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Lombard effect, speech communication and the design of large (public) spaces.

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Summary

The Lombard effect describes the phenomenon that, especially in large, bare rooms, high sound levels can occur, caused by groups of people, e.g. at cocktail parties. Empirical formulae show that the most important variables are the number of people, the reverberation time and the volume of the room. It appears that the most appropriate instrument to somehow control those sound levels is the amount of sound absorption in the room.

The assumption has been made that the behaviour of the persons present in the room is ruled by the desire to have conversation with each other. Conversation circles are formed, the diameter of which is adapted to the ambient noise level. Extensive literature is available on the subject of speech intelligibility in noise. In this study the noise sources are the speakers themselves. For several theories on this subject, the sound levels to be expected in a room were calculated. They diverge in absolute values, partly because the definition of speech levels is not always clear and free from ambiguity. Nevertheless the dependence on the amount of sound absorption is consistent. This enables deduction of simple rules for the design of the acoustical properties of the room.

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1. Introduction

It is a common experience that the noise level caused by the conversation of groups increases with the number of people; proportionally at first, when not many people are present yet, but even stronger if certain limits (noise level or number of people) are exceeded. At social events like cocktail parties, this phenomenon can often be regarded. This raises the question if the sound level caused by the people in a room can be predicted or estimated in some way. At least as important is the question to what extent the acoustical properties of the room determine the sound levels, and can be manipulated accordingly.

The mean sound power level of a speaker in a normal environment (not too noisy) is about 65 dB(A) re 1 pW. From the number of speakers (n) in a room, and the amount of sound absorption (A [m^2]) the resulting sound level in the (diffuse) reverberant field can be calculated:

$$L_p = 65 + 10\,lg\left(\frac{4n}{A}\right) \qquad (1)$$

The validity of this formula is limited to low ambient sound levels. As stated, sound levels can become (much) higher when the number of people increases. It is a realistic assumption, that the underlying reason is the intention of people to maintain conversation. Speakers want to make themselves heard; listeners want to understand what is said. A thought experiment can be useful to get a clear picture of the mechanisms involved.

Consider a room where a gathering is held. People arrive one by one; at first forming a circle, with only one speaker at a time. The distance between neighbours in the circle will be constant, e.g. 1 m. As the number of people grows, the perimeter and consequently the diameter of the circle do, until conversation becomes less easy, because the distance between the speaker and some of the listeners hinders the speech intelligibility. Then the circle breaks up into two smaller ones. These new circles keep growing with

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new participants entering, until they break up again. In this way, the number of speakers increases, and so does the sound level in the room. This causes the speakers to raise their voices. The effects of the number of occupants, trying to maintain or start their conversation, and of the amount of sound absorption can be expressed in a model, based on the extensive literature on speech intelligibility, preferred speech levels, etc.

Of course communication comprises more than speech and intelligibility. Saarinen [1] points at non-verbal communication, behaviour in a wide sense, including proxemics: the use of space by individuals in a group. These aspects are not taken into account. They should be kept in mind in the interpretation of experiments, and explain a part of the variance in the results.

2. Conversation circles.

As the vocal output of persons taking part in a conversation, depends on the background level, but the background level itself is largely determined by the vocal output of the speakers, the phenomena in conversation circles must be regarded as a system with feedback. Under certain assumptions, the process can be calculated, resulting in the sound level in a room as a function of the number of persons present and the amount of sound absorption. This sound level will be called the Lombard level, after the French physician who in 1911 first described the phenomenon, that speakers raise their voices when background noise levels increase.

The assumptions include:

* A diffuse reverberant sound field

* The vocal effort of each speaker depends only on the ambient sound level; several relationships are described [2][3][4];some of them have been used in this study

* The conversation groups form circles; the interpersonal distance between members of a circle is constant (1 m), for groups of five or more persons. For smaller groups – four or less – the interpersonal distance is smaller (0,5 to 1 m). The maximum distance D between two members of the group is the

