Ceiling baffles and reflectors for controlling lecture-room sound for speech intelligibility

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Reinforcing speech levels and controlling noise and reverberation are the ultimate acoustical goals of lecture-room design to achieve high speech intelligibility. The effects of sound absorption on these factors have opposite consequences for speech intelligibility. Here, novel ceiling baffles and reflectors were evaluated as a sound-control measure, using computer and 1/8-scale models of a lecture room with hard surfaces and excessive reverberation. Parallel ceiling baffles running front to back were investigated. They were expected to absorb reverberation incident on the ceiling from many angles, while leaving speech signals, reflecting from the ceiling to the back of the room, unaffected. Various baffle spacings and absorptions, central and side speaker positions, and receiver positions throughout the room, were considered. Reflective baffles controlled reverberation, with a minimum decrease of sound levels. Absorptive baffles reduced reverberation, but reduced speech levels significantly. Ceiling reflectors, in the form of obstacles of semicircular cross section, suspended below the ceiling, were also tested. These were either 7 m long and in parallel, front-to-back lines, or 0.8 m long and randomly distributed, with flat side up or down, and reflective or absorptive top surfaces. The long reflectors with flat side down and no absorption were somewhat effective; the other configurations were not.
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I. INTRODUCTION

The importance of classroom acoustics and of speech intelligibility is well recognized. The room-acoustical parameters affecting speech intelligibility are known; speech intelligibility tends to increase with increased speech-to-noise level difference (also referred to as signal-to-noise ratio) and to decrease with increased reverberation. Reverberation for speech intelligibility is best quantified by the clarity factor C_{50}, based on the early-to-late energy fraction. C_{50} is usually highly correlated with early-decay time (EDT) and reverberation time in classrooms.[1] The effect of speech-to-noise level difference on speech intelligibility dominates that of reverberation.[2] Studies[1,3,4] have confirmed that the values of these parameters are often nonoptimal. Thus, the question remains as to how to achieve the optimal values of the parameters in real classrooms in a practical, cost-effective way. Many newly designed or renovated classrooms use absorptive materials to reduce reverberation and late-arriving energy beneficially. However, these absorptive materials also cause a detrimental decrease in speech levels, and may reduce beneficial early reflections.

The purpose of the study reported here was to find an effective way to design lecture rooms — i.e., larger classrooms with an instructor at the front of the room, speaking to a group of students in front—and control sound to achieve optimum reverberation and adequate speech levels, especially at the back of the room, for speech intelligibility. The effectiveness of novel systems of ceiling baffles and reflectors for optimizing speech intelligibility is investigated, using a room-prediction model and physical scale modeling.

A room consists of a floor, walls, and ceiling. Among these three room components, the ceiling is chosen to be modified because it has a large flexibility compared to the walls and floor, and it can help reflect a teacher's voice toward the back of the room. Various ceiling-baffle and ceiling-reflector configurations were designed. Each design was incorporated into computer and physical, reduced-scale lecture-room models, and the effects of the baffles and reflectors on the sound field were determined, to evaluate the designs.

II. METHODS

A. Lecture-room configurations

A typical medium-sized university lecture room was selected as the basis for the tests. Figure 1 shows the floor plan. The lecture room has 96 seats, length = 15 m, width = 8.5 m, and height = 4 m (volume = 510 m^3, total surface area = 443 m^2, volume to surface-area ratio = 1.15 m). The room surfaces, and the seats and their writing tablets, are sound reflective. The midfrequency reverberation time measured in the unoccupied classroom was about 2 s. The corresponding reverberation radius was 1.3 m. Average octave-band surface-absorption coefficients calculated using diffuse-field theory varied from 125 to 2000 Hz as follows: 0.22, 0.12, 0.08, 0.08, 0.08. A speech source was positioned either at the front-center or at the front-side of the lecture room, and three listening positions were positioned in front (p1C—

