Individual control as a new way to improve classroom acoustics

A simulation-based study

Zhang, Dadi; Tenpierik, Martin; Bluyssen, Philomena M.

DOI
10.1016/j.apacoust.2021.108066

Publication date
2021

Document Version
Final published version

Published in
Applied Acoustics

Citation (APA)
Zhang, D., Tenpierik, M., & Bluyssen, P. M. (2021). Individual control as a new way to improve classroom acoustics: A simulation-based study. *Applied Acoustics*, *179*, Article 108066.
https://doi.org/10.1016/j.apacoust.2021.108066

Applied Acoustics 179 (2021) 108066

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Individual control as a new way to improve classroom acoustics: A simulation-based study

Dadi Zhang *, Martin Tenpierik, Philomena M. Bluyssen

Faculty of Architecture and the Built Environment, Delft University of Technology, the Netherlands

ARTICLE INFO

Article history:
Received 2 March 2020
Received in revised form 26 October 2020
Accepted 25 March 2021

Keywords:
Room acoustics
Individual control
Ray-based simulation
Lombard effect

ABSTRACT

Previous studies indicate that acoustic improvements at classroom-level, such as using ceiling panels, do not work well to solve noise problems in classrooms. Therefore, this study introduced a new way – individual control – to improve classroom acoustics. The acoustic effect of five different classroom settings is simulated: two individual-level acoustic improvement settings ("Single-sided canopies" and "Double-sided canopies"), two classroom-level acoustic improvement settings ("Half-ceiling" and "Full-ceiling"), and one "Control" setting. The simulation was accomplished with Computer Aided Theatre Technique (CATT-Acoustic™), which is a ray-tracing-based room acoustics prediction software package. According to the two main ways of using classrooms (instruction and self-study), the simulations were run for two situations: instruction situation and self-study situation, and the Lombard Effect was taken into consideration in the self-study situation. The results showed that in both situations, all of these improvement settings, compared with the "Control" setting, could shorten the reverberation time and increase the speech transmission index, and the improvements caused by the individually controlled canopies were more obvious than caused by the ceiling panels. Additionally, in the instruction situation, the individual-level improvements could increase the sound pressure level of the teacher's speech, while in the self-study situation, the individual-level improvements could decrease the sound pressure level of other children's talk. In the future, it is recommended to produce and test different individually controlled devices in a lab or real classroom to verify these results.

1. Introduction

In the past decades, the acoustic conditions in classrooms have drawn much attention. Current conditions of acoustic quality in classrooms as well as effects of poor acoustics on children's health and performance have been studied [1–3], and many acoustic guidelines have been issued [4,5]. A previous Dutch study indicated that noise is the biggest indoor environmental problem in classrooms: 87% of primary school children reported to be bothered by it [6]. One year later, a lab study involved some of the same group of children demonstrated that children perceived sounds better in the acoustically treated room than in the untreated room [7]. Besides, some other studies also showed that poor room acoustics have an adverse impact, not only on children's school performance [8], but also on their later life [9,10]. To create an effective learning environment, many recommendations and standards on classroom acoustics have, therefore, been developed.

Most countries have their own acoustic criteria for schools. For example, the United Kingdom Building Bulletin 93 [5] provides a comprehensive guidance and recommendations for the acoustic design of schools. According to it, the teaching and studying space should provide a suitable Reverberation time (RT) for "clear communication of speech between teacher and student" and for "clear communication between students". Besides, the Nordic countries also have their own performance criteria, and a previous study found that the RT limits are getting tighter (shorter RT) in these countries [11]. In 2015, the Netherlands tightened its own primary school guidelines which classify three different quality levels (A: very good; B: good; C: acceptable) for the acoustics of classrooms [12].

According to these guidelines and some previous studies, classroom acoustic conditions are usually evaluated by the following parameters: reverberation time (RT), Sound Pressure Level (SPL), and Speech Transmission Index (STI) or any other speech intelligibility variable [5,13–15].

---

* Corresponding author at: Julianalaan 134, 2628 BL, Delft, the Netherlands.
E-mail address: d.zhang-2@tudelft.nl (D. Zhang).

https://doi.org/10.1016/j.apacoust.2021.108066
0003-682X/

- RT is regarded as an important evaluation indicator in many standards, sometimes it even is the only indicator, and usually only an upper limit is clearly defined, while a lower limit is rarely mentioned [16]. Over the past decades, the requirements concerning RT have become much stricter. However, a too short RT could also be a problem since it could lead to overdamping negatively impacting the audibility of sound. Therefore, an extremely short RT (shorter than 0.3 s) should also be avoided [7,17].
- Besides, SPL is another vital acoustic parameter used to assess classroom acoustics, , especially when it comes to speech intelligibility [20]. However, most classroom acoustic standards only pay attention to background SPL [4], while the SPL of teachers' speech or children's talk are hardly mentioned.
- Additionally, the STI is also a common index used in many school acoustics guidelines [18]. As a speech metric, the STI describes the effect of room reflections and ambient noise on speech intelligibility between a sound source and a listener [19].

In terms of good acoustics in classrooms, the stipulations about RT are clear and easy to find. Thus, RT was often used as the factor (sometimes even the only factor) to divide good acoustic and bad acoustic [21,22]. In the Netherlands, the specific requirement of RT in classrooms of primary school was described in Frisse Scholen 2015 [12] (see Table 1). Concerning SPL, most standards only mention the background SPL should be <35 dB (A) [4,12], while the stipulation of overall SPL in occupied classrooms is relatively rare since it depends on the learning activities. During instruction, the function of the classroom is to provide a good environment to ensure that children can hear their teacher well, therefore, the SPL of the teacher's speech near the children's positions should be high enough, especially higher than the background noise level (including noise produced by the children) [23]; while during self-study, the classroom should provide the children with a quiet environment to help them concentrate on their own work, therefore, an SPL due to other children's talk (which was the main noise source in classrooms [6]) as low as possible should be the aim [24]. For STI, one of the speech intelligibility metrics [19], its evaluation is shown in Table 2. Requirements of STI also depend on the learning activities. According to the Duplex Mechanism Account of Auditory Distraction (DMAAD) theory [25,26], human's attention can be distracted in two ways: 1. Interference-by-process: distraction caused by the interference inside the brain between the processing of intelligible speech related sounds and of a semantic task performed. 2. Attentional capture: distraction caused by the sound containing information that is salient or might be relevant to the person. Therefore, in a classroom, during instruction, the STI should be high to ensure that the teacher's message is conveyed well; while during self-study, the STI should be low to keep children from being distracted by other children's talk.

Table 1
Requirements on RT in Dutch guidance– Frisse Scholen 2015.

	Class C: Acceptable	Class B: Good	Class A: Very good
The average reverberation time in the octave bands 250 to 2000 Hz.	Maximum of 0.8 s.	Maximum of 0.6 s.	Maximum of 0.4 s.

Based on the above mentioned studies, in this paper, the better classroom acoustics is defined as a shorter RT (within limits), higher SPL (of the teacher's voice) and higher STI of teacher's speech during instruction, while a shorter RT (within limits), lower SPL (of the noise produced by the children) and lower STI of children's talk during self-study. However, the value of STI is influenced by the RT and background noise level [22,27]. For example, a shorter RT relates to a higher STI [25], and in a self-study situation, reducing the SPL of children's talk (which is the main noise source) will automatically increase the STI. Therefore, in this study, only a higher RT and lower SPL are regarded as the requirements in a classroom during self-study.

After the implementation of these standards and regulations, much effort has been given to improve the acoustics of many classrooms. A common way is the use of sound absorption materials, such as acoustical ceiling tiles, carpet, and sometimes acoustic wall panels [27]. However, most of these improvements are made at classroom-level; little has been done concerning the preferences and needs of individual child. Only for children with special requirements, some individually controlled devices are available, for example, the use of individual amplification systems for children with hearing loss [28]; or special headphones or earmuffs for children with autism spectrum disorder or with attention deficit disorder [29,30]. In fact, individual control, as an effective way to increase satisfaction, has already been used to improve many aspects of indoor environmental quality, such as thermal, air or light quality [31–34]. Additionally, according to a previous field study, an individually controlled sound absorbing device was the most wanted device in classrooms among school children in primary schools in the Netherlands [35]. However, is it really possible to apply individual control to improve classrooms acoustics? If so, how well do individually controlled acoustic devices work? And what are the pros and cons of individual-level control compared with classroom-level control?

To answer these questions, this present paper, as a first attempt, simulated the acoustic performance of two types of individually controlled acoustic devices in a classroom, and compared the results with the effects of two types of traditional acoustic improvements. Additionally, to clearly demonstrate the acoustic performance of all of these improvements (both at individual-level and at classroom-level), the results were also compared with a control setting without any acoustic improvement. All of the simulations were conducted in two different situations, i.e. the instruction situation and the self-study situation.

