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Correlation of room acoustic parameters and noise level in eating establishments

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Abstract – This article addresses the impact of the occupancy level, the average acoustic absorption and the so-called acoustic capacity of a space, which is proportional with the volume and inversely proportional with the reverberation time, on the behavior of talking people in an eating establishments. Four different settings were compared: two casual dining restaurants, a self-service student canteen and a small faculty club. The Lombard effect was observed in all cases. In a restaurant with an average amount of absorbing surface of 2.4 m^2 or more per person, the sound pressure level increased with more than 3 dB per doubling of the number of people. Results for the student canteen show that people started to communicate less when the number of people present was so high that the absorbing surface dropped under 1.5 m^2/person (80 people). The level even stopped to increase with increasing occupancy from 150 people present and beyond, corresponding with 0.8 m^2 of absorbing surface per person. This is roughly consistent with an estimated value for the acoustic capacity of that space, which was 189 people (corresponding with a table occupancy of about 72%). In the latter circumstances, the background noise level, as expressed by $L_{A,95}$ was as high as 69 dB. Overcoming this level for oral communication would require a not sustainable vocal effort. In the tests performed in other restaurants, the observed occupancy was below 60%, which, thanks to the higher number of absorbing surfaces in those restaurants, was well below the acoustic capacity.

Keywords: Restaurant, Noise level, Vocal effort, Lombard effect, Speech

1 Introduction

Customers' appreciation of restaurants, bars or café's is based on their conscious or subconscious multifactorial judgement. Sociological studies have shown that the most frequently observed factors that influence restaurant customers' satisfaction are the quality of food and its presentation, the dining experience, the restaurant ambience, the cleanliness, the price/quality factor, the kindness of waiters, and often also a the presence of something unique or typical for the particular place [1–3]. In view of the previous, an architect has substantial tools to influence the restaurant ambience, e.g. by keeping eye on interior solutions and decorations. Also, by taking care about the acoustic, thermal and visual comfort, an architect may significantly influence the character and atmosphere of a place. A unique ambiance can make a particular restaurant stand out from others and increase its attractiveness [4, 5].

In general, the more customers, the better revenue for restaurant owners. However, from the acoustical point of view, the more people present in a room, the higher is the noise level caused by the talking crowd. In a restaurant, people act as listeners and sound sources at the same time. Individual sounds from visitors, the ventilation system and operational activities contribute to soundscape. This affects not only the speech intelligibility but also leads to people increase their vocal effort. Studies have shown that the soundscape in a restaurant can to a certain extent influence the perception of taste of served food or drinks [6, 7]. Restaurant noise also affects the intelligibility of verbal communication. A high noise level is therefore often considered disturbing and unpleasant. It should be noted that also a too silent restaurant ambience is often unwanted, as it may provoke a strange feeling about the place and a perceived or effective lack of speech privacy. A certain level of background sound is therefore desirable to ensure the privacy of speech during conversations at different tables. For this reason, music or radio sound is often used to mask speech and reduce its intelligibility when travelling in

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between different tables, mainly when too little people are present inside the room.

Different studies have reported on noise measurements carried out in student restaurants. Rychtáriková and Vermeir [8] have published a study that compared a student restaurant in Leuven (Alma) with a café of Trappist monks in Westmalle (Trappistencafe), Belgium. An increase in sound pressure level with doubling of the number of people present was found to be 6 dB in the former and 5 dB in the latter. White [9] examined the acoustic conditions in five catering establishments specialized in gourmet food where the measured A-weighted sound pressure level in unoccupied spaces was between 44 dB and 66 dB. With 10 to 94 customers, the values have ranged from 66 dB to 80 dB. Similar research, focusing on the Lombard effect [10], was conducted in a territory-wide noise survey in restaurants in Hong Kong by To and Chung [11]. Measured values of noise were found between 67 dB to 83 dB and a mathematical model for prediction of background noise levels was introduced. The occupancy density was identified as the main influencing factor for restaurant noise. Christie [12] investigated the impact of the objective parameters (such as reverberation time, room volume, overall sound absorption of a room) on the noise conditions in areas where people were the dominant sound sources. Several other researchers verified the presence of the Lombard effect on noise in so-called multi-talker environments in terms of proposal of prediction model [13–16]. The vocal effort of a talker at different distances from a listener and in different acoustic environments was investigated by Pelegrín-García et al. [17]. They found that talkers increased their vocal level by 1.3 till 2.2 dB per doubling of distance. While communicating, speakers and listeners naturally adapt to different noise levels, either by changing their distance or the vocal level. The Lombard effect is not only typical for verbal communication in noise. It also occurs in monologues in noisy environment, e.g. in a lecture of a teacher in a classroom. This is in line with the findings of Brunskog et al. [18], who measured objective room acoustic parameters of a classroom. Their main goal was to investigate whether objectively measurable room parameters can be related to an increase in the voice sound power of talkers and to the talkers' subjective assessments of the rooms. The study shows that significant changes in the sound power of the speaker can be observed in various premises. The size of the room and the "gain" of the room were found to affect these changes in vocal effort. On the base of this, a new room acoustic quantity "room gain" has been proposed. Also, an investigation by Pelegrín-García et al. [19] made use of the measurement of objective acoustic parameters, among which the reverberation time, the speech transmission index and the background noise level. The study concerned 30 classrooms and included a measurement method for two room acoustic parameters that are relevant for a speaker: voice support and room gain. A prediction model for these parameters was developed for a diffuse acoustic field.

In this paper we report on measurements of the dependence of the sound pressure level on the number of people present in four restaurants, with the goal to verify the influence of different architectural features on the overall level and on the vocal effort of the speakers. First, we investigate the correlation between the room acoustics parameters and the noise level caused by talking crowds. Second, we show to what extent the total sound absorption in the room influences the sound pressure level produced by people. Finally, we discuss the impact of architectural aspects, such as room shape, ceiling height, size of the tables, distance between chairs and the number of restaurant guests per floor area.

2 Description of the investigated scenarios

2.1 Scenario 1: Student restaurant SvF STU (canteen)

The student restaurant of the faculty of Civil Engineering (Fig. 1) is a self-service canteen. It is a typical example of an eating establishment with obvious acoustic discomfort. The floor dimensions are approx. 21 × 23 m, height of the ceiling is 3.8 m and the volume is approximately 1775 m^3. The total area of the interior surfaces is 1493 m^2. The floor (466 m^2) is made out of concrete slab with paving from the red marble. The walls are built from bricks, of which 3/4 are covered by plaster and 1/4 by ceramic tiles. The room ceiling is covered by suspended gypsum board. One of the walls consists of windows with area of ca 60 m^2. The capacity of the restaurant is 264 persons, but usually there are more than 264 people present at the same time, when taking into account students queuing for food.

2.2 Scenario 2: Faculty club – civil engineering faculty STU Bratislava (Shupitoo)

The Faculty Club Shupitoo (Fig. 2) is known as a place with pleasant acoustic conditions, as confirmed by interviews with visitors and employers [20]. The capacity of the restaurant is 18 tables with approximately 71 seating places. The floor dimensions are 17.5 × 8.5 m, the height of ceiling is 3 m and volume of the room is 525 m^3. The total surface area of interior surfaces is 513 m^2 (from which the floor takes 145 m^2). One large wall area is covered by perforated gypsum boards and one of the side walls contains windows with surface area of 40.5 m^2. The suspended ceiling is made out of perforated metal plates with sound absorbing properties. The lowered ceiling is suspended at a distance of approximately 1.5 m below the concrete slab, thus helping to absorb sound at low frequencies.