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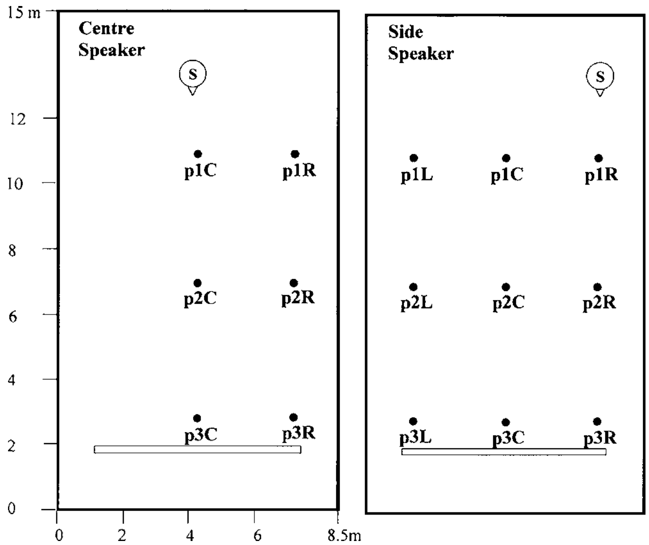

FIG. 1. Lecture-room floor plan showing the speech-source (S) and receiver (p) positions, and dimensions (in m).

source/receiver distance – 2.0 m), middle (p2C – 5.5 m), and back (p3C – 9.0 m) seats on the centerline of the lecture room. Six additional listening positions were used when predicting the acoustical conditions in side areas of the lecture room (see Fig. 1).

B. Ceiling baffle and reflector configurations

Two basic types of ceiling baffles and reflectors were studied. The first involved parallel ceiling baffles, projecting down from the ceiling and running front to back in the classroom. They were expected to absorb reverberant sound incident on the ceiling from a wide range of angles, reducing late-arriving energy, while leaving speech signals, reflecting from the (reflective) ceiling between the baffles to the back of the room, unaffected. Both sound-absorptive and sound-reflective baffles were considered. Different shapes, materials, spacings, and depths of the ceiling-baffle configurations were tested in pilot studies. Six configurations were selected for detailed study using computer prediction and scale-model measurement. These were reflective (configuration R) and absorptive (A) baffles, 0.6 m deep, separated by either 0.3 m ($R1/A1$), 0.6 m($R2/A2$) or 1.2 m ($R4/A4$).

Based on the baffle results, ceiling reflectors involving lengths of obstacles of semicircular cross-sectional shape (configuration C), suspended from the ceiling with either the flat (CF) or curved (CC) side down, were evaluated in the scale model. These were expected to reflect and scatter speech sounds like "fittings" in an industrial workshop (see below). The shapes were inspired by common suspended light fixtures. The diameter of the semicircular reflectors was 0.3 m, the distance from the ceiling to the bottom of the reflectors was 0.6 m. They were 7 m long, and ran front-back in the lecture room, separated by 1.2 m, and with either the flat side down without absorption on the upper curved side (CF), with the flat side down and absorption on the upper curved side (CFA), or with the curved side down and no absorption (CC). Alternatively, either 30 (configuration

FIG. 2. (Color online) Photographs of the 1/8-scale model without ceiling baffles or reflectors: (a) showing the seats and rear partition; (b) showing the model speech source and microphone.

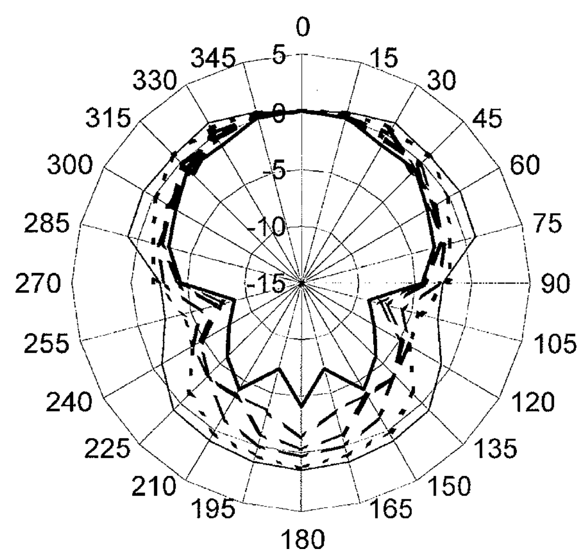

FIG. 3. Measured octave band, horizontal-plane directivity factors (in dB) of the 1:8-scale-model speech source; levels are normalized to 0 dB at 0°: (——) 63 HzFS; (······) 125 HzFS; (–·–) 250 HzFS; (– – –) 500 HzFS; (– ·· –) 1000 HzFS; (——-) 2000 HzFS.