2. Methods

The present study comprised of several computer simulations, conducted by a ray-tracing-based room acoustics prediction software named Computer Aided Theatre Technique (CATT-Acoustic™) [36].

2.1. The classroom layout

In this study, the simulated classroom refers to the Experience room in the SenseLab [37]. The room is a box of 6.5 m long, 4.2 m wide, and 3.3 m high. As shown in Fig. 1, this room contains

Table 2
Corresponding relation between the STI value and speech intelligibility evaluation.

STI ranges	0.00–0.30	0.30–0.45	0.45–0.60	0.60–0.75	0.75–1.00
Speech intelligibility evaluation	bad	poor	fair	good	excellent

Fig. 1. Experience room in the SenseLab [37].

a glass door (0.98 m × 2.8 m), two windows (0.6 m × 0.8 m), two plenums (below and above), and 16 desks and chairs. A suspended ceiling is installed under the upper plenum, 2.8 m above the floor. It comprises of several lighting panels, perforated steel panels with speakers or air supply (used in the case of mixing ventilation) behind them and sound absorption panels. On the long side of the upper plenum, the air is exhausted via line grills (in the case of displacement ventilation). The computer floor, on top of a plenum 0.45 m above the ground floor, comprises of panels with linoleum flooring material. Both the floor and the ceiling panels can be changed. All the walls are made of 2 × 8 mm laminated safety glass and can be covered by sound-absorbing wall panels. Along the bottom of the wall, there is a 0.2 m plinth with small holes through which air can be supplied on the long side (in the case of displacement ventilation) and exhausted on the short side (for the mixing ventilation setting).

In the present study, as shown in Fig. 2, the acoustic conditions of five different settings were simulated. The first one was the "Control" setting (see Fig. 2(a)), in which no acoustic improvement was implemented. All the surfaces, including the ceiling, were set as reflecting materials (i.e., glass, metal and linoleum) whose sound absorption coefficients can be found in Table 3. This is an extreme setting and not used in the real room. The second and third settings (see Fig. 2(b) and 2(c)) represented classroom-level improvements, with either half or complete covering of the ceiling with acoustic tiles; the wall surfaces comprised entirely of glass. These are typical acoustic conditions in primary schools in the Netherlands. The fourth and fifth settings (see Fig. 2(d)–(g)) represented the individually controlled improvements, 16 either single or double-sided sound-absorbing canopies were hung above each desk inside the classroom. The single-sided canopy, as its name implies, is made of one layer of sound absorbing material (with 0.84 m^2), and only its inner side can absorb sound effectively, while the double-sided canopy is made of two layers of sound absorbing material (with 1.69 m^2), and both of its sides can absorb sound effectively. All the canopies were hung at 1.8 m above the floor to avoid bumping. These canopies had two working modes: open mode (see Fig. 2(d) and (f)), used during teacher's instructions, and closed mode (see Fig. 2(e) and (g)), used during self-study of the school children.

2.2. Acoustic model

One of the main difficulties for an accurate simulation is the availability of acoustic information of the materials. In this study, the information of most materials was not available. Therefore, the initial simulation model was built based on estimated values of the sound absorption and scatter coefficients found in literature; then the input data was adjusted correspondingly to make sure that the simulated results were close enough to the values measured inside the room.

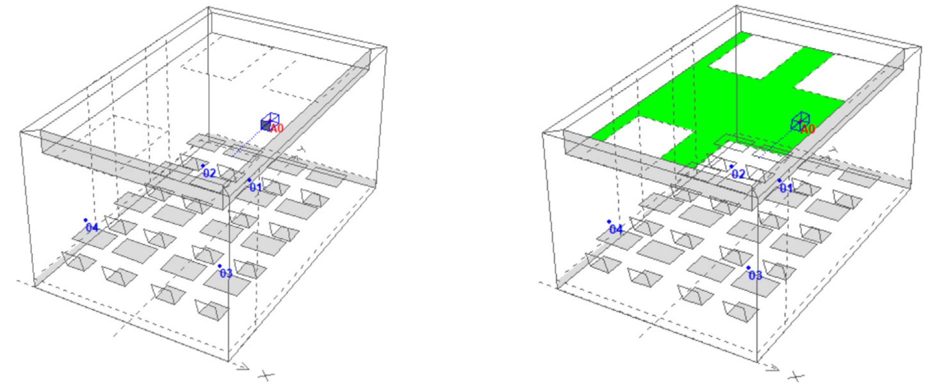
In the simulation, all the materials, including ceiling tiles, wall panels, glass, floor and furniture, were set as the same materials used in the Experience room of the SenseLab. Two of them were sound-absorbing materials, namely the ceiling tiles "Ecophon Master™ A" and the wall panels "Ecophon Akusto Wall A". Their data was taken from the manufacturer's website, while for the other materials the values were taken from two absorption coefficients tables from previous studies [38,39]. Based on this, the first simulation was conducted and the results were compared with the measured results. Then, the absorption coefficients and the scatter coefficients of these materials were adjusted accordingly to run the next simulation. After several iterations, the final absorption and scatter coefficients of all the materials were set (Table 3). The final comparison between the simulated and the measured results, being the validation of the simulation model, is introduced in the next section.

The amount of sound-absorbing material used in each setting was calculated to evaluate its effectiveness. As shown in Fig. 2, for the "Control" setting (a), no sound-absorbing material was used, so, the amount of the additional sound-absorbing material was 0 m^2. For the "Half ceiling" setting (b), half of the ceiling was covered with sound-absorbing ceiling tiles, the geometric amount of which was 13.5 m^2. This setting corresponded to the real setting in the Experience room. The ceiling panels that do not contain sound absorbing panels contain lighting fixtures or perforated panels with speakers or air supply. For the "Full ceiling" settings (c), as the name suggests, the whole ceiling was covered with sound-absorbing ceiling tiles, and the geometric amount of it was 27.0 m^2. For the "Single-sided canopies" setting (d) and (e), 16 canopies, whose inner sides were covered by sound-absorbing material, were hung above the desks, and the total geometric amount of sound-absorbing material used in this setting is the same as setting (b), which was 13.5 m^2. Lastly, for the "Double-sided canopies" setting (f) and (g), there were also 16 canopies but with both sides covered by sound-absorbing material: 27.0 m^2.

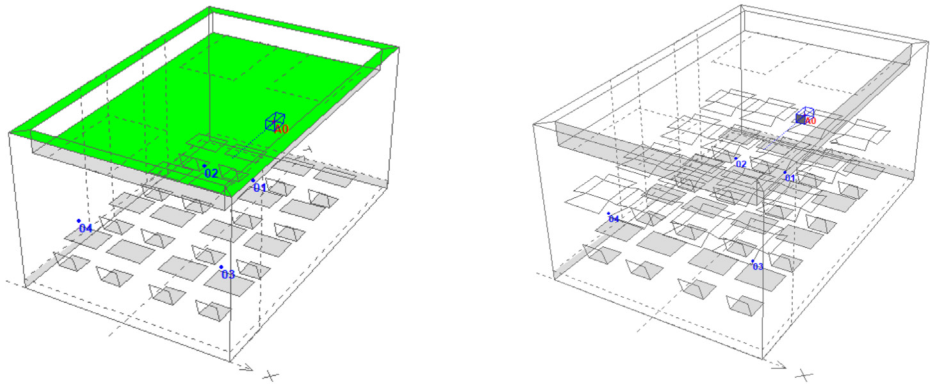
2.3. Settings of simulations

2.3.1. Sources and receivers

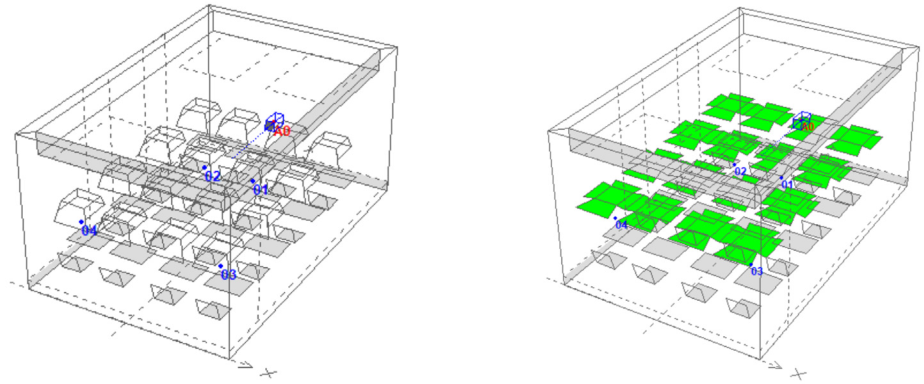
Five sources and four receivers were implemented in the simulation. One source represented the teacher, located at a height of 1.5 m on the centreline of the room, 1.0 m from the front wall, and it directed towards the centre of the classroom. According to the user's manual of CATT-Acoustic™ v9.1 [36], the teacher's vocal effort at 1 m distance (dB(A)) (125–16 k Hz) was set, as an average of females and males, as < 51.2 57.2 59.8 53.5 48.8 43.8 38.8 33.8 > . This was the only sound source that was used in the instruction situation, and the direction of the source was toward the centre of the room (see Fig. 3(a)). The other four sources represented four talking children whose vocal effort at 1 m (dB(A)) was set as < 50.4 56.4 58.4 52.4 48.4 43.4 38.4 33.4> (125–16 k Hz), and they were located at a height of 1.1 m in four positions distributed