2.3 Scenario 3: Restaurant Breweria 1

Restaurant Breweria 1 (Fig. 3) has a different architectural style and opening hours compared to the two previous restaurants. The capacity of the restaurant is limited to 21 tables with 84 seating places. The floor dimensions are approx. 20 m × 12 m. The basic volume is 816 m^3, with average ceiling height 3.4 m. The total area of interior surfaces is 919 m^2 (from which 241 m^2 is the floor surface). The construction of floor consists of concrete slab with ceramic tiles. The walls are made out of bricks covered by plaster,

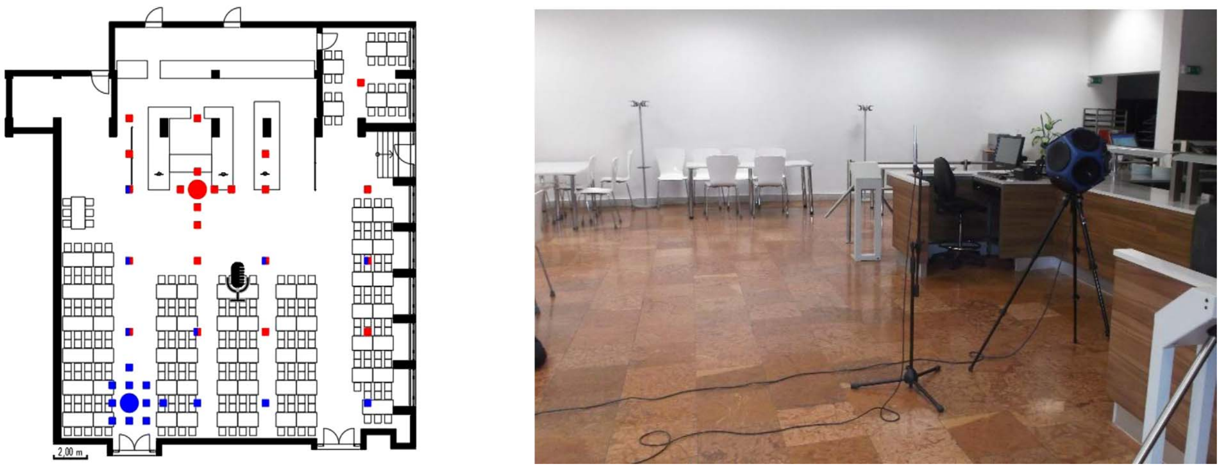

Figure 1. Floor plan (left) and photo (right) of STU SvF restaurant with indication of sound sources and microphone positions. Circles indicate sound sources, squares indicate microphones during impulse response measurements. The black microphone indicates the position and orientation of the monitoring device.

Figure 2. Floor plan (left) and photo (right) of Faculty Club Shupitoo, with indication of sound sources and microphone positions. Circles indicate sound sources, squares indicate microphones during impulse response measurements, the black microphone indicates the position of the sound pressure level monitoring device.

or by tiles imitating bricks. One of the walls consists of large windows (40 m^2). Most of the interior surfaces in this restaurant are acoustically hard and thus sound-reflective.

2.4 Scenario 4: Restaurant Breweria 2

From the point of view of interior design, the capacity and function of restaurant Breweria 2 (Fig. 4) are very similar to ones of restaurant Breweria 1. However, it has a different shape and volume and the interior space of the restaurant is divided into compartments by means of glass panels. There are twenty tables with 81 seating places. The floor dimensions are 19.5 m $\times$ 9.5 m and the ceiling height is 3.2 m. The total area of interior surfaces is 562 m^2 (from which the floor takes 157 m^2). The floor consists of laminated parquet on a polyurethane pad and a concrete slab. The walls have the same properties as those in Breweria 1: they are covered by plaster or by tiles imitating bricks.

3 Measurements

Two kinds of acoustic measurements were performed in the four chosen scenarios: (1) Impulse response measurements for determination of room acoustic parameters [21] and properties of each space, and (2) Sound pressure level measurement during the time when the restaurant is open and serves a lunch menu, followed by statistical noise analysis. The number of present people was monitored in time intervals of 1 minute, in order to track the correlation between the number of talking people (who act as dynamic sound sources) on the actual noise level.

Impulse response measurements were performed using omnidirectional microphones (Behringer ECM8000 with flat sensitivity in the frequency range of investigation, 125 Hz – 8 kHz) and an omnidirectional sound source (Norsonic Nor276), using exponential sweep excitation. The positions of sound sources and microphones are shown

Figure 3. Floor plan (left) and photo (right) of restaurant Breweria 1, with indication of sound sources and microphone positions. Circles indicate sound sources, squares indicate microphones used during impulse response measurements, the black microphone indicates the position of the sound pressure level monitoring device.

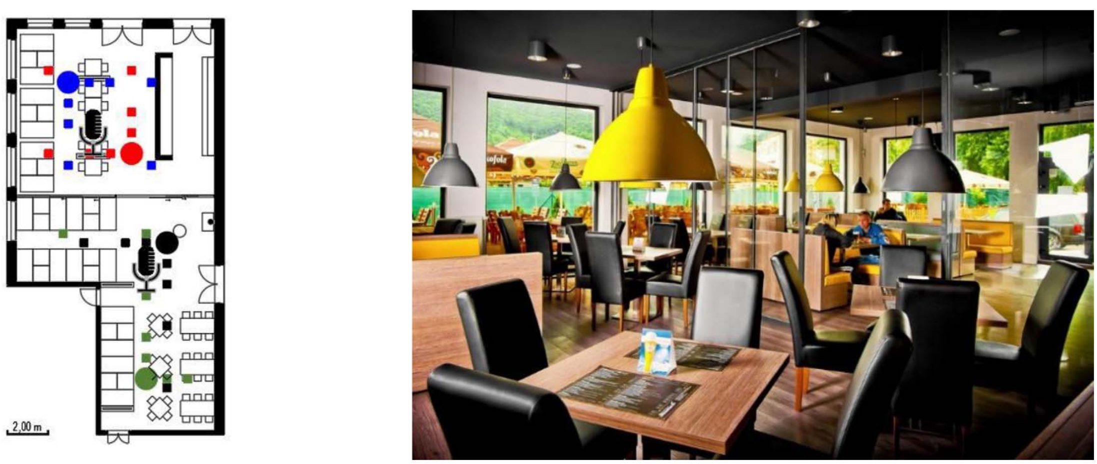

Figure 4. Floorplan (left) and photo (right) of restaurant Breweria 2, with indication of sound sources and microphone positions. Circles indicate sound sources, squares indicate microphones during impulse response measurements, the black microphone indicates the position of the sound pressure level monitoring device.

in Figures 1–4 (circles indicate sound sources and squares indicate positions of microphones). The heights of the sound sources were 1.5 m above the floor and the heights of the microphones were chosen as 1.2 m above the floor. For individual measured points, the signal was averaged via three signal repetitions. The sampling frequency of recording was 44.1 kHz.

Several acoustic parameters were calculated from measured impulse responses. In this article we show the results of the reverberation time values T_{20}, T_{30}, the early decay time *EDT*, and the Deutlichkeit D_{50}, determined according to ISO 3382 [22]. Special attention was given to values of D_{50} at two speaker-listener distances: $d_1 = 1.6$ m and $d_2 = 3.2$ m, representing respectively a situation in a restaurant where a sufficient speech intelligibility should be reached among the people dining together at one table (d_1), and a situation where a certain privacy of speech between neighbouring tables (represented by distance d_2) is desired. The reported values of D_{50} at distances d_1 and d_2 were calculated by averaging values obtained for multiple source and listener positions, while maintaining the source-receiver distance (d_1 or d_2). Further on we list the mean values per octave band together with the standard deviation. It should be noted that by definition, the values of D_{50} assessed the influence of room reverberation in absence of other sound sources than the source of interest. They thus reflect the speech intelligibility in case of a quasi-unoccupied restaurant. For extrapolating D_{50} values to a more crowded situation, one should take into account deterioration due to noise from speakers on neighbouring tables, background music and cutlery sounds, and possible improvement due to the additional sound absorption of people in the room.

The four scenarios were also compared via the mean sound absorption coefficient of the respective interior surfaces, as calculated from the reverberation time using

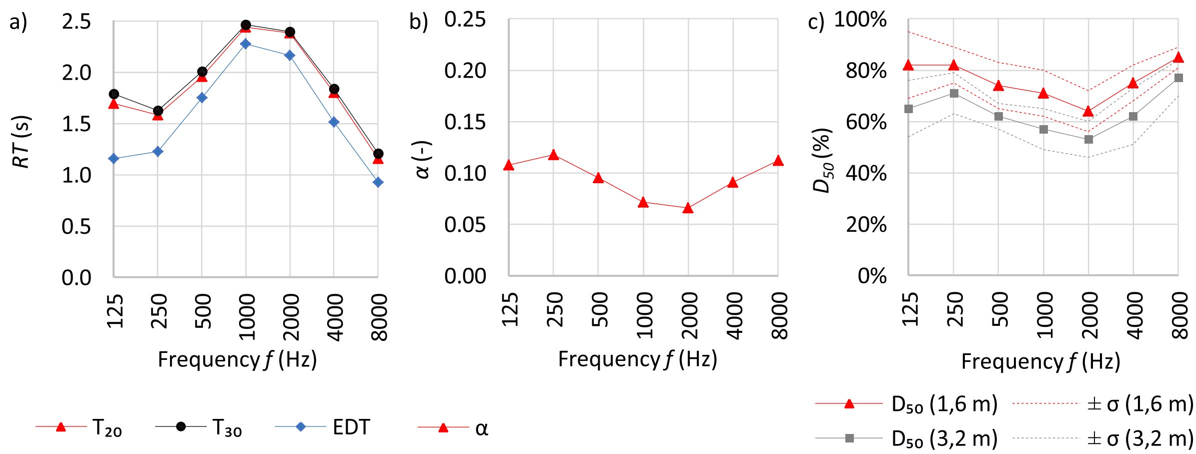

Figure 5. Scenario 1, student restaurant: average values of T_{20}, T_{30}, EDT (a). Mean absorption value of interior surfaces (b) and Deutlichkeit D_{50} at the microphone positions placed at the distance 1.6 m and 3.2 m from the sound source (c).

