The development of architectural guidelines for the acoustical quality in rooms for mentally challenged people

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A research project is going on to improve the acoustical quality in living rooms and work spaces for mentally challenged people. Measurements have been done in four living spaces and two work places. From these measurements improvements will be proposed, where after new measurements will be carried out. Results are compared with the output from a ray-tracing computer model and with calculations based on simple rules for diffuse rooms. Differences in the order of 0-3 dB have been found for measurements versus ray-tracing, while deviations with the simple method vary from 0-5 dB.
The aim of the total research project is to improve existing situations, but also to develop guidelines for architects and acoustical engineers for future plans. In this respect U_{50} is a useful variable to calculate the necessary amount of absorbing material in a room whit more than one speaking person. It is superior to the reverberation time and easier to use than *STI*.

1. INTRODUCTION

There are many complaints about the acoustical quality in living rooms for mentally challenged people. The absorption of furniture and curtains is very low, mainly for cleaning reasons, so long reverberation times are found. Many handicapped people (about 30%) also suffer from hearing problems, but probably the main problem is that they live with more people within a room in order to keep the ratio between nursing staff and pupils low. Since they may have different activities (talking, watching television, cooking, etc.), they live (in acoustical terms) in a "multi-source" environment.

To improve the acoustical quality a research project has been started. One of the first problems was to choose an acoustical *quantity* to establish *quality*. Most acousticians (in this field mainly audiologists) use the "speech transmission index" (*STI*) and we used *STI* as well in measurements and ray tracing techniques. However, a second aim was to make the method suitable for architects and then *STI* is to complicated.

The reverberation time (*RT*, from Sabine's or Eyring's method) is often used to make a first estimation of the acoustical quality. It has one major drawback in multi-source environments since it does not incorporate the source-receiver distance. This is contrary to common practice, where approaching a speaker improves the speech intelligibility.

It is the aim of the present paper to explain the design method we developed. We will denote that method by "simple method" throughout this paper. Results from the simple method are compared with those from measurements and ray-tracing calculations. At the end one example is given of the guidelines for architects; a more extensive overview of the guidelines, however, is given in a separate paper [1]. There also the influence of the placement of absorbing materials is dealt with in more detail.

2. ACOUSTICAL QUANTITIES

2.1 Measurements and ray-tracing

Acoustical quantities used in this research are based on the Schroeder integral, written here as:

$$S(t) = \int_t^\infty h(\tau)d\tau = \int_t^\infty p^2(\tau)d\tau\ , \qquad (1)$$

where *p(t)* stands for the response to a sound pressure pulse. It is used both in measurements and ray-tracing simulations.

From this integral a few values are deduced: The *sound pressure level* (L_p) is calculated from *S(0)*. The *reverberation time* (*RT*) is found from curve fitting along the curve between -5 to -35 dB relative to *S(0)*; in our case the *early decay time* (*EDT*) is fitted between -1 and -11, although other values are found in literature as well. The *speech transfer index* (*STI*) is also calculated with common methods.

To express the speech intelligibility we follow Bradley [2], distinguishing "useful" and "detrimental" sound energy, arriving before and after 50 ms respectively. Adding noise energy (*NE*) from other sound sources as well leads to a variable, commonly denoted as U_{50}:

$$U_{50} = 10\log\left[\int_0^{50} h(t)dt \Big/ \left(\int_{50}^{\infty} h(t)dt + NE\right)\right]. \qquad (2)$$

If *NE* = 0 this value is denoted as C_{50}.

2.2 Simple rules for diffuse rooms

For a room with one sound source in a single room with an ideal diffuse field a few simple expressions are used (e.g. see [3]).

The *reverberation time* can be calculated from the Sabine or Eyring formulas. In diffuse rooms no difference is found between *RT* and *EDT*.

To calculate the sound pressure level it is a common procedure to split the sound field into a direct component and a diffuse reverberant part. The normalized squared rms-pressures, being related to the local energies, can be written respective as:

$$E_{dir} = W_0 / 4\pi r^2\ , \qquad (3a)$$

and as:

$$E_{rev} = 4W_0\,(1-\bar{\alpha})/A\ , \qquad (3b)$$

where r represents the source-receiver distance; $\bar{\alpha}$ stands for the mean absorption coefficient of the total space and A for the total amount of absorbing surface. W_0 is an arbitrary source strength.