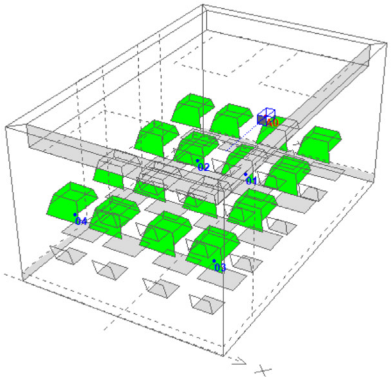
(a) Control setting (0m^2) (b) Half ceiling (13.5m^2)



(c) Full ceiling (27.0m2) (d) Open single-sided canopies (13.5m^2)



(e) Closed single-sided canopies (13.5m^2) (f) Open double-sided canopies (27.0m^2)



(g) Closed double-sided canopies (27.0m^2)

Fig. 2. Schematic diagrams of the settings.

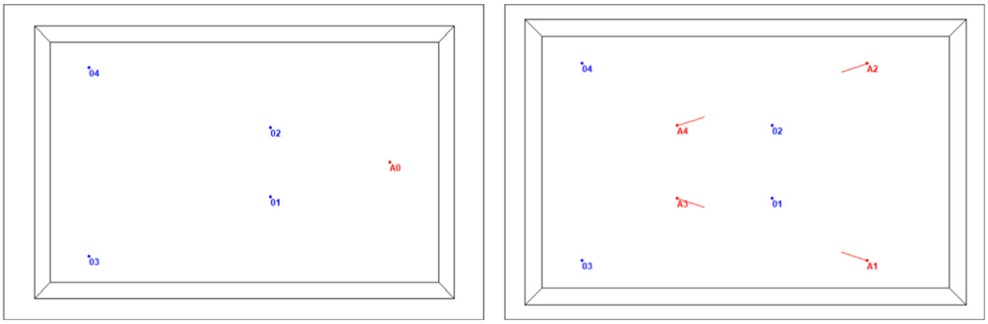
throughout the classroom. These four sources were used in the self-study situation, they were set as two pairs of chatting children: 01 talked with 03, and 02 talked with 04 (see Fig. 3(b)).

The four receivers represented four children and were located at a height of 1.2 m in four positions distributed throughout the classroom. These four receivers were used in both situations. The loca-

Table 3
Absorption and scattering coefficients of different materials.

	125 HZ	250 HZ	500 HZ	1 k HZ	2 k HZ	4 k HZ
Ecophon Focus A	0.50 *0.10*	0.70 *0.10*	0.60 *0.10*	0.58 *0.10*	0.70 *0.10*	0.55 *0.10*
Ecophon Akusto Wall A	0.40 *0.10*	0.50 *0.10*	0.65 *0.10*	0.76 *0.10*	0.90 *0.10*	0.99 *0.10*
Linoleum	0.08 *0.10*	0.07 *0.10*	0.05 *0.10*	0.05 *0.10*	0.06 *0.10*	0.02 *0.10*
Glass	0.09 *0.10*	0.05 *0.10*	0.07 *0.10*	0.068 *0.10*	0.025 *0.10*	0.01 *0.10*
Metal	0.10 *0.10*	0.08 *0.10*	0.04 *0.10*	0.04 *0.10*	0.05 *0.10*	0.01 *0.10*
Furniture	0.02 *0.10*	0.02 *0.10*	0.02 *0.10*	0.02 *0.10*	0.04 *0.10*	0.03 *0.10*

Note: All the upright values are the absorption coefficients, and all the italic values are the scatter coefficients.



(a) Instruction situation (b) Self-study situation

Fig. 3. Distribution of sources (A0-A4) and receivers (01–04).

tions 01 and 02 were chosen on the mean free path from the source A0; the locations 03 and 04 were chosen nearby the corners of the room with 1.0 m distance from the two walls.

2.3.2. Prediction method

Three prediction methods can be applied in the CATT-Acoustic^{TM} [36]. The ray-tracing type “Predict S × R” was used in this study because of its advanced algorithms and detailed results for all the combinations of sources and receivers. In terms of the ‘Algorithm’, “Longer calculation with detailed auralization” was selected since it is a more advanced prediction based on actual diffuse ray split suitable for more difficult cases with uneven absorption. Also, it gives a low random run to run variation at the expense of a longer calculation time. ‘Number of rays’ was set to “auto”, and it can be continuously fine-tuned using the algorithm. ‘Echogram length’ was set to the default value (1000 ms) for most settings, except for the “Control setting”, in which the ‘Echogram length’ was set to “auto”, to make sure it is longer than the estimated longest RT of all frequencies. The simulated physical environment was 20 °C with 50% relative humidity, based on which the air absorption was estimated by the software. Because of the surfaces of the education furniture and the canopies, edge-diffraction was included in the simulations and the ‘specular to diffraction’ option[7] was selected as a balance between the actual situation and computation time.

2.4. Lombard effect

If only one child speaks in a classroom, a certain SPL will be generated; while when several children talk in that classroom, as a common phenomenon, they will begin to speak louder to make sure that their voices can be heard. This effect is known as the Lombard effect [40], and is affected by the presence of absorption materials in a room. In a poor acoustic environment with little absorption, generally the sound pressure level will be higher as a result of which, people will start to speak even louder; while in a good acoustic environment with much sound absorption, the SPL will be lower and the speech intelligibility higher as a result of which people will tend to speak less loud and the number of people who speak will drop as well [41,42].

Fig. 4. Setting of the classroom in the SenseLab.

To further specify the impact of the Lombard effect, several models were developed by previous studies [43,44,45]. However, most of these models were built based on measurements with adults. According to Whitlock and Dodd [46], the difference of the Lombard effect between adults and children cannot be ignored. Therefore, they developed another model (see Equation (1)) to predict the total SPL in classrooms with talking children.

$$F = \frac{B - SL + 10logN - 20log\left(0.057\sqrt{V/T}\right)}{1 - L} \tag{1}$$

where:

B is the base (resting) voice level [dB];
S is the starting level for the Lombard effect [dB];
L is the Lombard coefficient, [dB/dB];
N is the number of talking children, -;
V is the volume of the classroom [m^3];
T is the reverberation time of the classroom [s].

Based on their experiments with children, the coefficients were determined as follow:

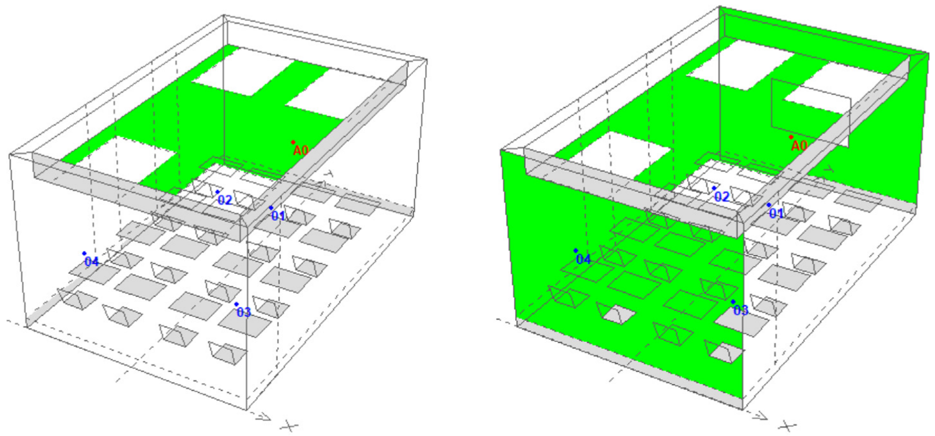
B = 53.4 dB(A), S = 25.7 dB(A), and L = 0.19 dB/dB.