Sabine's formula (with consideration of influence of sound absorption in the air (Eq. (1)):

$$\bar{\alpha} = \frac{0,161\,\mathrm{V}}{T_{30}.S_{\mathrm{tot}}} - \frac{4\,\mathrm{mV}}{S_{\mathrm{tot}}}, \quad (1)$$

where V (m^3) is the volume of room, T_{30} (s) is the reverberation time, S_{tot} (m^2) is the total area of interior surfaces and m (m^{-1}) is the attenuation coefficient for atmospheric absorption.

Measurements of the time evolution of the sound pressure level (noise measurement) were performed at two microphone positions, using omnidirectional microphones (Behringer ECM8000) placed at 2 m above the floor (black microphone on the ground floor scheme). The number of people present people was monitored with the help of a video recording of low enough quality (face features not recognizable) to comply with privacy requirements, at a frame rate of one per second during 2–5 h. For the sake of privacy compliance, the monitored sound was automatically converted to incomprehensible noise with the same frequency characteristic and amplitude. The people also were informed about monitoring during the experiment.

Long-term noise (sound pressure level) measurements were performed in each restaurant, with the main aim to determine the correlation between the number of talking people and the actual noise level in the given architectural settings. The number of people in each room was counted and saved in 1-minute intervals. Based on this information and on visual observations that about half of the people present in a restaurant was talking, the number of talking people was estimated.

The information about the amount of talking people in each room was then used for an estimation of the total sound pressure level that would be produced by people at normal vocal output, without taking into account the Lombard effect, using the following expression [23]:

$$L_{\mathrm{P,tot}} \cong L_{\mathrm{P,diffuse}} \cong L_{S,A,1\,m} + 10\log_{10}(N_{\mathrm{S}}) + 10\log_{10}\left[\frac{16\pi c T_{30}}{24\,\mathrm{V}\,\ln(10)}\right], \quad (2)$$

where N_{s} is number of speaking persons, $L_{\mathrm{S,A,1\,m}} = 54$ dB is the vocal effort at a distance of 1 m for relaxed vocal effort [24], c (m/s) is speed of sound, V (m^3) is volume of room, T_{30} (s) is reverberation time.

4 Results and analysis

4.1 Impulse response measurements

Reverberation time values measured in Scenario 1 (Student restaurant SvF STU) were maximal in the middle frequencies, with $T_{30} = 2.5$ s (Fig. 5). As it is often observed, in comparison with T_{20} and T_{30}, the *EDT* values were consistently about 10–20% lower in all octave bands. The average sound absorption coefficient of interior surfaces was found to be about 0.07 around 2000 Hz. Around 250 Hz, the absorption was higher, 0.12, probably due to low frequency absorption by the suspended ceiling and the different pieces of furniture (chairs and tables). For middle frequencies, which are important for speech intelligibility, D_{50} values are about 60–75% at $d_1 = 1.6$ m source-receiver distance and 50–60% at $d_2 = 3.2$ m.

The average reverberation time in the second restaurant, the Faculty Club SvF STU Bratislava – Shupitoo, is varying between 1.2 s at low frequencies down to 0.6 s at high frequencies (Fig. 6). There is a clear difference between *EDT* and T_{20} (resp. T_{30}) mainly at low frequencies. Compared to the student restaurant SvF STU, the Faculty Club is smaller and its mean sound absorption coefficient $\bar{\alpha}$ (0.14–0.24) is twice as high. The latter can be attributed to the sound absorbing ceiling (low frequency absorption) and the wall that is made of perforated gypsum boards (middle and high frequency absorption). The value of D_{50} at $d_1 = 1.6$ m is accordingly high, around 80%. Doubling the distance (d_2), D_{50} reduces to 50–60 %. The combination between a high Deutlichkeit for a distance that is characteristic for a conversation between people on the same table (d_1) and a low Deutlichkeit for speech produced at another table (d_2) gives a good potential for a good balance between a good intelligibility of conversations of interest (between

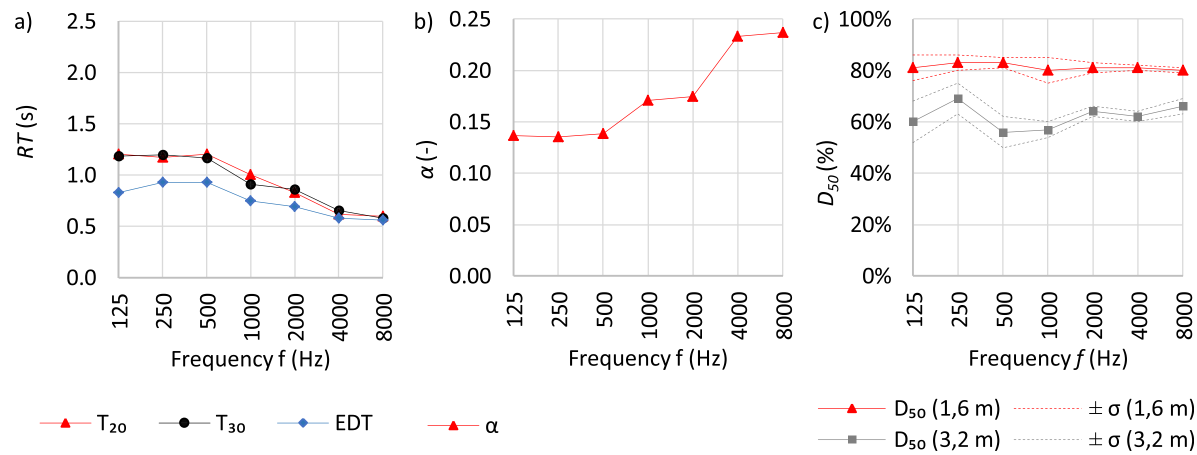

Figure 6. Faculty club: spectra of T_{20}, T_{30}, EDT (a). Mean alpha of interior surfaces (b) and Deutlichkeit D_{50} (c), for two source-receiver distances (1.6 m and 3.2 m).

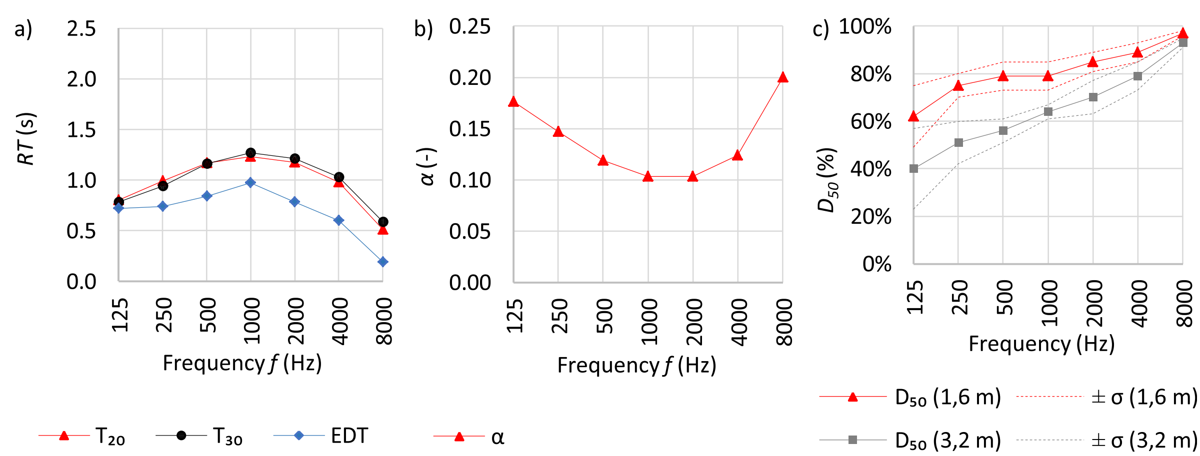

Figure 7. Breweria 1: spectra of T_{20}, T_{30}, EDT (a). Mean alpha of interior surfaces (b) and Deutlichkeit D_{50} (c), for two source-receiver distances (1.6 m and 3.2 m).

people sitting short by on the same table) while maintaining sufficient privacy with respect to neighbouring tables.