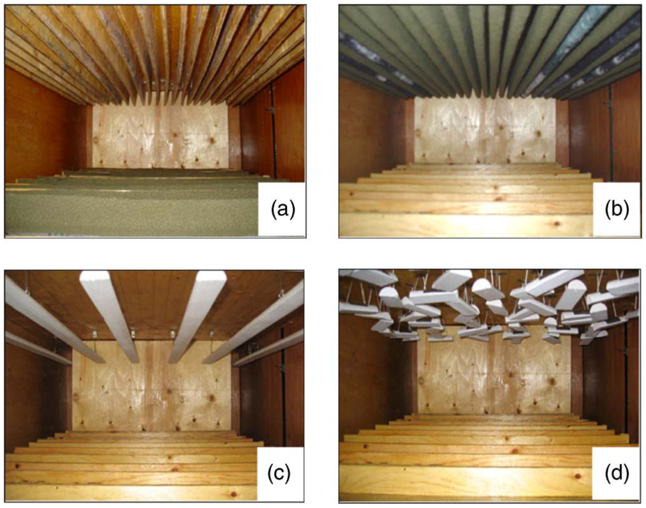

FIG. 4. (Color online) Scale-model ceiling baffle and reflector configurations in the unoccupied ("u") and occupied ('o') lecture room: (a) R1o; (b) A1u; (c) CFu; (d) CF60u.

CF30) or 60 (CF60) reflectors, 0.8 m long, were hung randomly from the ceiling with flat side down and no absorption.

C. Physical scale modeling

The lecture room was also studied without and with ceiling baffles or reflectors using a 1:8 scale model. According to the fundamental principle of the scale-modeling technique,[5] according to which all dimensions are scaled down by the scaling factor, the lecture room with length=15 m, width =8.5 m, and height=4 m, was a 1.88 m $\times$1.06 m$\times$0.50 m 1/8 scale model. The floor of the model was polished concrete. The walls, ceiling, the partition at the back of the room, and the rows of seats, were made of varnished plywood. Figure 2(a) is a photograph of the model, showing the rows of seats and the rear partition. In order to investigate how the effects of ceiling baffles and reflectors vary with

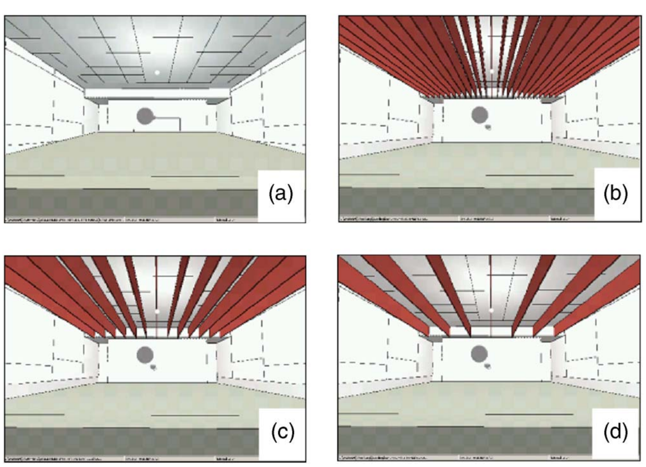

FIG. 5. (Color online) Computer models of the lecture room with: (a) no baffles; (b) $R1/A1$ baffles; (c) $R2/A2$ baffles; (d) $R4/A4$ baffles. Note the 1-m-deep seat block in all configurations.