2.5. Validation of the simulations

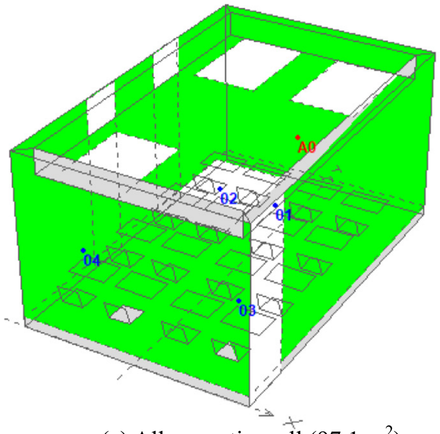
As mentioned in Section 2.2, several RT measurements were performed to validate the simulation results inside the Experience room in the SenseLab for the different settings. During the measurements an omni-directional source (Norsonic Nor276) with power amplifier (Norsonic Nor280) was used, connected to a laptop via a Behringer UCA222 audio interface, and a sound analyser (Norsonic Nor140) as microphone, connected to the same laptop via the same audio interface, was used. The height of the centre of the speaker was 1.4 m above the floor and of the microphone 1.2 m above the floor. Via the computer, logarithmic sweep signals were generated and played by the sound source. The raw signal was recorded by the sound analyser and transferred to the laptop where it was analysed in a custom-made MATLAB script. Per measurement 4 sweeps were generated and averaged before calculating the RT (T-20 and T-30) using regression analysis. The size of the room was exactly the same as the simulated classroom and unoccupied during the measurements. Only the instruction situation was taken into consideration; the position of the speaker was the same as the source no. 1 in the simulations; the receiver points were the same as the four receivers in the simulations (see Figs. 4 and 5).

The geometric amounts of sound-absorbing material used in these settings (for the validation of the model only) were as follows:

- Setting (a), the whole ceiling, except for the lighting area, was covered with sound-absorbing material, and the corresponding geometric area was 27.3 m2;
- Setting (b), next to the ceiling, additionally the front and rear walls of the room were covered with acoustic panels, the corresponding geometric area was 54.7 m2;
- Setting (c), next to the ceiling, additionally all the walls, except for the windows and door area, were covered with sound-absorbing materials, the corresponding geometric area was 97.1 m2.



(a) Glass wall (27.3 m^2) (b) Half-acoustic wall (54.7 m^2)



(c) All-acoustic wall (97.1 m^2)

Fig. 5. Settings in the verified simulation.

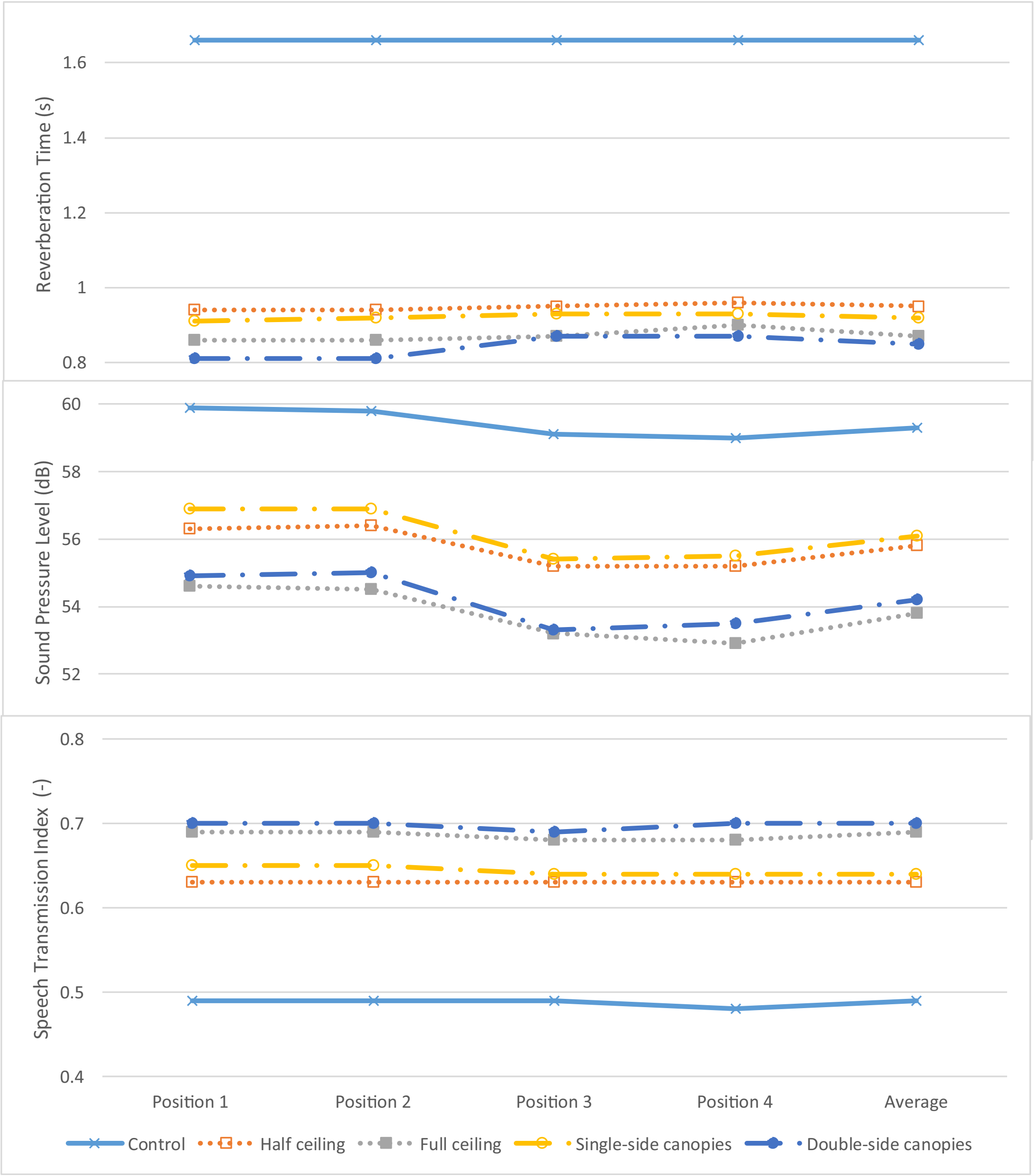


Fig. 6. Acoustic simulation results in different positions in the instruction situation.

The results of the measurements and the simulations are shown in Table 4. In the "No panel" setting (a) and "All panels" setting (c), the differences between the simulation results and the measurement results were less than the just noticeable difference for reverberation time [47,48]. As indicated by previous studies [49], the simulated results can hardly be identical to the measured ones because of the measurement errors and discrepancy between the real object and its physical and mathematical model. Therefore, in this study, the difference between the simulated and measured RTs was assumed to be satisfactory.

3. Results of the simulations

The simulations were conducted for two different scenarios: one without the Lombard Effect (both the instruction and the self-study situation), and one with the Lombard Effect (only the self-study situation). Three acoustic variables (RT, SPL and STI) were calculated in each situation for each setting by means of ray-tracing using CATT Acoustic. To get the STI, background sound levels for different frequencies were calculated first and inputted in the software (see Table 5). For the control setting, the background sound levels were kept as the default setting in the CATT; for the four improvement settings, the background levels were calculated based on the following equations:

$$\Delta L_P = 10\log\frac{A_{con}}{A_{imp}}$$

where ΔL_P is the difference of background sound level between the control setting and the improvement settings; the A_{con} is the amount of sound-absorbing area in the control setting; A_{imp} is the amount of sound-absorbing area in the improvement settings.

3.1. Instruction situation (without Lombard Effect)

In the instruction situation (with frontal teaching), the ultimate purpose of the classroom was to provide an acoustic environment in which the teacher's voice can be clearly transmitted to each

Table 4
Comparison of reverberation Time resulting from measurements and simulations.