Measurements of the reverberation time in Breweria 1 resulted in values of 0.5–1.3 s, with a maximum in the middle frequencies (Fig. 7). Note that the maximal sound levels produced by human voices fall in this frequency range, i.e., between 500 and 2000 Hz. The mean sound absorption coefficient varies between 0.10 and 0.20. In this location, the large glass wall together with high ceiling made out of plasterboard contribute to sound absorption at low frequencies, while the thin porous surface imitating brick masonry acts as a porous sound absorber at very high frequencies. In order to understand the basic characteristics of this room and thus also the speech intelligibility in the absence of noise, D_{50} was analysed in the same way as in previous cases. The Deutlichkeit values at 1.6 m distance are above 75% for all frequencies important for human speech. The values at double distance are between 60% and 75%. For this location, the standard deviation between different measurement positions was much larger than in previous two cases, indicating that the speech intelligibility and privacy for restaurant guests in Breweria 1 depends significantly on the choice of the dining table.

As mentioned above, the restaurant Breweria 2 has a very similar interior design as Breweria 1, but its smaller volume brings along a shorter reverberation time. Values of T_{20}, T_{30} and *EDT* are depicted in Figure 8. The speech intelligibility indicator D_{50}, which is defined as the ratio between early energy and total energy in the impulse response without presence of background noise, is very high at both investigated source receiver distances (1.6 m and 3.6 m). This is logical, since this room is rather compact with moderate reverberation time. The very good speech intelligibility till larger distances from a speaker resembles the situation of a well-designed classroom.

In order to compare the acoustic situation in the four rooms, we consider the average sound absorption $\bar{\alpha}$ (–) (Fig. 9). Breweria 2 and Shupitoo yield the highest sound absorption at middle frequencies. Shupitoo scores the best in the high frequency range, which is favourable for damping the sound of cutlery, etc. Breweria 2 has better properties in the low frequency range, which is beneficial to damp

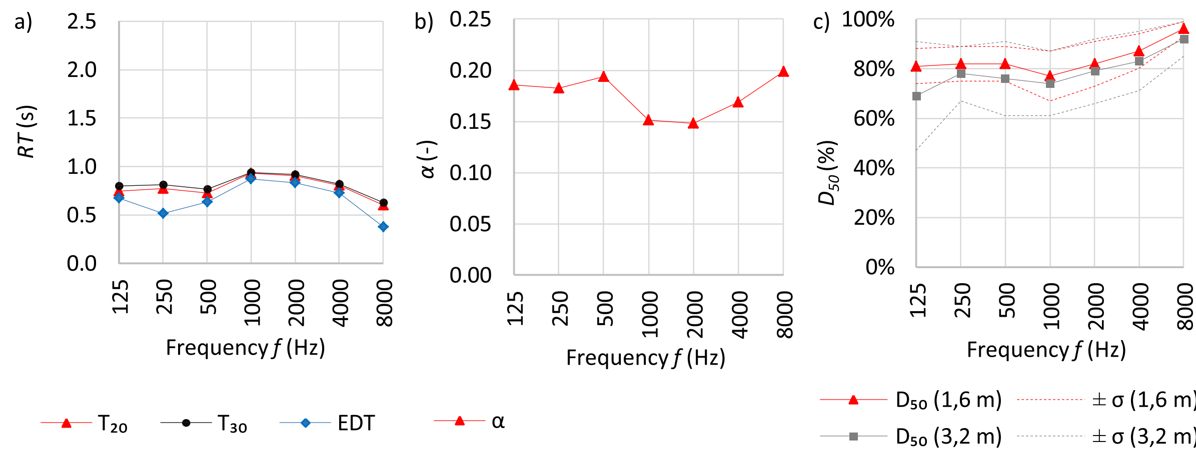

Figure 8. Breweria 2: spectra of T_{20}, T_{30}, EDT (a). Mean alpha of interior surfaces (b) and Deutlichkeit D_{50} (c), for two source-receiver distances (1.6 m and 3.2 m).

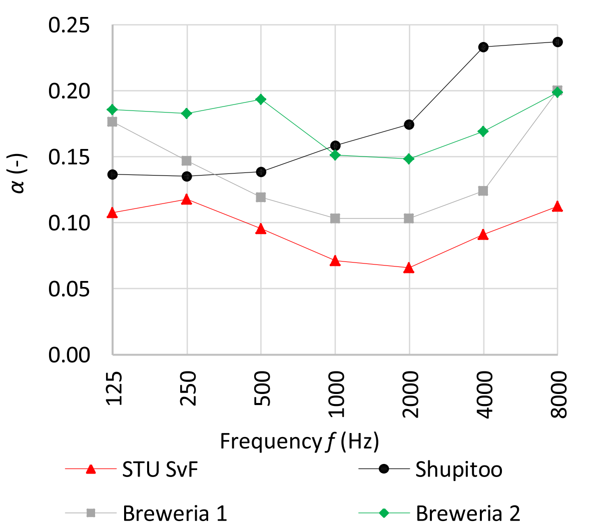

Figure 9. The mean sound absorption coefficient in the four investigated cases.

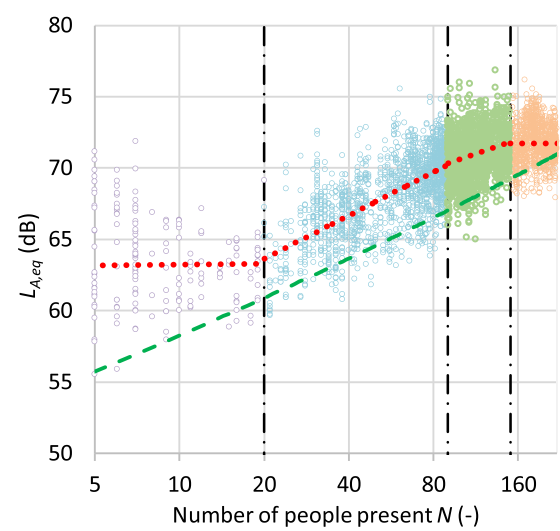

Figure 10. Correlation between the number of present people and the sound pressure level in the student restaurant SvF STU. The simulated dashed green curve in Figure 10 represents the sound pressure level assuming diffuse field conditions (Eq. (2)), assuming 1 person per 4 people present, is talking with average sound pressure level $L_{\mathrm{S,A,1\ m}} = 54$ dB at one meter distance (equivalent with a point source with an A-weighted sound power level of 65 dB [23]). The diffuse field assumption is feasible since for all measured spaces the spectral values of T_{30} and T_{20} are very similar and do not deviate too much from EDT.

the background sound coming from male voices and human steps. The student restaurant has very little sound absorption. Breweria 1 lies somewhere in between.

4.2 Analysis of the noise measurements

4.2.1 Scenario 1: Student restaurant SvF STU

As a first step, the background noise level in the room was measured in the absence of students. The soundscape was characterized by noises originating from the kitchen, fridges, the ventilation system, etc, with values of $L_{\mathrm{p,A}} = 46$–48 dB. According to Ref. [24], these values of sound pressure level are slightly lower than those produced during a conversation in a quiet environment ($L_{\mathrm{S,A,1\ m}}$).

Figure 10 shows the dependence of the total sound pressure level in the student restaurant on the number of people present. Measurements were taken during lunchtime in a period of two weeks, in intervals of 15 s. The lowest number of people present in the student restaurant was 5, the average maximum amount was around 230 and the maximum value of equivalent sound pressure level $L_{\mathrm{A,eq}}$ was approximately 75 dB. The evolution of the piecewise linear red dashed trendline through the experimental data indicates that there are four acoustic regimes, characterized by a different increase of sound pressure level per doubling of the number of people present. The dashed green line indicates the increase in sound pressure level according to diffuse field theory (no Lombard effect). This line is shown for reference and has a slope of 3 dB per doubling of the amount of people present.