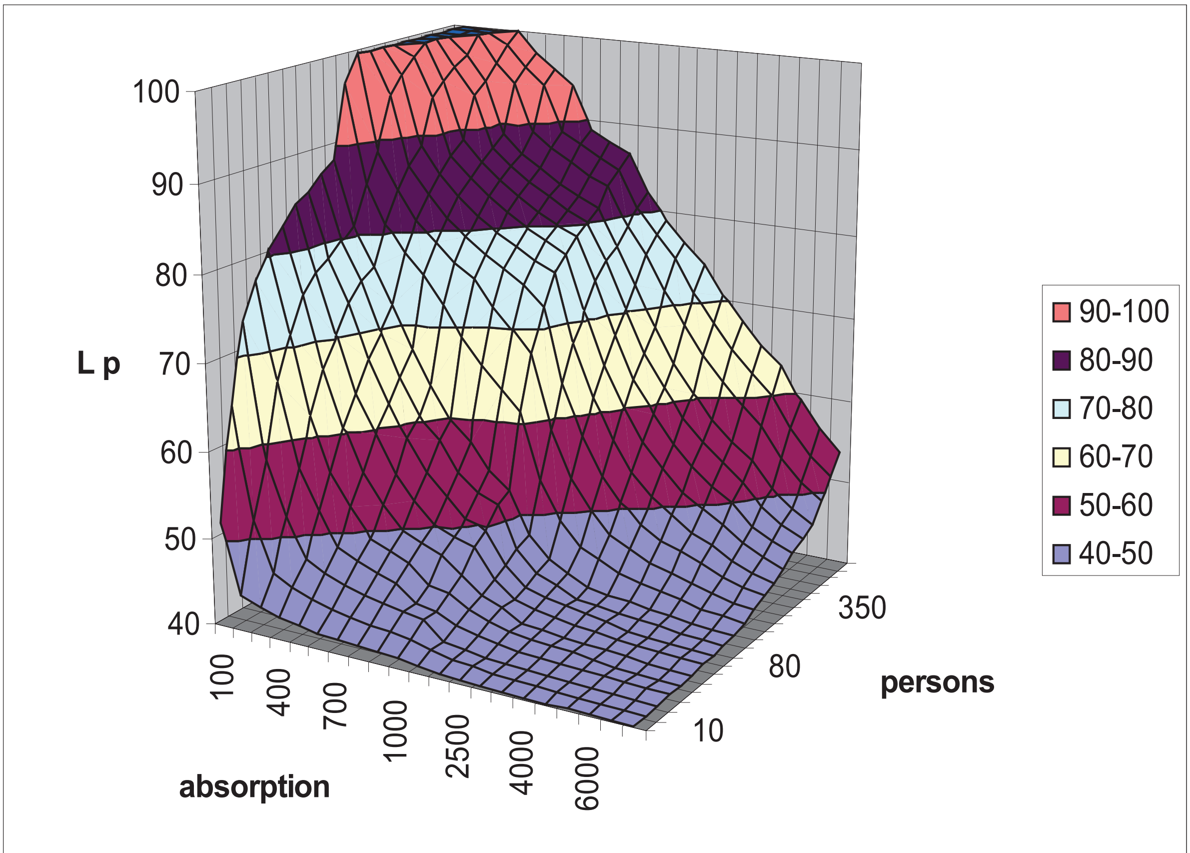

Figure 1 Lombard-2 function (ISO 9921- criteria)

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diameter of the circle. In formula:

$$D = nd/\pi \quad (2)$$

n = number of members

d = interpersonal distance

This distance D is taken to determine the (worst case) speech intelligibility.

The members of the group are supposed to take part in the conversation. Therefore they strive for understanding the speech of each other member. Only one member speaks at a time. If speech intelligibility is unsatisfactory people will leave the circle, to join some other circle or to form a new one. This process is simulated by assuming first that all persons present form one circle. If speech intelligibility is unsatisfactory, the number of circles is increased by one, and people are spread equally over the circles. This process is repeated until speech intelligibility is satisfactory, or the conversation circles consist of only two persons. The ambient noise level at the end of each iteration process is the Lombard level, a function of two variables: the number of people and the amount of sound absorption. This function is called the Lombard-2 function.

The personal vocal effort (as a function of the ambient sound level) and the criterion for speech intelligibility can differ. For each criterion the whole process can be repeated, yielding a new Lombard-2 function. In figure 1 an example is given.