The total sound pressure level L_p can then be calculated as:

$$L_p \approx 120 + 10\log\left(E_{dir} + E_{rev}\right). \qquad (4)$$

For the calculation of C_{50} a combination is used of equations (2), (3) and (4). Similar equations for C_{50} and U_{50} can be found in literature, but it is not very common to include the direct sound separately in the early energy as will be done in the following equations. The big advantage is that the value of C_{50} from the new simple method depends on the source-receiver distance. This is in accordance with every day practice: approaching a speaking person increases the speech intelligibility.

The sound field is divided into the useful and detrimental energy and we find respectively:

$$E_{use} = E_{dir} + E_{rev}\left[1 - \exp\left(-0.69 / RT\right)\right], \qquad (5a)$$

$$E_{detr} = E_{rev} \exp\left(-0.69 / RT\right). \qquad (5b)$$

And from this:

$$C_{50}(r) = 10 \log\left(E_{use} / E_{detr}\right). \qquad (6)$$

In noisy situations an extra term *NE* (like in equation 2) is added to the reverberant energy to calculate $U_{50}(r)$ from $C_{50}(r)$.

STI is used very often in practical situations, but there is one drawback using *STI* in the simple method as well: though it is not too difficult to calculate it numerically from measurements or ray-tracing simulations, it is hard to predict from simple exponential functions. Nevertheless a very coarse comparison between $U_{50}(r)$ and *STI* will be made in the next section.

3. ACOUSTICAL STANDARDS

It is not easy to find acoustical standards from literature for mentally challenged people. For "normal" ears a C_{50} value of +3 to +5 dB is considered as "excellent" for speech intelligibility. The desired signal-to-noise ratio is often taken as 15 dB. For mentally challenged people some literature can be found where a reverberation time in the order of 0.3 to 0.5 is advised [4], while the S/N-ratio is advised as 20 dB. This last value is useful if the noise signal comes from ventilation systems, outdoor traffic noise, etc., but it can not be used if the noise signal comes from other talking people in the room, since that will lead to unrealistic values.

As said earlier, many field workers use *STI*-values. Then a value of $STI \geq 0.7$ is commonly accepted as "excellent". With the aid of the graphs in Houtgast and Steeneken [5] it is possible to translate the value 0.7 into value $U_{50}(r) = +6$ dB. This result is also found if we assume that the modulation transfer function (which is the basis for *STI*) for early reflections is very close to 1.0. Then *STI* can be calculated from U_{50} as:

$$STI = (U_{50}(r) + 15) / 30, \qquad (7)$$

and vice versa.

Results from measurements and simulations show that this assumption is correct when de reverberation time is 0.6 s or lower. When *RT* is in the order of 1 s, differences are in the order of 8%, which is still acceptable for our simple method.

4. COMPARING RAY- TRACING AND THE SIMPLE METHOD

Calculations have been carried out to compare ray-tracing results with the simple method. Two examples are given in figures 1a and 1b for an existing rectangular workspace (9.6*6.5*3.4 m). It included furniture. A row of microphone positions has a shortest distance of 0.30 m to the sound source. Results are given for L_p and C_{50}. Two cases are given, one case has $\alpha = 0.1$ for the ceiling, all other surfaces are even less absorbing, so a mean value of 0.066 is used for the total space. The second case has a highly absorbing ceiling ($\alpha = 0.9$), so a mean value of 0.17 is found.

For these two cases the agreement between the ray-tracing model and the simple method is good. Even better agreement is found for those cases where the absorption is homogeneously distributed over all surfaces.

Figure 1 also shows why incorporating the direct field into equations (5) and (6) is useful. In the common model for C_{50} the value from the simple method is constant through the entire room.

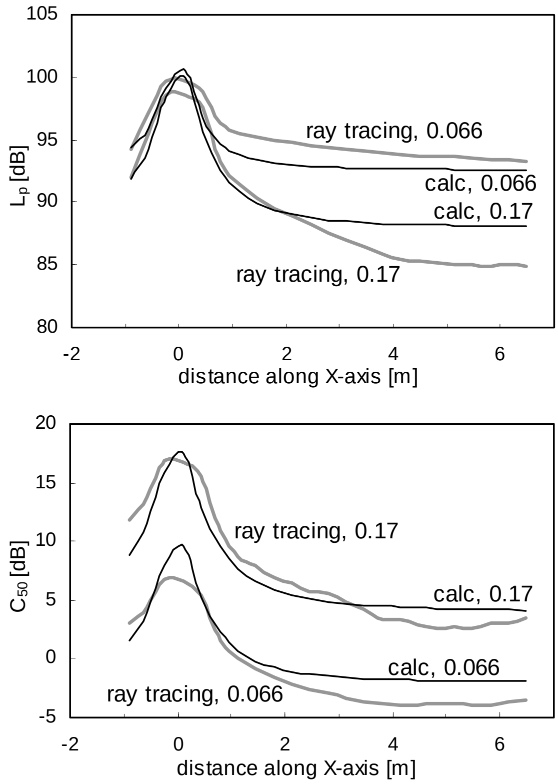

FIGURE 1. Calculations for the sound pressure level (top) and the C_{50}-value (bottom). The horizontal axis gives the distance between the microphone and the source along the x-coordinate. The distance along the y-axis is 0.10 m and along the z-axis 0.20 m. Source Power is 100 dB.

