20 \cdot T} \quad (5)$$

where V is the volume in m³ and T is the reverberation time in seconds in furnished but unoccupied state at mid frequencies (500 Hz to 1000 Hz). Here is used group size g = 3.5 and absorption per person A_P = 0.35 m².

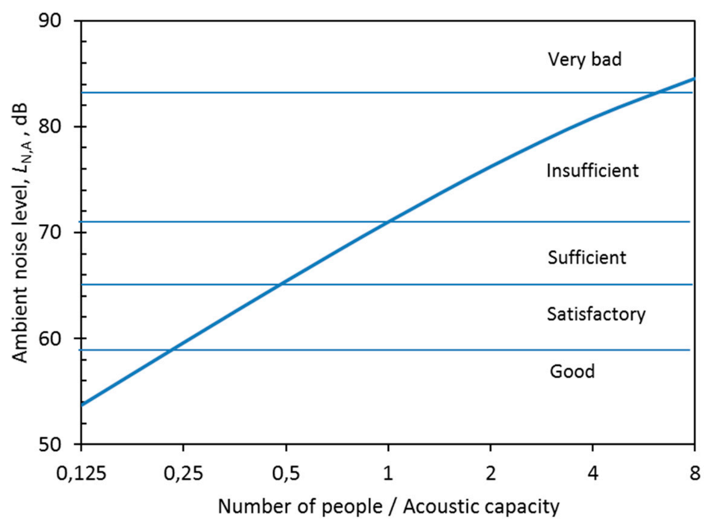

Figure 10. Ambient noise level as a function of the number of people relative to the acoustic capacity of the room. The corresponding quality of verbal communication in a distance of 1 m is also indicated. (Figure courtesy of Euronoise 2015, Rindel [1]).

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Figure 10 shows the ambient noise level as function of the number of persons relative to the acoustic capacity. When a restaurant is fully occupied, it is typical that the acoustic capacity is exceeded by a factor of 2 or more. This means that the quality of verbal communication is insufficient in a standard distance of 1 m. However, other distances may apply, but this depends on the size of the tables

6.2. Table size and distance of communication

Table 6 gives the SNR as function of ambient noise level and distance of communication. The most important cells in the table are those with SNR = -3 dB, because this is the limit for sufficient quality of verbal communication. In the distance r = 1.0 m the corresponding ambient noise level is 71 dB.

Examples of tables in a restaurant are shown schematically in Figure 11. Sitting at a long table you can have a conversation with the person next to you (r = 0.5 m) or across the table (r = 0.7 m to 1.0 m) where distance depends on the width of the table. The round table for 10 people is very common in a banquet, and having a conversation across the table (r = 2 m) is mostly quite impossible, as this would require a noise level of maximum 59 dB. However, conversations may be possible between three persons (r = 1.0 m and r = 0.5 m). If the noise level goes up to 77 dB, it is only possible to speak with the person sitting next to you. Similarly we get the typical distances of conversation for the other tables in Figure 11; round table with six people (r = 1.4 m), square table with four people (r = 1.0 m), and small table with two people (r = 0.7 m). These distances are of course approximate and rounded to match the examples shown in Table 6.

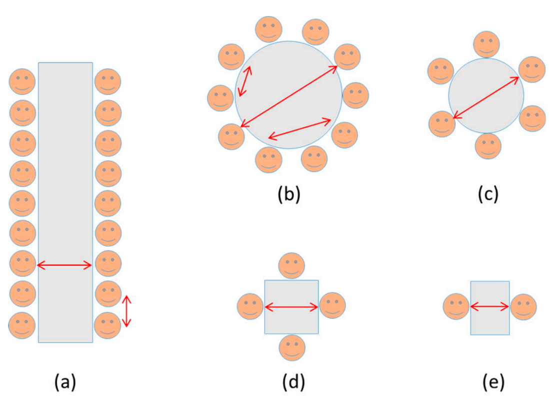

Figure 11. Examples of tables with indication of distances of verbal communication. (**a**) Long table, typical distances 1.0 m and 0.5 m; (**b**) Round table for ten, typical distances 2.0 m, 1.0 m and 0.5 m; (**c**) Round table for six, typical distance 1.4 m; (**d**) Square table for four, typical distance 1.0 m; (**e**) Square table for two, typical distance 0.7 m

Table 6. Quality of verbal communication in terms of calculated SNR as function of distance and ambient noise level.