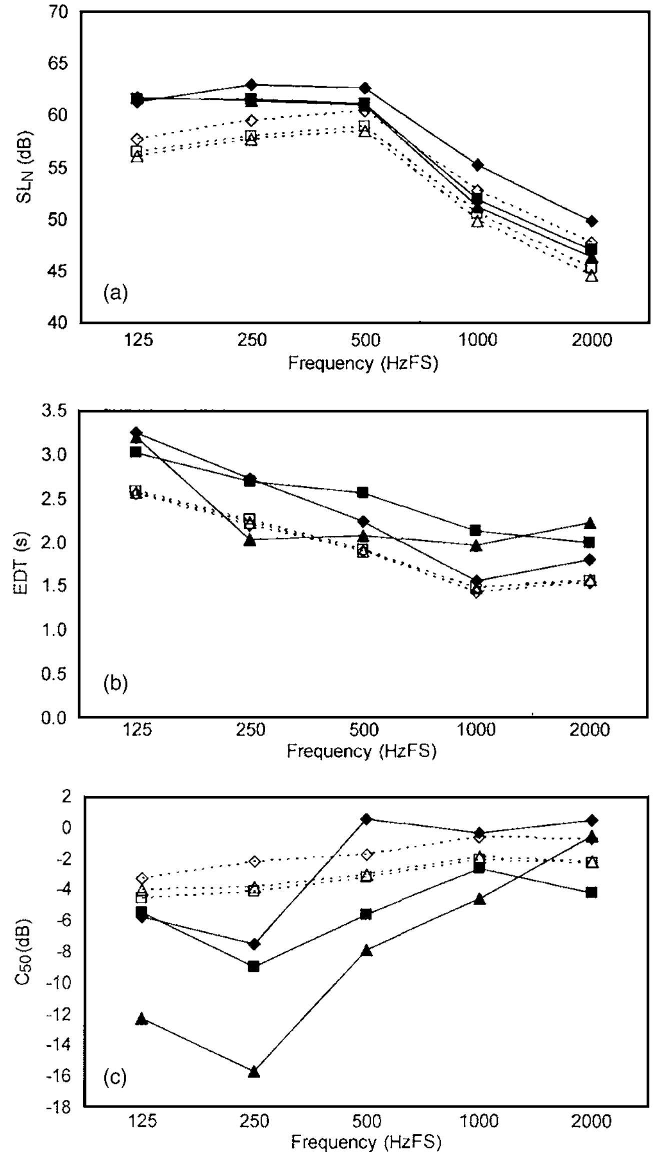

FIG. 6. Variation with frequency of (a) speech level SL_N, (b) early-decay time EDT, and (c) early-to-late energy fraction C_{50} at three central positions with the center speaker in the unoccupied lecture room without ceiling baffles or reflectors, as measured in the scale model and as predicted: (–◆–) p1C measured; (–■–) p2C measured; (–▲–) p3C measured; (···◇···) p1C predicted; (···□···) p2C predicted; (···△···) p3C predicted.

room occupancy in the lecture room, two different occupancies (unoccupied and 37% occupied/26 students) were considered in the scale model.

Air absorption is a major consideration in scale-model measurement. Air absorption increases approximately with the square of the frequency.[6] In a scale model, wavelength-to-dimension ratios are maintained, so wavelengths are scaled down by the scale factor, resulting in scaled-up model test frequencies. Since the test frequencies are high, air absorption is excessive in a scale model and cannot be neglected. For prediction, air-absorption exponents were calculated at the model test frequencies for the temperature and relative humidity measured in the scale model, as described in Ref. 6.