No panel	125	250	500	1 k	2 k	4 k	Average (125–4 K)
Position 1	0.79	0.92	0.86	0.88	1	1.15	0.93
	0.63	*1.00*	*0.75*	*0.81*	*1.02*	*1.26*	*0.91*
Position 2	0.79	0.9	0.86	0.87	0.98	1.15	0.93
	0.68	*0.99*	*0.76*	*0.81*	*1.01*	*1.30*	*0.93*
Position 3	0.81	0.91	0.87	0.89	1.07	1.16	0.95
	0.94	*0.93*	*0.77*	*0.76*	*0.96*	*1.12*	*0.91*
Position 4	0.87	0.93	0.87	0.88	0.99	1.16	0.95
	0.92	*0.81*	*0.78*	*0.76*	*0.96*	*1.19*	*0.90*
Average (4 positions)	0.82	0.92	0.87	0.88	1.01	1.16	0.94
	0.79	*0.93*	*0.77*	*0.79*	*0.99*	*1.22*	*0.91*
Half panels	125	250	500	1 k	2 k	4 k	Average (125–4 K)
Position 1	0.56	0.56	0.52	0.51	0.55	0.55	0.54
	0.69	*0.67*	*0.68*	*0.68*	*0.69*	*0.76*	*0.70*
Position 2	0.56	0.57	0.52	0.51	0.55	0.56	0.55
	0.77	*0.75*	*0.70*	*0.68*	*0.63*	*0.69*	*0.70*
Position 3	0.56	0.56	0.52	0.52	0.56	0.57	0.55
	0.65	*0.73*	*0.67*	*0.67*	*0.65*	*0.71*	*0.68*
Position 4	0.56	0.57	0.52	0.52	0.58	0.59	0.55
	0.70	*0.74*	*0.68*	*0.68*	*0.68*	*0.74*	*0.70*
Average (4 positions)	0.56	0.56	0.52	0.51	0.56	0.57	0.55
	0.70	*0.72*	*0.68*	*0.68*	*0.66*	*0.73*	*0.70*
All panels	125	250	500	1 k	2 k	4 k	Average (125–4 K)
Position 1	0.37	0.29	0.26	0.23	0.19	0.20	0.25
	0.37	*0.21*	*0.22*	*0.17*	*0.14*	*0.15*	*0.21*
Position 2	0.36	0.28	0.25	0.24	0.19	0.20	0.26
	0.27	*0.25*	*0.22*	*0.17*	*0.15*	*0.16*	*0.20*
Position 3	0.37	0.29	0.26	0.27	0.20	0.22	0.27
	0.36	*0.29*	*0.19*	*0.19*	*0.16*	*0.16*	*0.23*
Position 4	0.36	0.29	0.27	0.23	0.21	0.21	0.26
	0.45	*0.27*	*0.19*	*0.15*	*0.16*	*0.17*	*0.23*
Average (4 positions)	0.36	0.29	0.26	0.24	0.20	0.21	0.26
	0.36	*0.26*	*0.21*	*0.17*	*0.15*	*0.16*	*0.22*

Note: All the italics represent the measurement results; all upright numbers the simulation results.

Table 5
The background sound level (dB(A)) used to calculate the STI values.

Settings	125	250	500	1 k	2 k	4 k	8 k	16 k
Control	45	38	32	28	25	23	21	19
Half ceiling	41	34	28	24	22	20	18	16
Full ceiling	39	32	26	23	19	18	16	14
Single-sided canopies	41	34	28	24	22	20	18	16
Double-sided canopies	39	32	26	23	19	18	16	14

Table 6
General acoustic simulation results in different situations.

Situations	Settings	RT (s)	SPL (dB(A))	STI (-)
Instruction	Control	1.66 (0.00)	59.3 (0.47)	0.49 (0.01)
	Half ceiling	0.95 (0.01)	55.8 (0.67)	0.63 (0.00)
	Full ceiling	0.87 (0.02)	53.8 (0.88)	0.69 (0.01)
	Single-sided canopies	0.92 (0.01)	56.1 (0.84)	0.64 (0.01)
	Double-sided canopies	0.85 (0.03)	54.2 (0.90)	0.70 (0.01)
Self-study (without Lombard effect)	Control	1.66 (0.00)	63.1 (0.46)	0.49 (0.01)
	Half ceiling	0.95 (0.01)	59.8 (0.53)	0.63 (0.01)
	Full ceiling	0.89 (0.01)	58.0 (0.72)	0.69 (0.01)
	Single-sided canopies	0.72 (0.01)	58.8 (0.98)	0.70 (0.01)
	Double-sided canopies	0.68 (0.01)	57.5 (0.92)	0.74 (0.01)
Self-study (with Lombard effect)	Control	1.66 (0.00)	64.7 (0.43)	0.48 (0.00)
	Half ceiling	0.95 (0.01)	61.2 (0.50)	0.63 (0.01)
	Full ceiling	0.90 (0.01)	59.4 (0.78)	0.69 (0.01)
	Single-sided canopies	0.71 (0.01)	60.2 (0.95)	0.70 (0.01)
	Double-sided canopies	0.68 (0.01)	58.9 (0.92)	0.74 (0.01)

Note: RT values are the average values of the 4 receiver positions, also averaged over the 250 to 2 k Hz octave bands; SPL values are the average A-weighted, equivalent continuous sound levels (LAeq) measured at the 4 receiver positions, averaged over the 250 to 2 k Hz octave bands; STI values are the average of the 4 receiver positions using the background noise levels of Table 5.

child, which corresponds to a high STI and a short RT. Considering that, the acoustic performance in the “Control setting” was the worst among the five simulated settings. As shown in Table 6, the average (over 250 to 2 k Hz octave bands) T-30 in the “Control” setting was 1.66 s which is significantly higher than the maximum value allowed by the Dutch guidelines (Fresh Schools 2015) [12] for the worst level (class C), and the STI just reached the fair level (see Table 1). Compared with the “Control setting”, all the improvement settings, both the addition of acoustic ceiling tiles and the implementation of acoustic canopies, did achieve better acoustics, namely by shortening the average RT and increasing the average STI significantly.

In general, the results of the “Double-sided canopies” setting and the “Full ceiling” setting were similar because of the same amount of sound-absorbing materials used in these two settings. Similarly, the results of the “Single-sided canopies” setting and the “Half ceiling” setting were also similar. In general, the settings with more absorption material provided a slightly better acoustic environment because of the lowest RTs and the highest STIs. And among these, the “Double-sided canopies” setting was even slightly better because in this setting not only the RT was lower and the STI higher, but also the SPL was slightly higher, so that all of the children could better hear and understand their teacher’s speech.

The detailed results for the four different receiver positions are shown in Fig. 6. No matter for which position, the improvement settings led to better acoustic conditions as compared with the “Control setting”. Concerning RT, among the four improvements, the “Double-sided canopies” provided the shortest average value, but showed more variation among the four receiver points as compared to the other settings. The RT in the rear positions was longer than in the front positions, and this trend was most clearly found for this setting. Concerning SPL, compared with the other improvements, the “Single-sided canopies” led to the highest value. For all the improvements, the distribution of SPL among these positions was quite uneven, the SPL in the rear positions was lower than in the front positions. Concerning the STI, the “Double-sided canopies” provided the best result and an even distribution among all positions.

3.2. Self-study situation without Lombard effect

In the self-study situation (with children talking), a quieter classroom provides a better learning environment. In a quiet environment, every child should be able to concentrate on their own schoolwork and avoid being distracted by other children’s conversation. In this case, as shown in Table 6, the “control” setting was still the worst since the average SPL in this setting was the highest. Moreover, the RT and STI in this setting were also poor, and the values were similar to the results in the instruction situation. A plausible explanation could be that the simulated configurations in these two situations were the same, only the sound source was changed from one frontal source (in the instruction situation) to four sources distributed throughout the room (in self-study situation).

In contrast to the “Control setting”, the acoustic improvements in the other four settings are clear: both the RT and SPL decreased, and the STI increased significantly. Comparing these improved settings, the “Double-sided canopies” setting was the best because in this setting both the RT and SPL were the lowest. Next were the “Single-sided canopies” and the “Full ceiling”. The average results for these two settings were similar although the amount of sound absorbing materials used in the “Full-ceiling” setting was twice as much as in the “Single-sided canopies” setting. The worst acoustic environment occurred in the “Half ceiling” setting.

The detailed results for the different positions are shown in Fig. 7. Concerning RT, the values in the two “canopies” settings were similar. The same also applied for the two “Ceiling” settings. Moreover, the “Canopies” settings were better than the “ceiling” settings. For all the settings, the differences in RT among the different positions were not significant. In terms of the SPL, the “Double-sided canopies” setting was the best, next were the “Full ceiling” and the “Single-sided canopies” settings, while the “Half ceiling” setting was the worst. For all settings, the SPLs in the rear positions were lower than in the front positions, which might be caused by the fact that positions 1 and 2 were just in between four talking children (see Fig. 3(b)), while positions 3 and 4 were only close to two talking children. With respect to the STI, the highest value occurred in the “Double-sided canopies” setting, followed by “Single-sided canopies” and “Full ceiling” settings, in which similar results were observed, while the “Half ceiling” setting resulted in the lowest index among the improved settings. Additionally, the distribution of the STIs among the four positions was relatively even.