	SNR (dB) - quality of verbal communication						
Distance	Ambient noise level, $L_{N,A}$, dB						
r, m	53	59	65	71	77	83	89
0.35	15	12	9	6	3	0	-3
0.5	12	9	6	3	0	-3	-6
0.7	9	6	3	0	-3	-6	-9
1.0	6	3	0	-3	-6	-9	-12
1.4	3	0	-3	-6	-9	-12	-15
2.0	0	-3	-6	-9	-12	-15	-18

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6.3. Background music

Background music is typically instrumental music played at a low level. It is not meant to be in the focus of an audience, but rather to fill the gaps of silence, that might occur. When used in restaurants and at social gatherings it should be played at a sufficiently low sound level, so it is not disturbing for normal vocal communication. Background music can have a masking effect, which contributes to a feeling of privacy in the meaning that a private conversation is not easily overheard by other people in the room. Thus, it may happen that people stop talking if the background music is stopped. Recommended maximum SPL of background music is around 60 dB to 65 dB.

Foreground music is played at higher levels than background music, and is meant to be noticed and enjoyed as entertainment [28]. The audience is not supposed to talk during the music. Recommended maximum SPL of foreground music is in the range 75 dB to 90 dB.

In a restaurant or at a social gathering the music contributes to the ambient noise level, which means an increase of vocal effort in conversations. Thus, the Lombard effect applies to the total noise level due to music and speech. Solving the problem leads to the following equation for the total noise level

$$L_{\mathrm{N,Total}} = 10\lg\left(E_{\mathrm{M}} + 0.5\cdot E_{\mathrm{N}}\left(1+\sqrt{1+\frac{4\cdot E_{\mathrm{M}}}{E_{\mathrm{N}}}}\right)\right), \text{ (dB)} \tag{6}$$

where the average SPL of the music is 10 lg(E_{M}) and the SPL of ambient noise from speech without music is 10 lg(E_{N}). The latter is the SPL given in eq. (2). From this result, it is straightforward to estimate the vocal effort (1) and the SNR with background music or other background noise.

Figure 12 shows the SNR as function of the ambient noise level without music, but with the sound level of the background music as a parameter. If the level of the music does not exceed 65 dB the quality of vocal communication can be sufficient (SNR > -3 dB), but of course only when the room is not too crowded (actually if $N < 0.7 \cdot N_{\mathrm{max}}$). For a satisfactory quality of verbal communication, the background music should not exceed 60 dB.

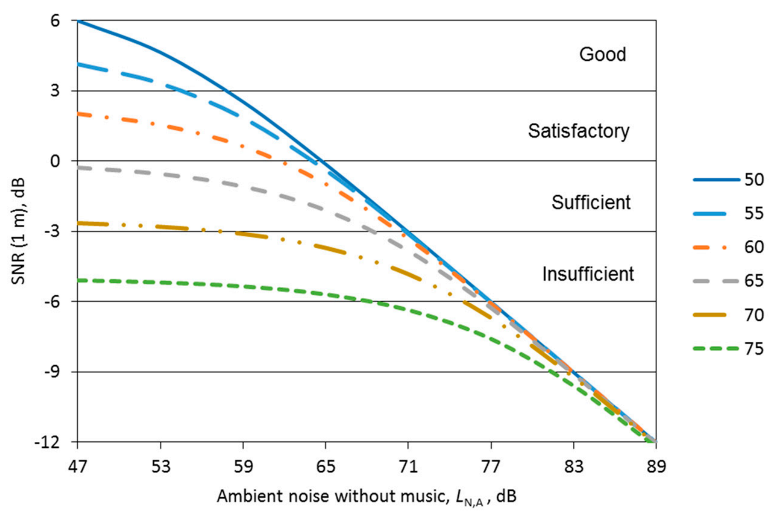

Figure 12. The influence of background music on the quality of verbal communication. The curves represent levels of music from 50 dB to 75 dB in steps of 5 dB. (Figure courtesy of Euronoise 2015, Rindel [1]).