Speech sources in lecture rooms are mainly human talk-

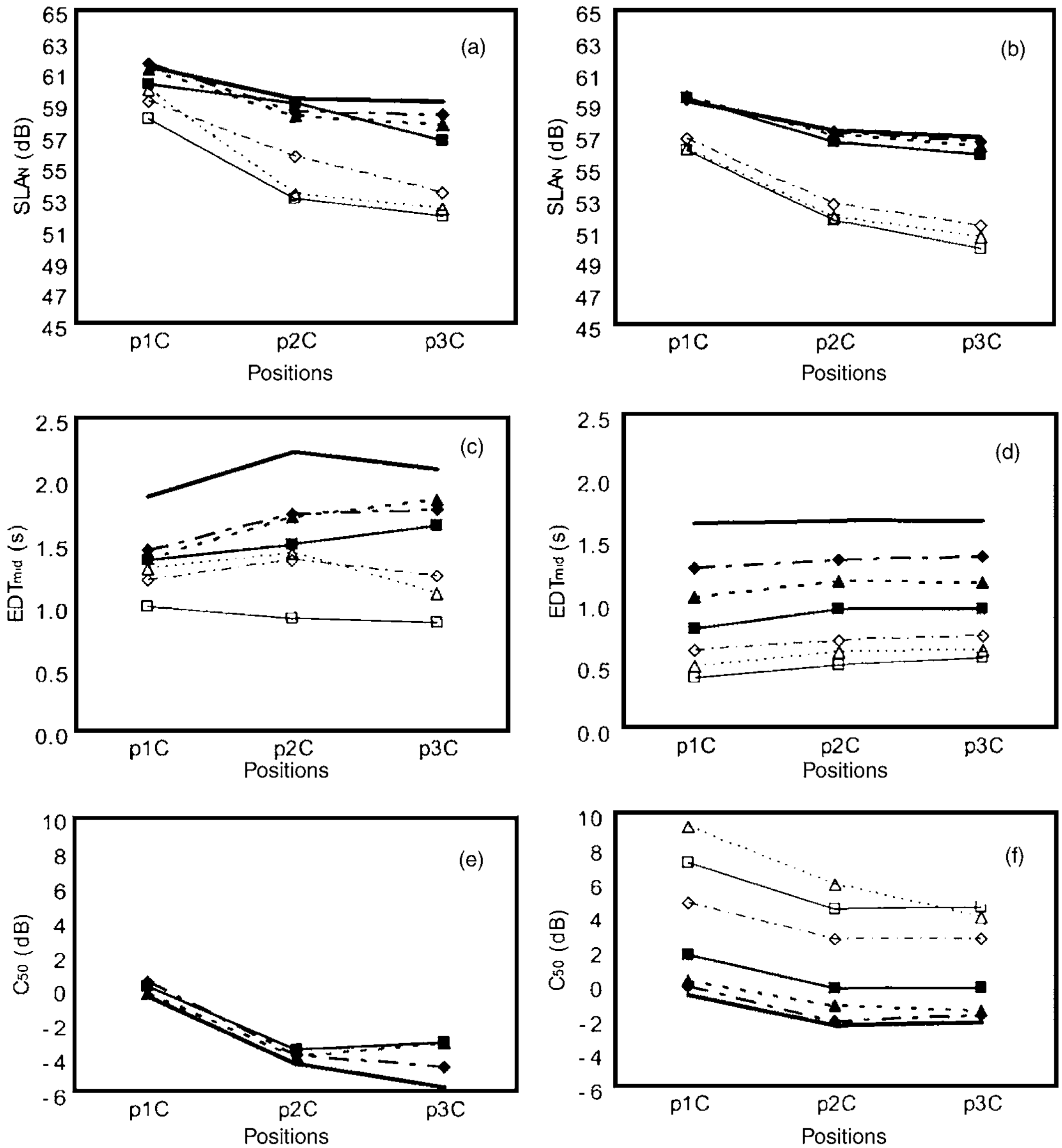

FIG. 7. Variation with position along the centerline with the center speaker of speech level SLA_N, early-decay time $\mathrm{EDT}_{\mathrm{mid}}$, and early-to-late energy fraction C_{50} in the unoccupied lecture room without and with reflective and absorptive ceiling baffles, as measured in the scale model and as predicted (C_{50} for the absorptive ceiling baffles is not available): (a) SLA_N, measured; (b) SLA_N, predicted; (c) $\mathrm{EDT}_{\mathrm{mid}}$, measured; (d) $\mathrm{EDT}_{\mathrm{mid}}$, predicted; (e) C_{50}, measured; (f) C_{50}, predicted. (———) no baffles, (–■–) $R1$, (- -▲- -) $R2$, (–·–◆–·–) $R4$, (–□–) $A1$, (- -△- -) $A2$, (–·–◇–·–) $A4$.