5. MEASUREMENTS VS. RAY-TRACING VS. THE SIMPLE METHOD

Measurements have been done in four living rooms and two workspaces. Per room two or three source positions were used. The microphone was on a rail of 1.50 m long; measurements were taken with 5 cm intervals. Two or three rail positions were used.

The same rooms have been simulated in the ray-tracing model. Absorption coefficients are required for all surfaces, including furniture. From literature values were estimated for 6 octave bands from 125 to 4000 Hz. *RT*'s were compared for both methods and α's (for one situation) were readjusted with the *same* factor for all materials and all six octave bands. Multiplication factors appear to be surprisingly small as they vary from 0.9 to 1.1, depending on the situation. Figure 2 shows two examples where C_{50}-values are compared.

The third step was to calculate C_{50}-values from the simple method for the same situations. Because source-receiver distances vary through the room, a region of results is calculated from equation (6). They are given in figure 2 as a rectangle drawn around all results.

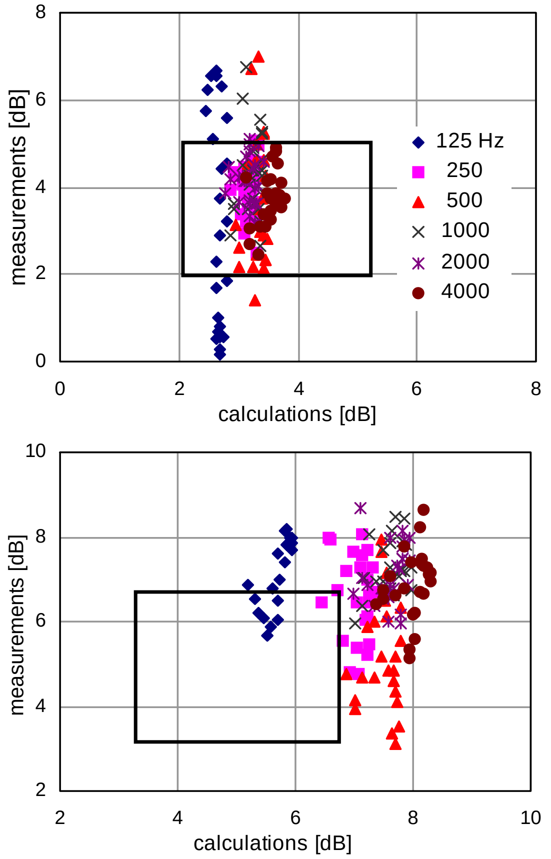

FIGURE 2. C_{50}-comparisons between measurements and calculations from ray-tracing for two situations. Rectangles show the ranges predicted by the simple method.

Some typical results from figure 2 are:

- The agreement in mean values between measurements and ray-tracing results is good, but no correlation is found for a point to point comparison.
- Variations in measuring results are always bigger then in ray-tracing results. This has been reported before in literature [6], and is mainly caused by standing waves in the room. As expected the lower frequencies show the highest variations.
- C_{50}-values show the highest variations. The variations in L_p-values and reverberation times (not shown here) are substantially smaller and the agreement of mean values is even better.

C_{50}-values from the simple method represented by equations (5) and (6) (rectangle in figure 2a) show a fair agreement with measurements and ray-tracing in about 80% of the cases. In other cases differences of 3 to 4 dB are found. The differences in the special case of figure 2b can be decreased from 3 to 1 dB by removing (both in measurements and ray-tracing) one table from the room that acts as a strong reflecting element between source and receiver. Of course, these adjustments are impossible in the simple method.

6. ARCHITECTURAL GUIDELINES

The C_{50}-values in figure 2a can be considered as "good" for a living room, the values in figure 2b are even "excellent". *RT*-values are in the order of 0.6 s. However, some of the other living rooms showed reverberation times as high as 1.1 s and negative C_{50}-values. There improvements are required.

In single-source situations (where C_{50}-values are used) improvements can be rather simple: adding absorptive materials on the ceiling is sufficient. However, C_{50}-values turn into U_{50}-values in a multi-source environment. U_{50}-values can be measured or calculated in the ray-tracing model by combining two source positions, but equation (6) also gives a good approximation assuming that the microphone is in the diffuse field of the "noise source".