7. Suggested acoustical requirements for restaurants

The adaptation of the universal design concept [2] means that it is necessary to define acoustical requirements for restaurants, canteens and other public eating facilities. The key parameters that control the acoustical conditions are volume V, reverberation time T and number of people N, i.e.

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number of seats. The graphical presentation in Figure 13 is based on Equation 4, which yields the SNR as function of $V/(NT)$ and the distance of verbal communication r.

In the reference distance $r = 1.0$ m we have $V/(NT) = 20$ for the borderline between sufficient and insufficient quality of vocal communication, so this might be taken as basis for the acoustical requirement. However, this might be too strict because a restaurant is seldom fully occupied. An 80 % occupancy may be considered a more realistic basis for the requirement. Then the required reverberation time yields:

$$T \leq \frac{1}{0.80 \cdot 20} \cdot \frac{V}{N} \cong 0.063 \cdot \frac{V}{N}, \quad \text{(s)} \tag{7}$$

The requirement must be related to the volume per person, which means that it is necessary to know the maximum number of seats in the room. In some cases this maximum number has to be accepted by the fire authorities, and an emergency escape plan that states the allowed maximum number of guests must be mounted clearly visible in the room. In order to fulfill the acoustical requirement there are three possibilities to consider:

1. The volume should be as big as possible. Some acoustically good restaurants have a high ceiling. This is something to consider in the early stage of planning.
2. Sound absorbing materials must be applied on surfaces where it is possible. The ceiling is obvious, but often parts of the walls must also be included. A thick carpet can also add more sound absorption, but in many cases this is not an option.
3. The seating plan should not be too crowded. The easy solution is to make a seating plan with a number of seats that does not exceed the acoustic capacity by more than 25 %.

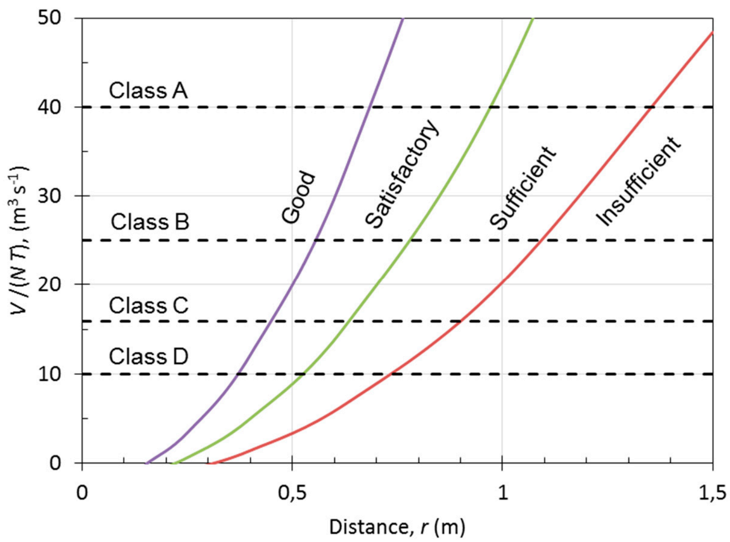

Figure 13. Quality of verbal communication at function of distance and the parameter $V/(NT)$. Suggested acoustical requirements in four sound classes are shown with dotted lines.

Some countries use sound classification for buildings, e.g. four classes A, B, C, and D where class A is best, class C is minimum requirements for new buildings, and class D is applicable for older buildings. Table 7 contains suggested requirements for the reverberation time in restaurants in four classes. These sound classes are indicated in Figure 13. Table 7 also shows the quality of verbal communication in terms of SNR in a distance of 1 m for different percentages of occupancy. For instance, 100 % occupancy in class A gives SNR = 0 dB, which is the borderline between satisfactory and sufficient. The same is obtained in class C with 40 % occupancy.

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Table 7. Suggested minimum requirement reverberation time in restaurants in four sound classes. The SNR in a distance of 1 m is shown as a function of the occupancy (number of people in percentage of the total number of seats).