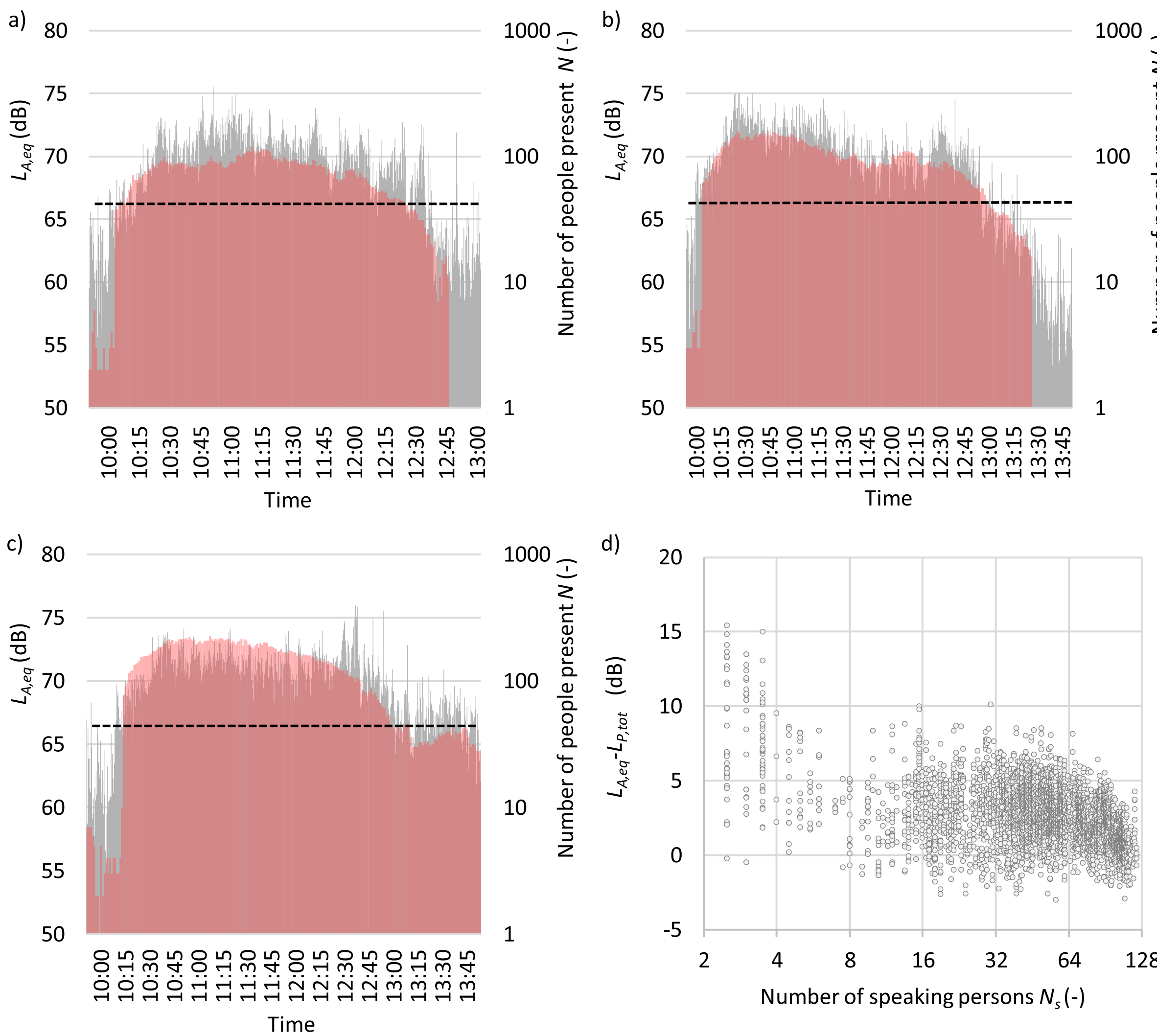

Figure 11. Time evolution of the noise level in STU-Bratislava student restaurant on Monday (a), Thursday (b) and Midday (c). The sound pressure level values are depicted in grey and the number of people present in pink. The acoustic capacity $N_{\max} = 40$, is indicated by the horizontal black dashed line In d), the difference $L_{\mathrm{A,eq}} - L_{\mathrm{P,tot}}$ is plotted depending on the number of theoretically active sound sources, i.e. half of the persons present.

In the purple zone, for a relatively small amount of people present (<20), the sound pressure level fluctuates significantly. The strong fluctuations are probably caused by the large size of the room and the uncontrolled spread of people. (2 – blue rings). In the blue zone, with between 20 and 90 students present, the increase of sound pressure level with increasing amount of people is slightly larger than the one of the reference line, implying a moderate Lombard effect: with increasing background noise people keep adapting their vocal level in an attempt to be intelligible for their listeners.

In the green zone, with between 90 and 160 people present, the slope decreases to about 2 dB/doubling of number of people present, indicating that the acoustic capacity of the space is reached. The above-mentioned adaptation thus weakens from about 90 people present, i.e. from an occupation level of about 1 person per 5 m^2 of ground surface and higher. Interestingly, this saturation effect occurs for an occupation level that is substantially larger than the value obtained from a model for the acoustic capacity $N_{\max}$ proposed by Rindel [14],

$$N_{\max} = \frac{V}{20T} \tag{3}$$

with V the volume of room and T the reverberation time (s) (average values obtained for octave bands 500 Hz and 1000 Hz). Calculation of the $N_{\max}$ for student restaurant, delivers a value 40. (Theoretically this value would range from 36 – for the reverberation time at 500 Hz, which is the center of gravity of the speech spectrum [26] up to 44 people, for the reverberation time at 1000 Hz). We can see that this is less than half of the here observed occupation number of 90. However, when we take into account the visual observation that about half of the people were simultaneously talking, then the prediction for $N_{\max}$ would be consistent with the number of talkers present.

In the orange zone, for more than 150 people present (for 1 person per 3 m^2), the sound pressure level does not increase anymore with increasing number of people present, implying that the overall noise level is so high, that some people simply stop to talk, or that less newcomers entering the restaurant start to talk, due to the already too loud environment. Another cause might be that people get closer to each other so that they are more intelligible without increase of vocal power (as seen in earlier laboratory experiments [25]).

In order to illustrate the fluctuation of noise levels versus time (depending on the amount of people present in the room), 3 typical examples (3 week – days) are presented in Figure 12. A massive entry of students into the canteen can be seen at lunchtime. Similar to Figure 11, also in Figure 12 a quasi-constant noise level of around 70 dB is observed in case the number of people in the room exceeds 90. For a lower occupancy, the noise level correlates well with the number of people. Figures 12a–12c show also the noise level in the initial stage without the visitors of restaurant, only with the staff present (from time 0 on x-axis until red bars/number of people present rapidly grows up). The background noise level is high enough to people increase their vocal effort by entering to the room.

Figure 11c represents a situation in which the number of customers exceeds the capacity of the restaurant (ca 200 people), which is, in this case, 4× its theoretical acoustic capacity. As long as N, the number of present people, is below two times $N_{\max}$, the noise level increases with increasing N, but after a few minutes (with even more people inside the room) the level drops again to around 70 dB, the value obtained at $N_{\max}$.

The occurrence of the Lombard effect is illustrated in Figure 11d, which depicts the difference between the real, measured equivalent noise level and the calculated noise level $L_{\mathrm{P,tot}}$. The graph shows that for small occupancy of the restaurant, the Lombard effect is high: people substantially increase their vocal power in an attempt to be more audible with respect to the background noise. With increasing occupancy and thus increasing background noise level, the Lombard effect decreases, as less people are able or willing to increase their voice due to the too high background noise level.

4.2.2 Restaurant club shupitoo

In Figure 12 the dependence of the noise on the number of occupants in the Restaurant Club STU Shupitoo, based on two weeks of measurement, is depicted. The maximum number of seating places was around $N_{\mathrm{seats}} = 50$ and the maximum equivalent sound pressure level was around 76 dB. Visual observation learnt that every second person led the conversations, which implies 25 people talking in case of maximum occupancy. According to equation (3), the average acoustic capacity of this space is approximately $N_{\max} = 24$. When comparing the simulated $L_{\mathrm{P,tot}}$ (N) curve (green dashed line) with the trend curve of measured values (red dotted curve), both similarities and differences can be observed with respect to the previous case (student

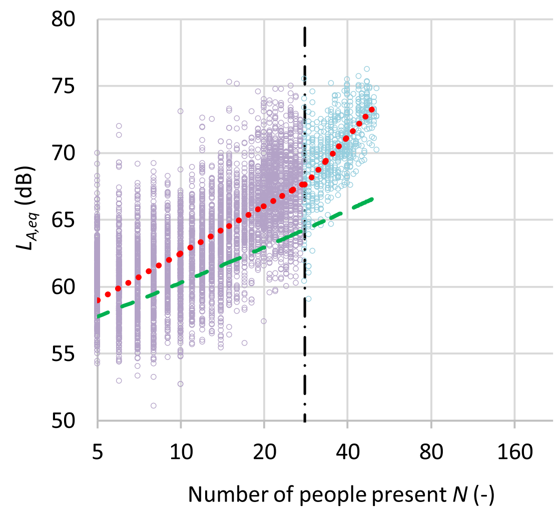

Figure 12. Dependence of the number of people present and the sound pressure level in restaurant Club Shupitoo. The black dot-dashed line indicates the situation for $N = N_{\max} = 24$, where the rate of increase of sound pressure level with increasing number of talking people accelerates.

restaurant). The equivalent sound pressure level increases with increasing number of people present. For less than $N = 30$ people, an increase of 3–5 dB per doubling of the number of people can be noticed. Interestingly, for higher numbers of people, the increase in sound pressure levels accelerates to between 6 and 8 dB per doubling of N. Customers and waiters working in this restaurant expressed their satisfaction about the acoustic comfort, [20] which is most probably thanks to good correspondence between the seating capacity N_{seats} and the acoustic capacity $N_{\max}$ of the restaurant.