3.3. Self-study situation with Lombard Effect

To make the simulations more accurate, the Lombard Effect was accounted for, but only in the self-study situation (with children talking) because in the instruction situation only one sound source, namely the teacher, was assumed to be present. In the simulation involving the Lombard Effect, the total SPL in the classroom should be higher than in the simulation without the Lombard Effect. To simulate this effect, the increase of each speaker’s voice level was calculated as follows:

1) Assuming a base condition with only one talking child in a classroom. According to Eqs. (1), the SPL in this room should be:

$$L_{p,base} = \frac{B - SL + 10\log 1 - 20\log\left(0.057\sqrt{V/T}\right)}{1 - L} = \frac{B - SL - 20\log\left(0.057\sqrt{V/T}\right)}{1 - L} \tag{2}$$

2) Increasing the number of talking children to 4. If the Lombard Effect is accounted for, then according to Eq. (1), the SPL in this room should be:

$$L_{p,4children\ with\ LE} = \frac{B{-}SL{+}10log4{-}20log\left(0.057\sqrt{V/T}\right)}{1{-}L} = L_{p,base} + \frac{10log4}{1{-}L} = L_{p,base} + 7.41 \tag{3}$$

3) If the Lombard Effect is not involved, based on the formula to calculate the combined SPL mentioned in[50], the total SPL in this room should be:

$$L_{p,\ 4children\ without\ LE} = 10 \times log\left(N \times 10^{L_{p,base}/10}\right) = 10 \times log\left(4 \times 10^{L_{p,base}/10}\right) = L_{p,base} + 10 \times log4 = L_{p,base} + 6 \tag{4}$$

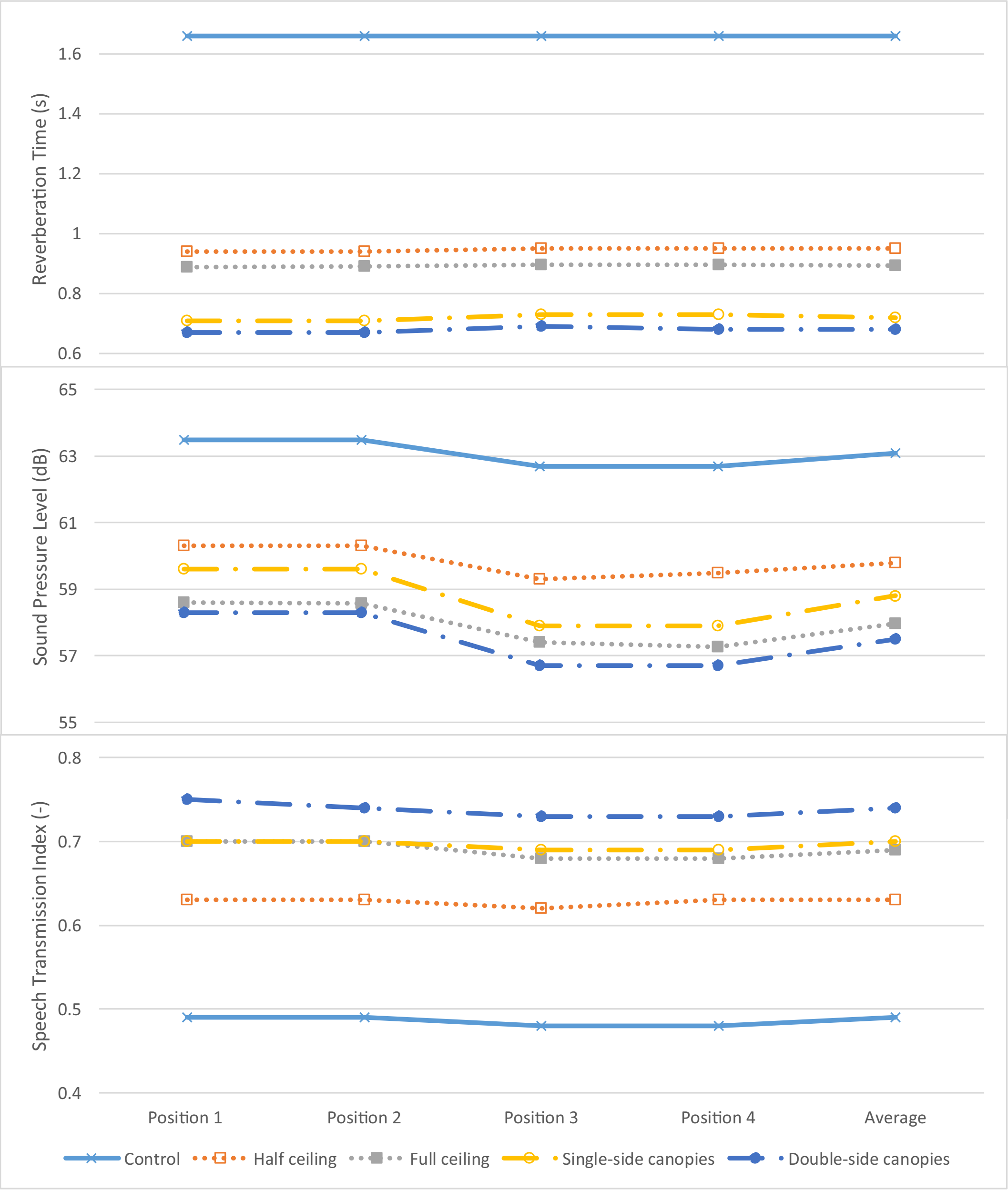


Fig. 7. Acoustic simulation results in different positions in the self-study situation.

4) Adjusting the sound pressure level of the sources by comparing the results between the calculation with and without Lombard Effect. The difference of children's voice level additionally increased by 1.41 dB(A) in the simulation involving the Lombard Effect.

Because of the Lombard Effect, in the simulations conducted in this section, therefore, the SPL of each source was increased by 1.41 dB(A), but keeping all the acoustic and geometrical settings the same as in the simulations without the Lombard Effect (i.e. Section 4.2). Thus, comparing the results with Lombard Effect to the results without Lombard Effect showed that RT and STI were almost the same, only the SPL was higher (see Table 6). Moreover, the ranking of these parameters among these five settings were also the same as in the last section. Concerning the RT and the STI, from the "Control" setting to the "Half-ceiling" setting, to the "Full-ceiling" setting, to the "Single-sided canopies" setting, to the "Double-sided canopies" setting, the acoustic conditions become better; while concerning the SPL, the rank of "Full ceiling" and "Single-sided canopies" changed; in this situation, the "Full ceiling" provided a slightly quieter environment than the "Single-sided canopies".

The detailed results for the different positions are shown in Fig. 8. The ranking of the RTs and STIs for the four positions were also the same as for the simulations without the Lombard Effect. This makes sense since the setting of these two series of simulations were exactly the same and only the SPL of the sources was increased in these simulations.

4. Discussion

The present study evaluated the acoustic quality in a simulated classroom for five different settings: one control setting, two

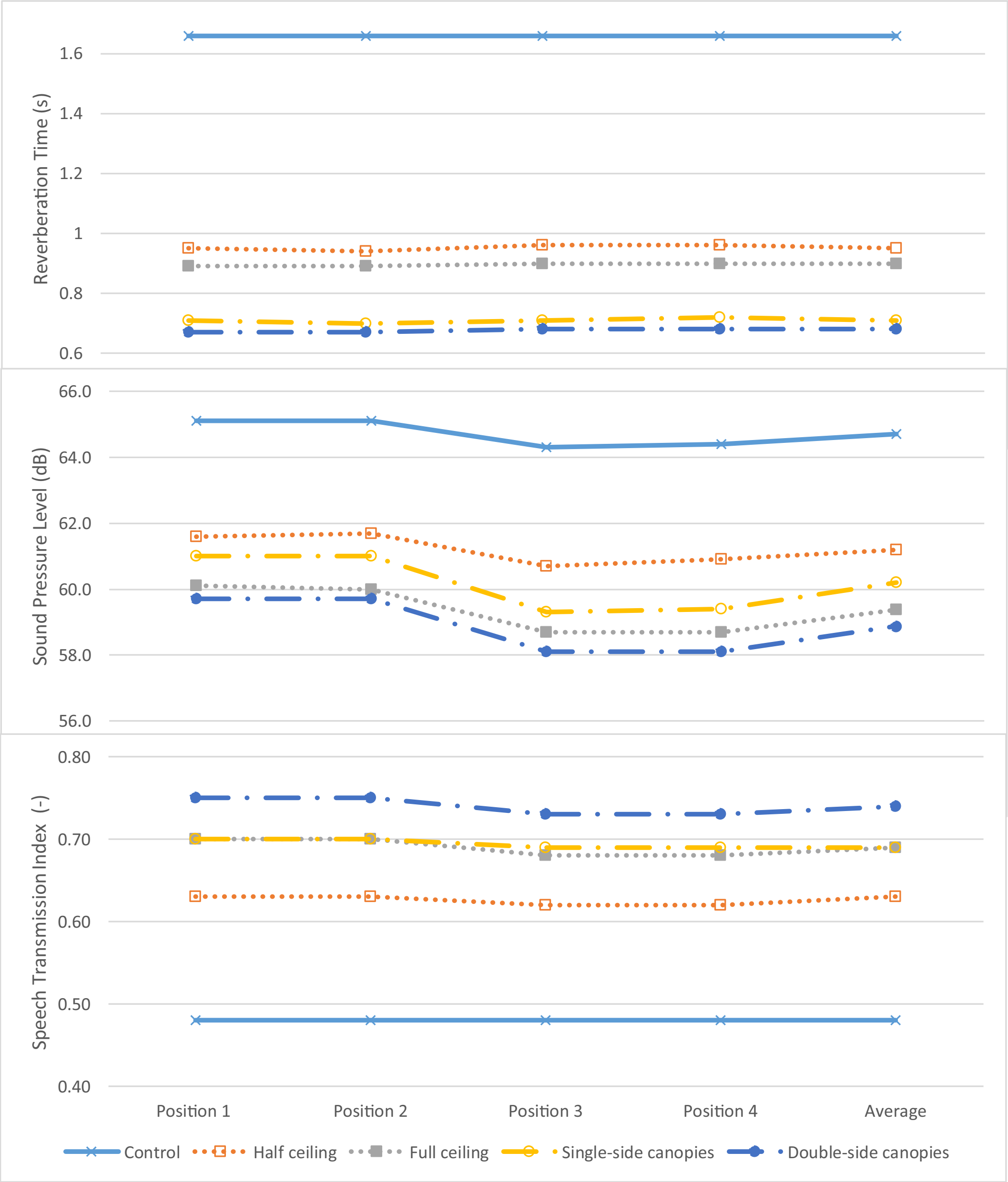


Fig. 8. Acoustic simulation results in different positions in the conversation situation.