Sound class	Class A	Class B	Class C	Class D
Reverberation time / volume per person (s/m^3)	0.025	0.040	0.063	0.100
Occupancy	SNR (dB) in 1 m distance			
100 %	0	-2	-4	-6
80 %	1	-1	-3	-5
63 %	2	0	-2	-4
50 %	3	1	-1	-3
40 %	4	2	0	-2
32 %	5	3	1	-1
25 %	6	4	2	0

8. Conclusions

For the characterization of the acoustical conditions in restaurants and similar environments, the quality of verbal communication is applied in addition to the ambient noise level. A signal-to-noise ratio of -3 dB for a speaker in a distance of 1 m corresponding to an ambient noise level of 71 dB is suggested as a realistic basis for design criteria. This leads to a combined requirement for the reverberation time and the volume; the volume per person should be at least $T \cdot 20$ m^3, where T is the reverberation time. Thus, the reverberation time should be as short as possible, but still a sufficient volume is a physical necessity for satisfactory acoustical conditions. It should be noted that 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.

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 acoustic capacity of a room. This is a simple way to indicate which number of persons should be accepted in order to obtain sufficient quality of verbal communication. In other words, if the number of people in the room exceeds the acoustic capacity, the ambient noise level may exceed 71 dB and the quality of verbal communication in a distance of 1 m is insufficient.

Both a simple prediction model and an advanced computer-based model for the ambient noise due to speech have been derived. The models take the Lombard effect into account, and have been verified for several test cases. In the design stage when alternative solutions for the acoustic design of a restaurant or similar facility are considered, the acoustic capacity may be a good parameter to present to architects, in addition to the calculated reverberation time or ambient noise level. This has already been used successfully in several projects, and it is clear that the maximum number of persons to allow sufficient acoustical conditions is much easier to understand for non-acousticians than noise levels or reverberation times.

For the owners of restaurants it may be interesting to know that the perception of food and drink is influenced by the ambient noise in the room, see Appendix A. However, the results go in opposite directions. In a fine restaurant the noise should be kept at a low level in order to maintain the taste qualities in the food. But for the owner of a bar, where the guests mainly come for drinks, a noisy environment means that more drinks are consumed in a shorter time. So, the quality of verbal communication might be less important in bars and a higher noise level (and thus a higher level of arousal) acceptable or maybe even wanted.

When music is played in restaurants or at social gatherings, it is important to distinguish between background music and foreground music. While foreground music is meant to catch the

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attention, background music should not interfere too much with verbal communication, and a maximum sound level of 60 dB is suggested.

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Appendix A. Drinking and eating in noisy environments

It is a widespread assumption that the noise level of a party increases with the amount of alcohol consumed. However, no proof of this is found in the scientific literature. Never the less there is no doubt that a relation exists between noise and alcohol consumption. Guéguen et al. [29] studied the drinking behavior in bars as function of the sound level of music, either at "usual" level, 72 dB to 75 dB, or at a typical level of "foreground" music, 88 dB to 91 dB. With the high sound level, significantly more drinks were consumed, the mean value for 60 persons being 3.7 versus 2.6 drinks at the usual level. The authors have suggested an "arousal" hypothesis to explain the findings; the high sound level leads to higher arousal, which stimulates to drink faster and to order more drinks. In a later follow-up study [30] it was confirmed that the average time spent to drink a glass of beer decreased from 14.5 ± 4.9 minutes with usual level of music (72 dB) to 11.5 ± 2.9 minutes with high level of music (88 dB).

Stafford et al. [31] have found that music and other forms of distraction leads to increase in alcohol consumption. In addition they found that sweetness perception of alcohol was significantly higher in the music compared to no music and other distraction conditions. The study gives support to the general distraction theory that noise disrupts taste and smell.

The effect of noise on food perception was studied by Woods et al. [32]. Test persons were exposed to white noise at levels of 45 dB to 55 dB (Quiet) and 75 dB to 85 dB (Loud), in addition to a no-noise condition. The ratings of sweetness and saltiness were influenced by the noise, and the food was reported to taste less intense in the noisy condition. This might be interesting news for owners of good restaurants, and it certainly gives a new twist to the discussion of the importance of good acoustics in restaurants.

Fiegel et al. [33] have found that background music can alter food perception, and that the effect depends on the music genre (classical, jazz, hip-hop, rock). They used the same SPL of the music in all cases, namely 75 dB. Especially in the presence of jazz stimulus, flavor pleasantness and overall impression of the food stimuli increased.

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