Figure 13 shows three examples of the time dependence of the sound pressure level and the occupancy from before till after lunch time during weekdays. People keep increasing their voice with increasing noise in the room, clearly illustrating the Lombard effect, and the sound pressure level correlates very well with the number of people present in the room.

The background noise levels before the arrival of first customers in this room were around 50–52 dB and were caused by sounds related to operational activities of the restaurant staff and to music played through loudspeakers.

4.2.3 Restaurant Breweria 1

The measurements in restaurant Breweria 1 were carried during the course of only one day (on a Monday). For this reason, the number of data and information is smaller in comparison with the previously discussed cases. The number of people present here was approximately 50. The impact of the increasing number of restaurant customers on sound pressure level is illustrated in Figure 14. No empirical information can be extracted on $N_{\max}$, but the data do show that the increase of the sound level with increasing number of people present is consistent with the theoretical prediction, at an absolute level that is 3 dB higher.

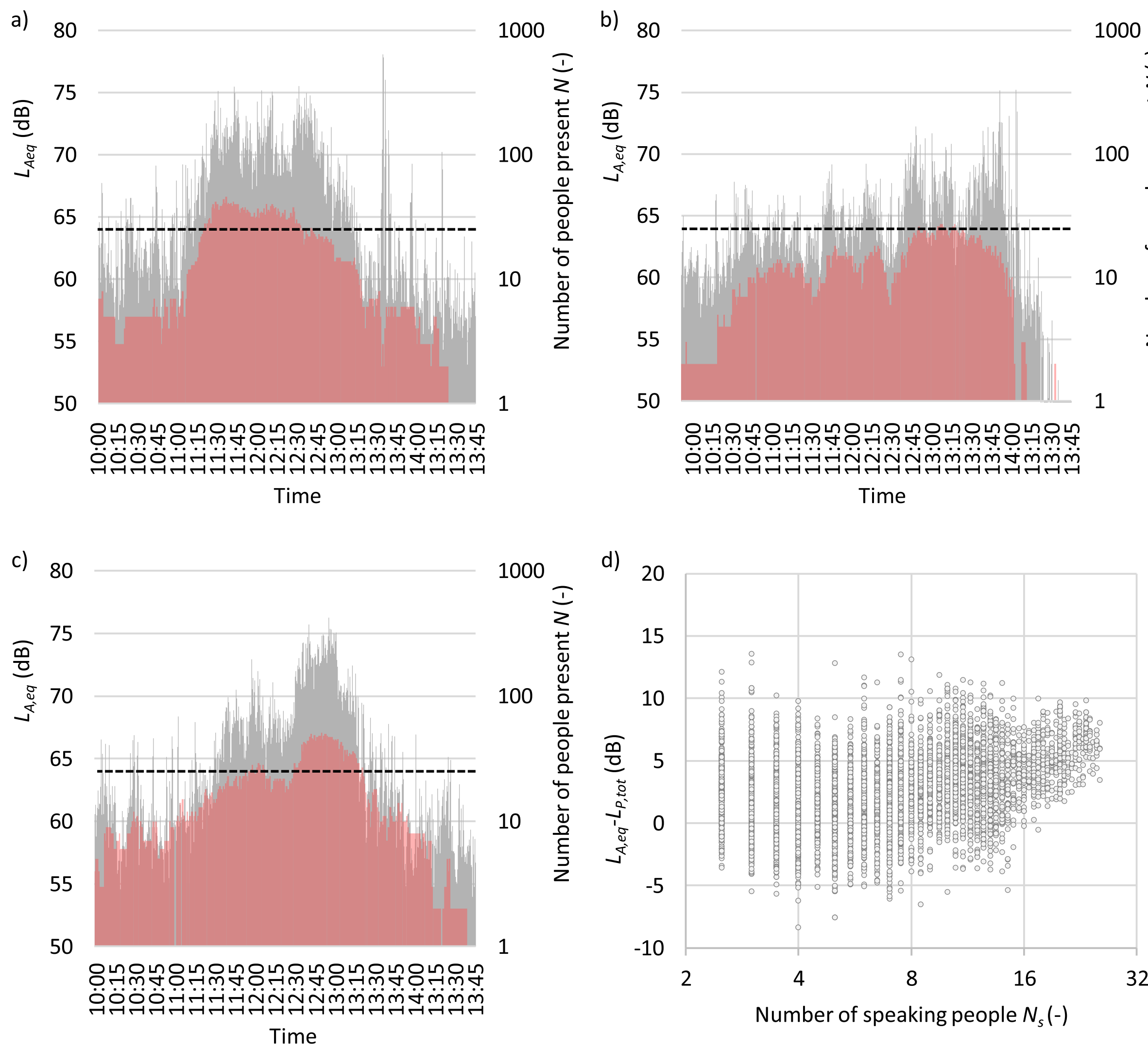

Figure 13. Time evolution of the noise level in restaurant Club Shupitoo on Thursday (a), Wednesday (b) and Monday (c). The sound pressure level values are depicted in grey and the number of people present in pink. The acoustic capacity $N_{\max} = 24$ and is indicated by the black dashed line. In the bottom right panel, the difference $L_{\mathrm{A,eq}} - L_{\mathrm{P,tot}}$ is plotted depending on the number of theoretically active sound sources, i.e. half of the persons present (d).

The detailed evolution of the number of people and the noise level during the measurement day is presented in Figure 15. The two parameters evolve in a quite similar way. Nevertheless, towards the end of the measurement period (after the lunch), the decay of the noise is slower than the one of the number of people. This indicates that people keep talking with increased voice, possibly due to change in type of background noise, such as music, or other sounds present in the room. Figure 15 (right) confirms the presence of Lombard effect in this scenario.

4.2.4 Restaurant Breweria 2

Noise measurements in restaurant Breweria 2 were performed on Tuesday. In comparison with the previous eating places, this restaurant has a different ground plan, with two compartments that have a similar reverberation time. During the measurement, also the occupancy and the distribution of the customers in the two compartments was similar.

The dependence of L_{P} on correlation with the number of people is plotted in Figure 16. Again, making the assumption that verbal communication was conducted by half of the people present, during this measurement, the maximal possible number of speaking persons was 14. Inserting the volume and the reverberation time in the frequency bands typical for speech in equation (3), $N_{\max}$, the acoustic capacity parameter was determined to be 30 people, which is more than double of the maximum occupancy during the measurement. The trend curve through the measured noise level data is almost collinear with the theoretically predicted one based on equation (2). In this restaurant people increased their voice only occasionally. This is a consequence of the compartmented structure and of the people sitting rather far away from each other, so that no spiral of competitive conversation was triggered.

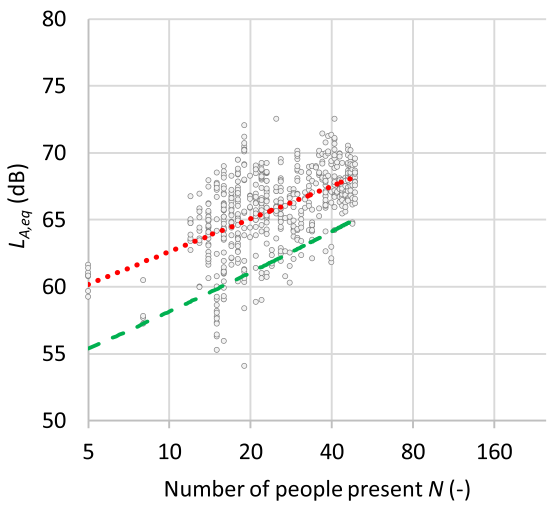

Figure 14. Dependence of the sound pressure level on the number of people present in restaurant Breweria 1 (Red dotted line). Green dashed line indicates the increase of sound pressure level in case no Lombard effect would occur.