classroom-level improvements (Half ceiling and Full ceiling) and two individual-level improvements (Single-sided and Double-sided canopies). In each of these settings, two situations were run: instruction situation (frontal teaching) and self-study situation (children talking). The requirements of the acoustic quality in these two situations are different because of the difference in learning activities. During instruction, the transmission of knowledge from teacher to children is the main purpose of the classroom; it should help the teachers' voice to be clearly and loudly transferred to every child's ear. Therefore, achieving a short reverberation time and high speech intelligibility and at the same time keeping the loudness of the teachers' voice should be the aim of the classroom's acoustic design. However, during self-study, the main purpose of the classroom is to create a quiet environment and to keep children from being disturbed by noise which mainly comes from their classmates. In this case, the SPL reduction of children's voices should be the aim. Based on these requirements, the simulated results of these settings were compared and analysed.

4.1. Effect of the classroom-level improvement

For the ceiling improvements, both the "Half ceiling" and the "Full ceiling" led to a shorter RT compared with the "control" setting, and as can be expected, the "Full ceiling" worked better than the "Half ceiling" in terms of shortening the RT. However, the difference in RT between these two settings was not as significant as the difference of the amount of sound-absorbing materials used in these settings. This just proves the conclusion found by Bistafa and Bradley [49] that the more absorption is added, the less accumulated reductions in the average RT can be measured. And in this study, this result might be explained by the fact that the several reflecting zones on the ceiling could contribute to the transmission of the voice to the rear positions. According to the comparison between the results obtained from the instruction situation and the self-study situation, no significant difference in RT and STI was found between these two situations; only the SPL was higher in the self-study situation which is caused by the multiple speakers.

4.2. Effect of the individual-level improvement

Concerning the individual-level improvements, namely the canopies, the acoustic quality also improved considerably compared with the "Control setting". Similarly, the "Double-sided canopies" worked better than the "Single-sided" canopies concerning RT and STI, and also here, the difference was not as big as the difference of the amount of sound-absorbing materials used in these settings.

For the comparison between the results obtained from the instruction situation and the self-study situation, the differences of the acoustic variables were significant for both the "Single-sided" and "Double-sided" canopies, although the amount of the sound-absorbing material was exactly the same. Therefore, it could be concluded that the mode/shape of the canopies and the nearness of the absorption material played an important role in the acoustic improvement. The closed canopies in the self-study situation lead to a shorter RT and higher STI than the open canopies in the instruction situation. Bistafa and Bradley [49] found similar results: different RT were achieved when the same amount of absorption was used in different configurations. In the present study, the significant differences between the two situations can be explained by the fact that in the self-study situation the sound sources were located under the canopies when the side wings of the canopies were dropped down, so that the sound-absorbing materials were closer to the sound sources.

4.3. The classroom-level improvement vs. individual-level improvement

In terms of RT and STI, both ceiling tiles and individual canopies were found to lead to significant improvements of the acoustic quality in the classroom. In general, the "canopies" provided an even better acoustic environment than the "ceilings", since the "canopies" tended to result in shorter RT and higher STI than the "ceilings". When the amount of sound-absorbing materials was kept the same, then the advantages of the "canopies" was even more obvious. In other words, the "Single-sided canopies" were better than the "Half ceiling", in terms of the acoustic quality, and the "Double-sided canopies" were better than the "Full ceiling". This difference might be caused by the relatively lower height and the changeable shape of the canopies. In the instruction situation, the open canopies looked like a suspended ceiling below the existing ceiling. In the self-study situation, the closed canopies looked like umbrellas partly covering the sound source, as a result of which the sound could be better absorbed keeping other children from being distracted.

4.4. Simulation involving Lombard Effect

To increase the accuracy of the simulation, the Lombard Effect was accounted for in the present study. Although the relationship between people's speech level and ambient noise level (i.e. Lombard Effect) has been identified by many studies, most of them only focused on adults. However, according to a study conducted by Whitlock and Dodd [46], the Lombard slope is different for children, and based on their formula, the difference of the SPL in the room due to the Lombard Effect was calculated as:

$$\Delta L_p = \frac{10\log N}{1-L} - 10\log N = \frac{L}{1-L} 10\log N \quad (5)$$

Therefore, as the first attempt, this study adjusted the children's voice level based on this Eq. (5) in the computer simulation. This adjustment almost did not change the results, except for the SPL, as compared to the original simulations. Nonetheless, the Lombard Effect still needs to be considered when conducting such simulations because it is a real phenomenon, and the closer to reality, the more realistic the simulation will be.

4.5. Limitation and strength

This study applied only one research method, namely computer simulation, to test the function of the new individually controlled devices, which might be an optional limitation since there are always differences between simulated and experimental results. For CATT-Acoustic™, a ray-tracing-based acoustic simulation software, simulating diffraction is a challenge because diffraction inherently is a wave-based phenomenon. In this study, this limitation was minimized by using the latest version of the software which has diffraction implemented in its simulation, albeit in a simplified way. Moreover, in order to further guarantee sufficient accuracy of the simulation, as model validation several repeated trials and comparisons between the simulated and measured results were conducted to reach suitable settings and material properties.

Moreover, currently no individually controlled acoustic improvement device is available to test in an experimental setup with actual users. While computer simulation is a good way to study a number of different conditions without any risk or additional costs. So, as a "better-faster-cheaper" method, computer simulation can be considered as a strength of this study.

4.6. Future studies

Individual control is a general and broad idea; the individually controlled devices simulated in this paper are just two examples of how can individual control could be used to improve classroom acoustics. There are many other types, shapes, and sizes of individually controlled devices possible to be used. In the future, some of them might be produced and tested in a real (field study) or lab environment to study their performance under different school tasks and children's response to these devices. This could provide more information about the functioning of these devices, which could lead to further improvements.

5. Conclusions

In conclusion, all the acoustic improvements worked effectively in terms of providing a good acoustic learning environment. Besides, no matter in which situation, instruction or self-study situation, the individually controlled canopies provided an acoustic environment which is closer to the related requirement[12], namely a shorter reverberation time, than the traditional improvement--the ceiling tiles. In the comparison between the two canopies, the "Single-sided canopies" might be superior to the "Double-sided canopies" for the following two reasons. First, for the RT and STI, in both situations the difference between the two were not significant, while the "Single sided canopies" only uses half of the amount of absorbing materials as the "Double-sided canopies". Second, for the SPL, in the instruction situation, the "Single-sided canopies" led to a louder environment with teacher's voice reaching further into the classroom, while in the self-study situation, a marginal difference was observed between these two settings. Based on these results, the "Single-sided canopies" are considered to be the best improvement of the four improvements tested.

CRediT authorship contribution statement

Dadi Zhang: Conceptualization, Methodology, Software, Writing - original draft. **Martin Tenpierik:** Resources, Writing - review

& editing, Supervision. **Philomena M. Bluyssen:** Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The first author was supported by the China Scholarship Council (CSC) Grant #201606460056.

References

[1] Zannin PHT, Marcon CR. Objective and subjective evaluation of the acoustic comfort in classrooms. Appl Ergon 2007;38(5):675–80.

[2] Kvernstoen Rönnholm and Associates INC, classroom acoustical study. 2007: US. p. 1-48.

[3] Dockrell JE, Shield BM. Acoustical barriers in classrooms: the impact of noise on performance in the classroom. Br Educ Res J 2006;32(3):509–25.

[4] Standard, A., S12. 60–2002. Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools.

[5] Department of Education, Building bulletin 93, Acoustic design of schools: Performance standards. 2015, The National Archives London.