ers. Source directivity can strongly influence speech levels in lecture rooms. For accurate scale modeling of the lecture room, a model speech source is required which radiates with the directional characteristics of human speech. Such a source was created using a 1:8-scale head made of modeling clay, formed around the narrow end of a hollow cone, driven at the wide end by a "tweeter" loudspeaker, which narrowed down to a 3-mm-diameter opening as the mouth, to represent human speech directivity in the scale model (see Fig. 2(b)). Of course, the cone causes internal reflections which distort the signal spectrum; however, the effect was small in the test octave bands measured in the study. The power levels and directivities of the model speech source were measured in an anechoic chamber. Figure 3 shows the measured horizontal-plane directivity.

The ceiling baffles were made of varnished plywood, and could be covered with thin industrial carpet to make them absorbent. The absorption of the carpet was estimated from the change in reverberation time that occurred when a sample of it was introduced into the empty model, and was similar to that of 50-mm-thick glass fiber at full-scale frequencies. The semicircular ceiling reflectors were made of painted wood; the same carpet was used to make them absorbent. The carpet was also used to cover the front and top surfaces of the rows of seats, to simulate the absorption of upholstered or occupied seats approximately; the corresponding occupancy (37%) was estimated from the reduction in EDT and the typical absorption per occupant at 1 kHz.[7] Figure 4 shows photographs of some of the scale-model ceiling baffle and reflector configurations.

Acoustical measurements were made using the Maximum Length Sequence System Analyzer, which measured the impulse response between the model speech source and the Bruel & Kjaer 4135, "1/4 in." microphone used to receive the sound signals. All measurements were made after pre-calibration of the equipment. Early-decay times (EDT in