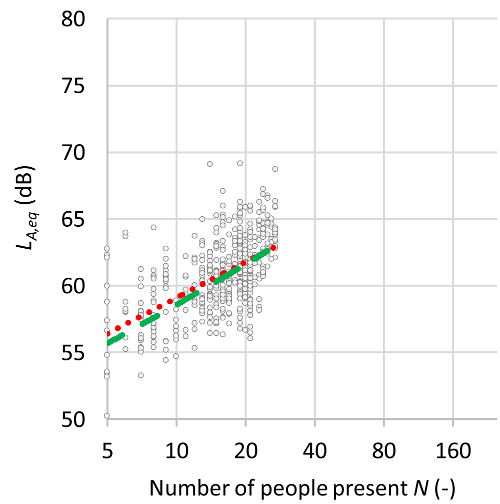

Figure 16. Sound pressure level as a function of number of people present in restaurant Breweria 2.

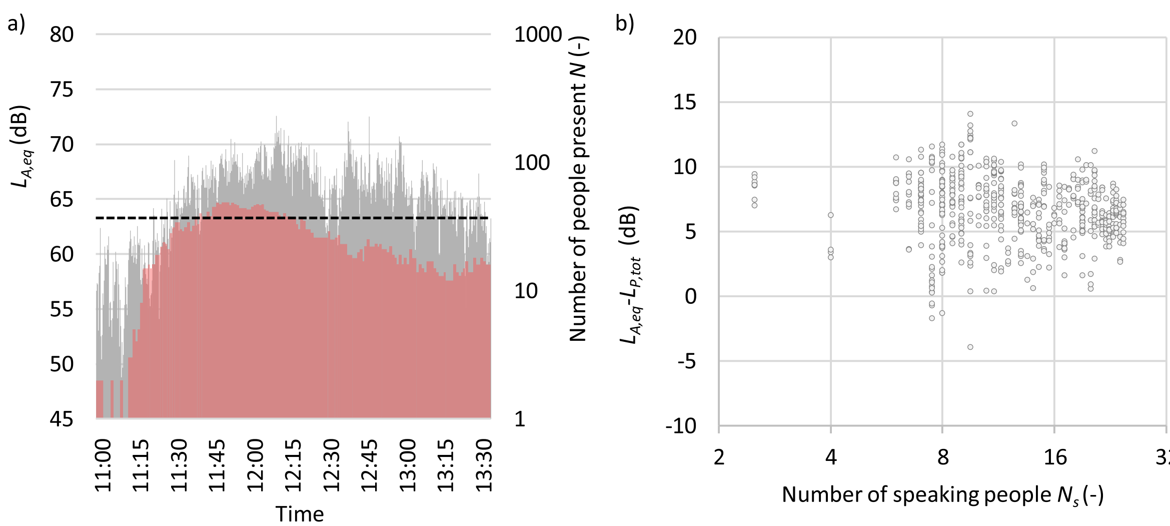

Figure 15. Noise level measurement in restaurant Breweria 1 on a Monday. (a) Evolution of sound pressure level (grey) and the number of people present (pink), versus time. (b) Difference $L_{\mathrm{A,eq}} - L_{\mathrm{P,tot}}$ versus the number of theoretical active sound sources (assumed to equal half of the number of persons present).

Figure 17 shows that despite the low number of people present in the room, the sound pressure level shows a clear correlation with occupancy.

Due to the low occupancy during this measurement, it was cumbersome to estimate the fraction of talking people and the associated Lombard effect. The background noise level in this restaurant was similar as in restaurant Breweria 1, approximately 54 to 56 dB. At this moderate noise level, indeed no significant Lombard effect is expected.

4.3 Comparison between restaurants

The left panel of Figure 18 shows a comparison between the reverberation time spectra of the 4 investigated restaurants, and the optimum range for comfortable communication according to standard DIN 18041 [27] and CSN 73 0527 [28]. The reverberation time spectra of restaurants Shupitoo (Faculty club), Breweria 1 and Breweria 2 are near optimum for almost all frequencies. The reverberation time spectrum of the canteen STU SvF is in its entirety above the optimal reverberation time range. Its maximum value occurs around 1000 Hz. It is approximately twice the optimal value. If we consider that the frequency content of human speech is dominated by the frequency bands from 250 Hz to 4000 Hz [29, 30], it is obvious that the acoustic comfort in general and the verbal communication in particular in that very reverberant space is problematic. This is also confirmed by the middle panel of Figure 18, which shows the average maximum noise level and the corresponding average number of people present.

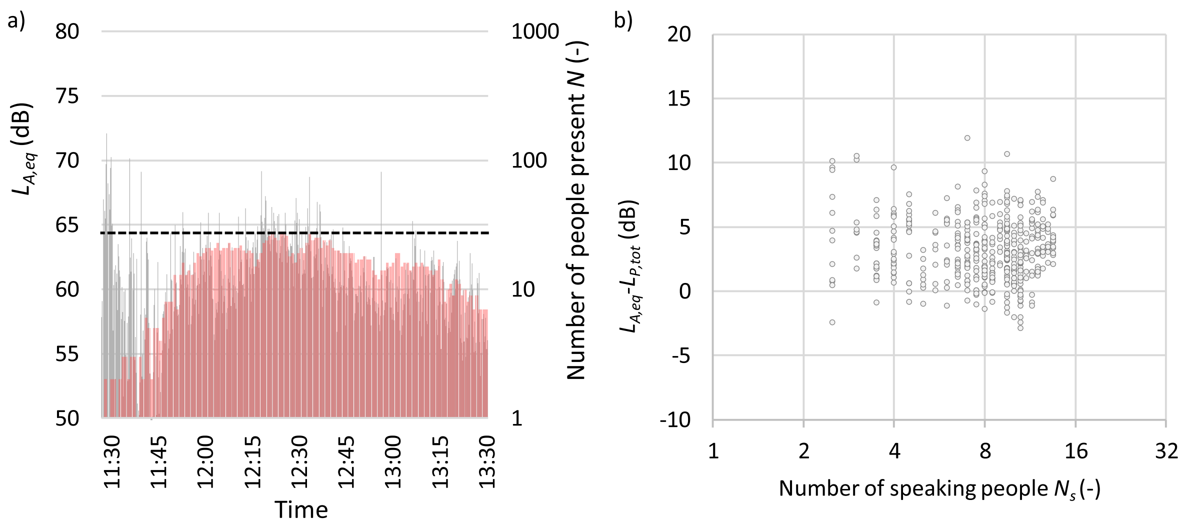

Figure 17. Noise level measurement in restaurant Breweria 2 on a Tuesday. (a) Evolution of sound pressure level (grey) and the number of people present (pink), versus time. (b) Difference $L_{\mathrm{A,eq}} - L_{\mathrm{P,tot}}$ versus the number of theoretical active sound sources (assumed to equal half of the number of persons present).

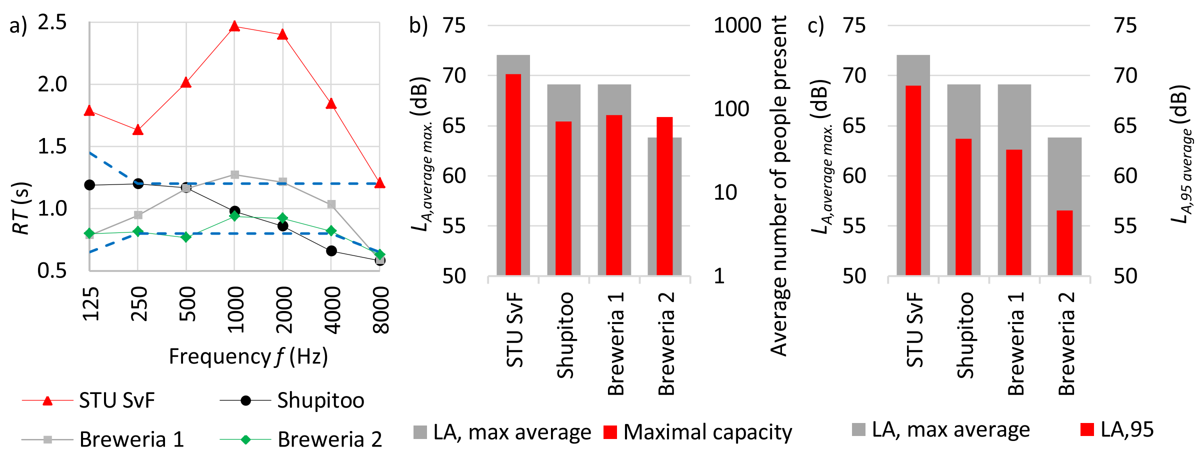

Figure 18. a) reverberation time T_{30} in the four restaurants, and boundaries of optimum range according to standards DIN 18041 and CSN 73 0527, b) average of maximum observed noise levels and the corresponding numbers of people present, c) comparison between the average maximum noise level and the average noise level $L_{\mathrm{A,95}}$.