[6] Bluyssen Philomena M, Zhang Dadi, Kurvers Stanley, Overtoom Marjolein, Ortiz-Sanchez Marco. Self-reported health and comfort of school children in 54 classrooms of 21 Dutch school buildings. Build Environ 2018;138:106–23.

[7] Zhang, D., M. Tenpierik, and P.M. Bluyssen. The effect of acoustical treatment on primary school children's performance, sound perception, and influence assessment. in E3S Web of Conferences. 2019. EDP Sciences.

[8] Zhang Dadi, Tenpierik Martin, Bluyssen Philomena M. Interaction effect of background sound type and sound pressure level on children of primary schools in the Netherlands. Appl Acoust 2019;154:161–9.

[9] Anderson K. Kids in noisy classrooms: what does the research really say. J Educ Audiol 2001;9:21–33.

[10] James D, Stead M, Clifton-Brown D, Scott D. A cost benefit analysis of providing a 'sound'environment in educational facilities. Proc Acoust Soc Austr 2012:21–4.

[11] Rasmussen B, Brunskog J, Hoffmeyer D. Reverberation time in class rooms–Comparison of regulations and classification criteria in the Nordic countries. Joint Baltic-Nordic Acoustics Meet 2012. 2012..

[12] The Netherlands Enterprise Agency, Programma Van Eisen Frisse Scholen 2015. 2015.

[13] Mikulski W, Radosz J. Acoustics of classrooms in primary schools-results of the reverberation time and the speech transmission index assessments in selected buildings. Arch Acoust 2011;36(4):777–93.

[14] Rabelo, A.T.V., J.N. Santos, R.C. Oliveira, and M.d.C. Magalhães. Effect of classroom acoustics on the speech intelligibility of students. in CoDAS. 2014. SciELO Brasil.

[15] Hirvonen, M., V. Hongisto, M. Kylliäinen, and K. Lehtonen, Standardi SFS 5907 rakennusten akustisesta luokituksesta. 2005, Akustiikkapäivät.

[16] Christensson Jonas. Good acoustics for teaching and learning. J Acoust Soc Am 2017;141(5):3457.

[17] Nijs Lau, Rychtáriková Monika. Calculating the optimum reverberation time and absorption coefficient for good speech intelligibility in classroom design using U50. Acta Acust United Acust 2011;97(1):93–102.

[18] Bradley JS. Speech intelligibility studies in classrooms. J Acoust Soc Am 1986;80(3):846–54.

[19] International Electrotechnical Commission, IEC 60268-16: Sound system equipment-Part 16: Objective rating of speech intelligibility by speech transmission index. 2011.

[20] Jianxin Peng. Chinese speech intelligibility at different speech sound pressure levels and signal-to-noise ratios in simulated classrooms. Appl Acoust 2010;71(4):386–90.

[21] Astolfi A, Puglisi GE, Murgia S, Minelli G, Pellerey F, Prato A, et al. The influence of classroom acoustics on noise disturbance and well-being for first graders. Front Psychol 2019;10:2736.

[22] Bistafa Sylvio R, Bradley John S. Reverberation time and maximum background-noise level for classrooms from a comparative study of speech intelligibility metrics. J Acoust Soc Am 2000;107(2):861–75.

[23] Sato Hiroshi, Bradley John S. Evaluation of acoustical conditions for speech communication in working elementary school classrooms. J Acoust Soc Am 2008;123(4):2064–77.

[24] Shield, B.M. and J.E. Dockrell. The Effects of classroom and environmental noise on children's academic performance. in 9th International Congress on Noise as a Public Health Problem (ICBEN), Foxwoods, CT. 2008.

[25] Hughes RW, Vachon F, Jones DM. Disruption of short-term memory by changing and deviant sounds: Support for a duplex-mechanism account of auditory distraction. J Exp Psychol Learn Mem Cogn 2007;33(6):1050.

[26] Hughes RW, Hurlstone MJ, Marsh JE, Vachon F, Jones DM. Cognitive control of auditory distraction: impact of task difficulty, foreknowledge, and working memory capacity supports duplex-mechanism account. J Exp Psychol Hum Percept Perform 2013;39(2):539.

[27] Siebein Gary W, Gold Martin A, Siebein Glenn W, Ermann Michael G. Ten ways to provide a high-quality acoustical environment in schools. Language Speech Hear Serv Schools 2000;31(4):376–84.

[28] McKay Sarah, Gravel Judith S, Tharpe Anne Marie. Amplification considerations for children with minimal or mild bilateral hearing loss and unilateral hearing loss. Trends Amplif 2008;12(1):43–54.

[29] Ikuta Nobuhiko, Iwanaga Ryoichiro, Tokunaga Akiko, Nakane Hideyuki, Tanaka Koji, Tanaka Goro. Effectiveness of earmuffs and noise-cancelling headphones for coping with hyper-reactivity to auditory stimuli in children with autism spectrum disorder: a preliminary study. Hong Kong J Occupat Ther 2016;28(1):24–32.

[30] Cook Andrew, Johnson Carl, Bradley-Johnson Sharon. White noise to decrease problem behaviors in the classroom for a child with attention deficit hyperactivity disorder (ADHD). Child & Family Behav Therapy 2015;37(1):38–50.

[31] Pasut W, Zhang H, Arens E, Kaam S, Zhai Y. Effect of a heated and cooled office chair on thermal comfort. HVAC&R Res 2013;19(5):574–83.

[32] Taub, M., H. Zhang, E. Arens, F. Bauman, D. Dickerhoff, M. Fountain, W. Pasut, D. Fannon, Y. Zhai, and M. Pigman, The use of footwarmers in offices for thermal comfort and energy savings in winter. 2015.

[33] Melikov AK, Skwarczynski MA, Kaczmarczyk J, Zabecky J. Use of personalized ventilation for improving health, comfort, and performance at high room temperature and humidity. Indoor Air 2013;23(3):250–63.

[34] Yamakawa Kazumi, Watabe Koji, Inanuma Minoru, Sakata Katsuhiko, Takeda Hitoshi. A study on the practical use of a task and ambient lighting system in an office. J Light Visual Environ 2000;24(2):15–8.

[35] Zhang Dadi, Ortiz Marco A, Bluyssen Philomena M. Clustering of Dutch school children based on their preferences and needs of the IEQ in classrooms. Build Environ 2019;147:258–66.

[36] CATT. CATT-Acoustic™ v9.1 powered by TUCT™ v2. 2019 [cited 2018 Aug 2018]; Available from: www.catt.se.

[37] Bluyssen Philomena M, van Zeist Freek, Kurvers Stanley, Tenpierik Martin, Pont Sylvia, Wolters Bart, et al. The creation of SenseLab: a laboratory for testing and experiencing single and combinations of indoor environmental conditions. Intell Build Int 2018;10(1):5–18.

[38] Cox, T. and P. d'Antonio, Acoustic absorbers and diffusers: theory, design and application. 2016: Crc Press.

[39] Acoustic Project Company. ABSORPTION COEFFICIENTS. [cited 2018; Available from: http://www.acoustic.ua/st/web_absorption_data_eng.pdf.

[40] Lombard E. Le signe de l'elevation de la voix. Ann Mal de L'Oreille et du Larynx 1911:101–19.

[41] Nijs Lau, Saher Konca, den Ouden Daniël. Effect of room absorption on human vocal output in multitalker situations. J Acoust Soc Am 2008;123(2):803–13.

[42] Rindel Jens Holger. Verbal communication and noise in eating establishments. Appl Acoust 2010;71(12):1156–61.

[43] Lazarus H. New methods for describing and assessing direct speech communication under disturbing conditions. Environ Int 1990;16(4-6):373–92.

[44] de Ruiter EPJ. Lombard effect, speech communication and the design of large (public) spaces. Forum Acusticum 2011.

[45] Delft University of Technology. The model for the lombard effect compared to literature data. Available from: https://bk.nijsnet.com/0226030_TH34_Lombardliteratuur.aspx.

[46] Whitlock, J. and G. Dodd, Classroom acoustics—controlling the cafe effect… is the Lombard effect the key. Proceedings of ACOUSTICS, Christchurch, New Zealand, 2006: p. 20-22.

[47] Blevins, M.G., A.T. Buck, Z. Peng, and L.M. Wang, Quantifying the just noticeable difference of reverberation time with band-limited noise centered around 1000 Hz using a transformed up-down adaptive method. 2013.

[48] Meng Z, Zhao F, He M. The just noticeable difference of noise length and reverberation perception. IEEE; 2006.

[49] Bistafa Sylvio R, Bradley John S. Predicting reverberation times in a simulated classroom. J Acoust Soc Am 2000;108(4):1721–31.

[50] Hansen, C.H., Fundamentals of acoustics. Occupational Exposure to Noise: Evaluation, Prevention and Control. World Health Organization, 2001: p. 23-52.