The process described here was implemented in a number of spreadsheet programs, one for each criterion of speech intelligibility and the connected personal vocal output function. These criteria embrace: international standard ISO 9921-1 [2]; implicit criteria of Webster [3], from his figure 1; criterion of Heusden et al. [4], preferred listening level if conversation circles are large (5 or more persons), required listening level if conversation circles are smaller. All calculations were made with sound levels expressed in dB(A).

3. Absorption per capita

An important step in data reduction could be made, if the Lombard-2 functions were reduced to functions of one variable. Therefore a new independent variable is introduced: A/n, the amount of sound absorption per person. The calculated Lombard levels are plotted against this variable, as shown in Figure 2. Because each value of A/n can be the result of several combinations of A and n, many data points can occur with a single A/n-value. As the figure shows, the spread is not very large, and there is a clear trend. The trend line can be called a Lombard-1 function: the sound level in a room as a function of the absorption per person (A/n).

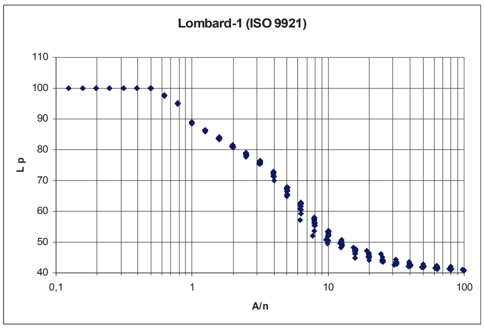

Figure 2 Lombard-1 function (ISO 9921)

In figure 3 the range of results for several Lombard-1 functions have been combined. The Lombard-1 curves all have the same trend, as was expected. As long as there is ample sound absorption per capita, and the sound levels are still low, the agreement between the Lombard-1 functions is large, and the differences might be attributed for an important part to differences in the social context, type of occasion, function of space etc. Different definitions of the speech level, especially the way of determining an equivalent speech sound level may be involved as well, for example ISO 8253-3 [5].

Basically a slope of – 10 dB/decade is expected; see formula (1). For values of A/n < 10 m^2 the curve is steeper, about – 30 dB/decade. The transition point can be estimated at roughly A/n = 5 - 10 m^2.

More or less arbitrarily a sound level of 60 dB(A) can be regarded as the start of noisiness in public spaces. The different Lombard functions lead to different A/n-values for which this limit is reached: Webster : A/n ≈10 m^2; Van Heusden: A/n ≈ 3