The verbally most active communication (highest dB per person ratio) occurred in restaurants Shupitoo (the Faculty Club), Breweria 1 and Breweria 2, which show relatively high noise levels even for relatively low numbers of people present. In the STU SvF canteen, in spite of a lower relative occupancy, but, as a consequence of the long reverberation time, the noise level was almost the same as in the case of Shupitoo or Breweria 1.

In the right panel of Figure 18 the average maximum noise levels in the different restaurants are compared with the respective $L_{\mathrm{A,95}}$ levels, which give a good idea on the background noise. Also according to this quantity, the canteen STU SvF is the most noisy place: the $L_{\mathrm{A,95}}$ background never drops below 69 dB. In order to achieve SNR of at least 0 dB, which is typically rated as "sufficient" in terms of speech intelligibility [15], the vocal effort needs to be at least the same level as the background noise. According to standards [24] and previous speech research [15, 16], the vocal effort that is needed to reach 69 dB at a distance of 1 m from a speaker is rated between "raised ($L_{\mathrm{SA,\ 1m}}$ = 66 dB)" and "loud ($L_{\mathrm{SA,\ 1m}}$ = 72 dB)". In case of restaurants Shupitoo and Breweria 1, the required vocal effort would only be 63–64 dB, which is rated between "normal ($L_{\mathrm{SA,\ 1m}}$ = 60 dB)" and "raised". In order to raise the speech intelligibility from "sufficient" to "good", the SNR would need to be raised to minimum 3 dB, which would imply a vocal effort yielding 72 dB, which is already quite strenuous for the vocal cords. Compared to the student canteen, Shupitoo, Breweria 1 and Breweria 2 can be considered to be quite pleasant in terms of verbal communication.

Table 1 shows the monitored parameters of the examined restaurants. The average absorption area per person appears to be the most influential parameter on the development of noise levels due to talking people. In the case

Table 1. Summary of parameters of the investigated restaurants.

Room parameters						
Value	Unit	Student canteen	Shupitoo	Breweria 1	Breweria 2
Maximal capacity	People	264	71	84	81
Average maximum of people present during the performed measurement	People	189	37	49	27
Average ceiling height	m	3.75	3.50	3.40	3.22
Surface	m^2	1493	513	919	562
Floor area	m^2	466	145	241	157
Volume	m^3	1775	525	816	506
Average table distance	m	1.35	1.64	1.50	1.12
Area per person (calculated from maximal capacity)	m^2/person	5.65	7.22	10.97	6.49
Volume per person (calculated from maximal capacity)	m^3/person	6.62	7.39	9.71	6.24
Average table area per person (calculated from maximal capacity)	m^2/person	0.26	0.24	0.27	0.26
Average D_{50} (1.6 m)	%	76	81	84	84
Average D_{50} (3.2 m)	%	64	62	71	79
Average reverberation time T_{avg}	s	1.91	0.95	0.99	0.81
Reverberation time at 1000 Hz	s	2.47	0.98	1.24	0.94
Reverberation time at 500 Hz	s	2.01	1.17	0.86	0.76
Reverberation time T_{20}, mid	s	2.24	1.1	1.05	0.85
Average acoustic capacity N_{max}	Persons	40	24	39	30
Average sound absorption	–	0.09	0.17	0.14	0.18
Average sound absorption area per person (calculated from maximum number of people present)	m^2/person	0.71	2.35	3.19	3.75
Average sound absorption area per person (calculated from maximal capacity)	m^2/person	0.51	1.22	1.53	1.25

of the school canteen, where the average absorption area is 0.7 m^2/person, there is a relatively high level of constant noise $L_{A,95}$ and due to the number of persons present, a low level of $L_{A,eq}$. In the case of Shupitoo, Breweria 1 and Breweria 2 restaurants, the floor area per person ranges from 2.4 m^2/person (Shupitoo) to 3.8 m^2/person (Breweria 2). There was a pleasant verbal communication in those restaurants, despite the relatively high level of $L_{A,eq}$. In the case of the school canteen, where the acoustic capacity of the space was significantly exceeded, the absorbing area corresponding to 20 people present is about 2.7 m^2/person.

Figure 10 shows the rise of the noise level parallel to the theoretical calculated value with shift of 3 dB in the interval from 20 to 90 people present. The average absorption area in the student canteen with 90 people present is approximately 1.5 m^2/person. Beyond 90 people present, and thus below 1.5 m^2 of absorption per person, the increase of noise level with increasing number of people decelerates and the rate of increase goes below 3 dB per doubling of amount of people present, which would reflect a situation of talking people whose vocal output is not affected by the surrounding soundscape. The noise level even saturates beyond a number of people present of 160. The absorption area corresponding to 160 people present is 0.8 m^2/person.

One could wonder whether the deceleration of the rate of increase that was found in the case of the school canteen with 90 people present and an average absorbing area of approximately 1.5 m^2/person, would also occur at a threshold value of 1.5 m^2/person in other restaurants. However, from the measured results, it was not feasible to verify this for the other examined restaurants, as such low absorbent area values per person were not achieved. The smallest absorption area (2.4 m^2/person) was achieved in the case of the Shupitoo restaurant, with a maximum number of 37 people present. Till that value, the noise level increased with increasing number of people present. This suggests that for an absorbent area of 2.4 m^2/person, the restaurant still has an acoustic environment that is ok for verbal communication.

5 Conclusions

Situations with the number of occupants equal than or larger than twice the acoustic capacity of the space show a significant impact of the Lombard effect on verbal communication with increasing number of people present. Typically, up to 1/2 of the people present were verbally active, but not more than the number of people corresponding to the acoustic capacity of the considered space N_{max}. Comparing the measured noise levels with predictions that assumed a typical vocal effort for each talker, and half of the present people talking, indicated the occurrence of the Lombard effect, with excess values up to 12 dB. The value of the acoustic capacity N_{max} proved to be a suitable parameter for determining the maximum number of talking people in a space. For a larger occupancy of the space, which occurred in the student restaurant, the rate of increase of sound pressure level with increasing number of people present was found to decelerate to lower than +3 dB per doubling of number of people present. The measurements showed that in spite of the larger occupancy, about 250, in student restaurant STU SvF, the sound pressure level (up to 75 dB) was not higher than in the smaller and less occupied restaurants, Shupitoo and Breweria 1, where the levels were significantly boosted by the Lombard effect. In the Breweria 2 restaurant, the noise levels were consistent with theoretical predictions that assumed the background level independent vocal effort, indicating that in that space, by virtue of the separation into two parts and larger distances between people present (approximately every second table was partially occupied) the Lombard effect was absent.

Observations made in the Shupitoo restaurant and the school canteen, where higher values of the people present were reached, allowed to assess the influence of the average sound-absorbing area per person on the development of verbal communication. Based on the rate of increase of sound pressure level with increasing number of people present, it turns out that for an average absorption area of 2.4 m^2/person, verbal communication was feasible, and that it was affected by the Lombard effect. However, when, in the case of the school canteen, the average absorption area fell below about 1.5 m^2/person (for 90 people present), the rate of level increase with increasing number of people present decelerated, and the sound level even saturated when the occupancy of the space was so high that the average absorption area went as low as 1 m^2/person. It should be stressed that compared to the other restaurants, the equivalent absorbing area of the surfaces of the student canteen was a factor 2 or more lower.

In order to ensure maximum comfort for the facilities, detailed analyses of people's behaviour in terms of psychoacoustic perception are essential. The lunch time, which is the most important work break of the day, should enable a pleasant exchange between colleagues and a relaxation to recharge their energy for the second half of the working day. A poor acoustic situation creates an environment that is reflected in the reluctance to communicate and to enjoy the time necessary for relaxation, as is the case of student restaurant STU SvF. The experiments show that in an acoustically pleasing environment (Shupitoo, Breweria 1 and Breweria 2), people do not experience problems to communicate even at higher noise levels, unless the clarity of sound is decreased, due to low absorption of surfaces and thus long reverberation time.

The measurements in the student restaurant showed an interesting trend of the sound pressure level versus the number of people present in the room, with indication of the occurrence of the Lombard effect, and, for a high occupancy, a gradual saturation of the sound pressure level. The latter observation indicates that the acoustic comfort was deteriorated to such extent that people started to be less talkative. Comparison of the room occupancy where the saturation occurred with a value for the acoustic capacity N_{max} of the space as calculated according to an expression proposed by Rindel [13] suggests that this value should not be interpreted as the number of people present, but as the number of talkers present. In the student restaurant, the fraction of talking people was about half of the total number of people present.

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