This has been done in the simple method which is the subject of the Internoise-paper [1] describing the architectural guidelines for a first estimation of the total amount of absorbing surface. Differences between ray-tracing and the simple method appear small if absorbing materials are homogeneously placed along the room. If this is not the case, differences may be in the order of 5 dB.

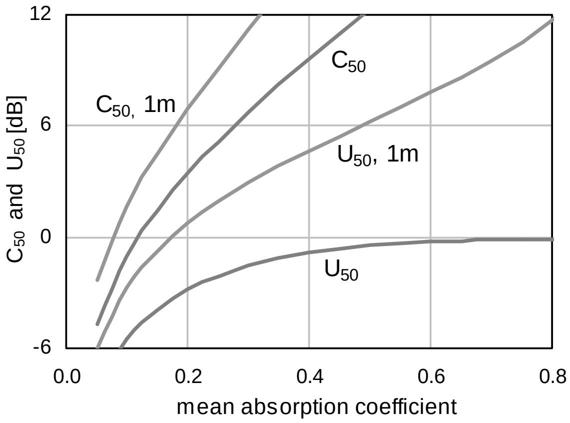

FIGURE 3. Values of $C_{50}(r)$ and $U_{50}(r)$ derived from equations (5) and (6) for r = 1 m and when the distance term is left out ($r \rightarrow \infty$), calculated in a 10*5*2.5 m room.

To explain the simple method, one example is given. Suppose a room which is 2.5 m high, and with floor dimensions of 5*10 m. First, there is one conversation going on with all listeners assumed at 1 m from the speaker. If there is no extra noise in the room, the speech intelligibility can be expressed in C_{50}-values if the energy of the direct source is omitted. These values are given in figure 3 as a function of the mean absorption coefficient in the room. To reach the +6 dB-level, the mean absorption coefficient must be in the order of 0.27. In fact these values are valid at big distances between source and receiver. When the distance is 1 m, the speech intelligibility is higher, so a mean value of 0.18 is sufficient for the absorption coefficient to reach $C_{50}(1m)$ = +6 dB.

For the U_{50}-values in the graph a second sound source is assumed in the reverberant part of the room. The source is assumed equally loud as the first one, so the common U_{50}-value never exceeds 0 dB. Incorporating the direct sound increases the U_{50}-value considerably at 1 m from the source, but the mean value of the absorption coefficient still should be 0.5 in order to reach the value of $U_{50}(1m)$ = 6 dB.

Of course there is only one curve for the reverberation time, thus neglecting the influence of source-receiver distance and of the noise energy. That is the reason why we prefer C_{50}- and U_{50}-values.

7. CONCLUSIONS

The given research shows that a ray-tracing model can give a very good approximation of the mean values of the acoustical quantities but deviations in the order of 4 to 5 dB may occur for specific situations, especially for C_{50}-values.

Simple equations from diffuse field theory, combined with the influence of the direct field are well suited for architects in the first steps of their plans. In some specific cases, however, errors of 5 dB or more can be found compared with a ray tracing model. Parameters that can be dealt with in the ray-tracing model but not in the simple method are: the influence of local reflectors, the distribution of absorbing panels through the room, the influence of room shape and diffusitivity of the walls. Some of these parameters will be dealt with in more detail in a separate paper [1] or have been described in a previous paper [7].

REFERENCES

1. L. Nijs, D. van Berlo, M. van der Voorden, Architectural guidelines to improve the acoustical quality in rooms for mentally challenged people, Internoise 2001, The Haque, 2001.
2. J.S. Bradley, Speech intelligibility studies in classrooms, J. Acoust. Soc. Am, 1986, 80, 846-854.
3. A.D. Pierce, Acoustics, New York, Ac. Soc. America, 1985.
4. M. Egli et al, Architectural Acoustics in Residences for Adults with Mental Retardation, Am. J. Mental Retardation, 1999, 104, 53-66.
5. T. Houtgast, H.J.M. Steeneken, A review of the MTF concept in room acoustics and its use for estimating speech intelligibility in auditoria, J. Ac Soc. America, 1985, 77, 1069-1077.
6. D. de Vries, J. Baan, Fluctuation of room acoustical parameters at small spatial intervals, Forum Acusticum, Berlin, 1999.
7. Nijs, L, R. Pellemans, M. van der Voorden, “The Prediction of Acoustical Quality in coupled Rooms”, Int. Building Physics Conf, 2000, Eindhoven, Netherlands, 139-146.