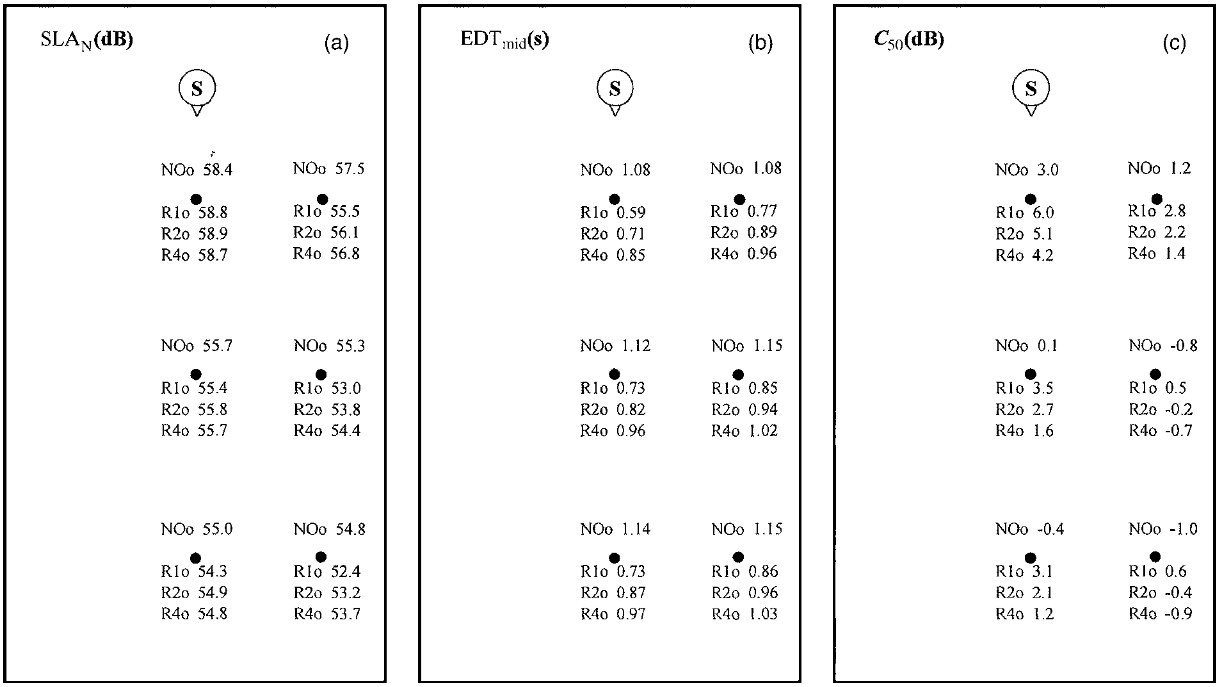

FIG. 8. Predicted variation with position of (a) SLA_N in dB, (b) $\mathrm{EDT}_{\mathrm{mid}}$ in s, and (c) C_{50} in dB without and with reflective ceiling baffles, in the occupied virtual lecture room with the center speaker.

s) and steady-state levels (with the speech-source output levels kept constant) were measured. Measurements were made in octave bands from 1 to 16 kHz (125–2000 HzFS–FS=full-scale equivalent value) at all three receiver positions. The octave-band steady-state levels were converted to total, A-weighted "speech" levels SLA_N corresponding to a typical adult talking in a "Normal" voice level, using the relative output power levels of such a talker[8] and of the model speech source. Average midfrequency $\mathrm{EDT}_{\mathrm{mid}}$ values relevant to speech intelligibility were calculated by averaging the octave-band EDTs at 500, 1000, and 2000 HzFS. In the case of the model without ceiling baffles or reflectors, average surface-absorption coefficients were calculated from the measured octave-band EDTs using diffuse-field theory; values increased with frequency from 0.06 to 0.1, close to