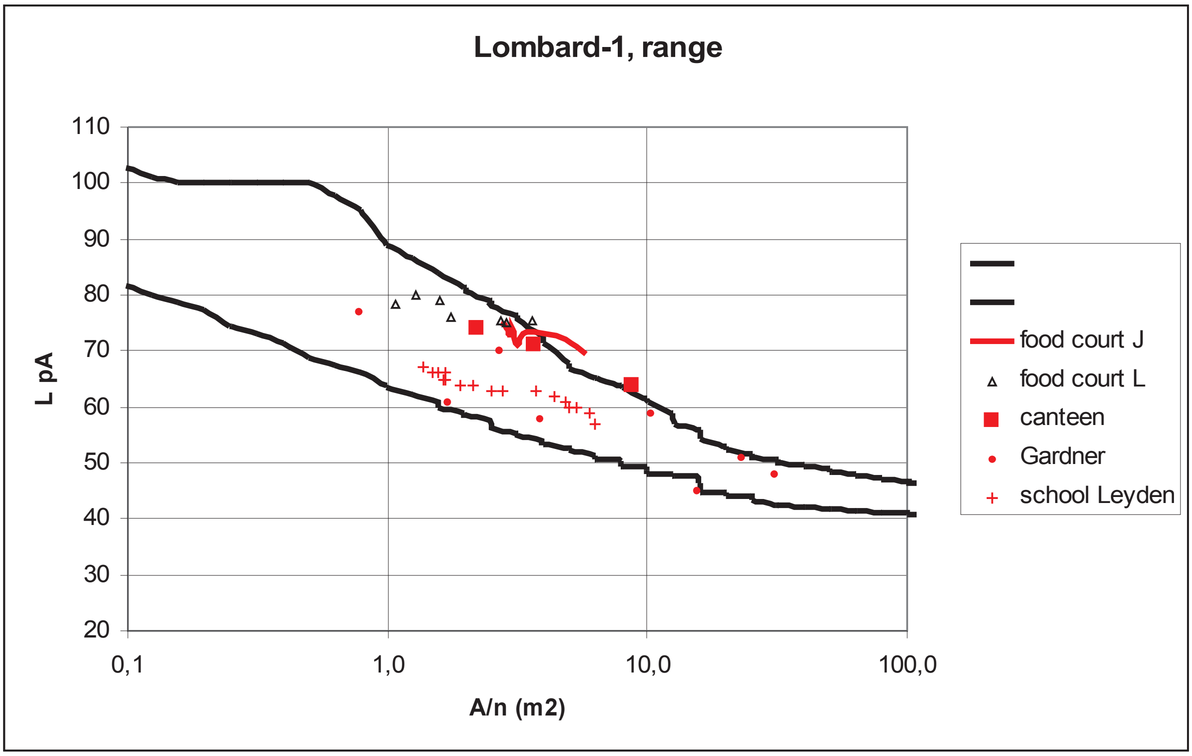

Figure 3 Range of Lombard-1 functions with measured data

m^2; ISO 9921: A/n ≈ 7 m^2.

A value of 5- 10 m^2 therefore seems a reasonable compromise, as a guideline for the minimum amount of sound absorption per capita in atria.

4. Examples Group Vocal Output

For a number of occasions, data regarding number of people, amount of sound absorption and measured equivalent sound levels were compiled; partly from literature i.c. Gardner [6], Tang et al. [7] (canteen), Navarro and Pimentel [8](food courts J and L),others from Peutz' archives (school Leyden). The data points are shown in Figure 3; they fit rather well in the calculated range.

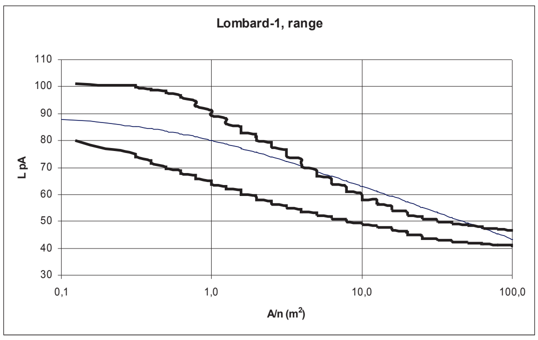

Figure 4 Lombard-1 range with Rindel formula

Rindel [9] too started from the assumption that people want to maintain conversation, in canteens, food courts etc. He gives a predictive formula for the sound level as a function of the sound absorption per capita; it has three parameter:

- the speech level rise due to increase of ambient noise c, here c=0,5 dB/dB;
- the size of the conversation group or the number of persons per speaker g, here g= 3 persons
- the amount of sound absorption per person a, here a= 1 m^2.

The Lombard-1 function with these parameters is shown in figure 4 as a thin smooth curve, and fits rather well in our framework. An important difference of Rindel's approach is the percentage of speakers (=100/g): in his model it is a (chosen) parameter, in our model it is an internal variable. This might be attributed to the specific ambiance of food courts, canteens etc., where people move less freely "from circle to circle".

5. Architectural guideline

An amount of sound absorption per person of around 5-10 m^2 can be adopted as a guideline for large public spaces. Sometimes the

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(maximum) number of people to be expected is known, and can be used directly. In other cases a density of roughly one person per 5-10 m^2 floor area can be assumed; this means an amount of sound absorption roughly equal to the floor area. If this condition is met, one may expect that the sound levels caused by the occupants in the atrium will not rise to extreme values, but remain below 60-65 dB(A). Of course, no guarantee can be given: noisy behaviour or higher density of occupants is ruled out.

Where higher densities of people are to be expected, for example at the entrance of a hotel or shops, sound absorbing surfaces or elements near these areas may be necessary, and feasible.

6. Reverberation time

In the preceding chapters the reverberation time was not mentioned. The reason is, that the speech intelligibility in the conversation circles is practically independent of reverberation time. The ambient noise is the limiting factor here. This does not mean that "the" reverberation time is not important at all [10]. Especially in large spaces where public address systems are used, the reverberation times should be regarded. Musical performances and reproduction of music of course have their own sets of requirements, including reverberation time. These aspects could require a much larger amount of sound absorption than proposed in the previous chapter.

7. References

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