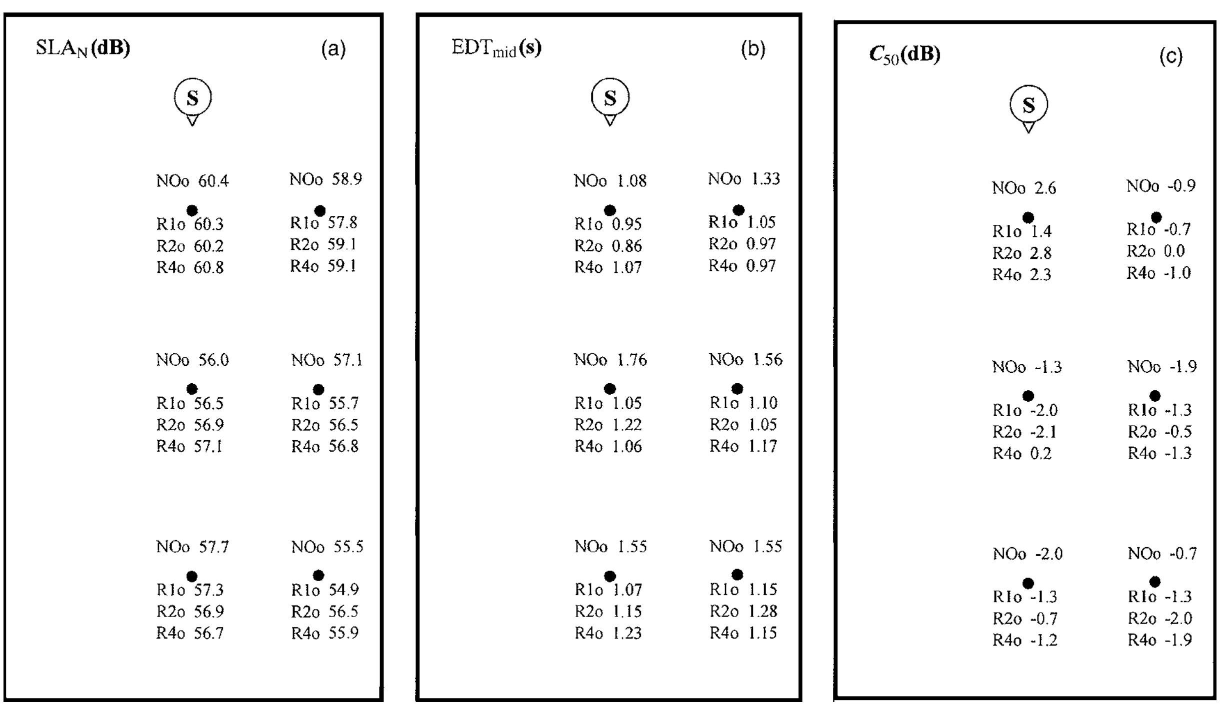

FIG. 9. Measured variation with position of (a) SLA_N in dB, (b) $\mathrm{EDT}_{\mathrm{mid}}$ in s, and (c) C_{50} in dB without and with reflective ceiling baffles, in the occupied scale-model lecture room with the centre speaker.

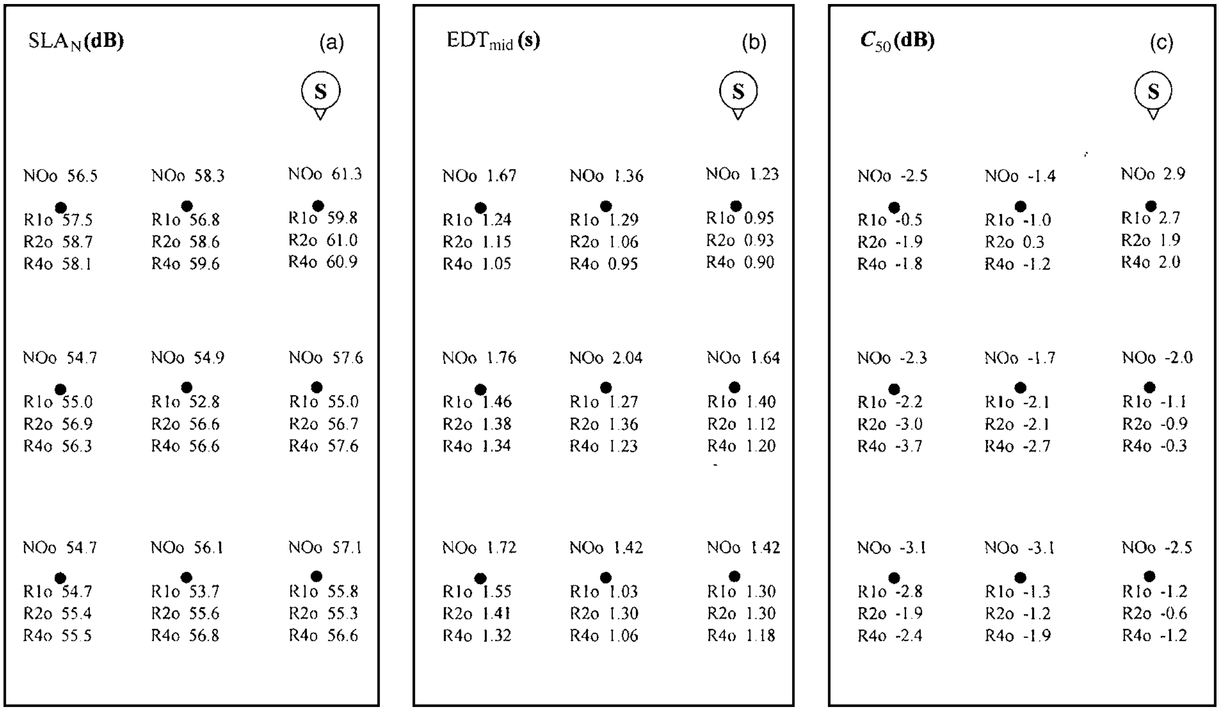

FIG. 10. Measured variation with position of (a) SLA_N in dB, (b) $\mathrm{EDT}_{\mathrm{mid}}$ in s, and (c) C_{50} in dB without and with reflective ceiling baffles, in the occupied scale-model lecture room with the side speaker.

those in the full-scale room. Taking into account the model scale factor, C_{50} was calculated by calculating $C_{50/8=6.25}$ from the model impulse responses.

D. Computer simulation

The ceiling baffles were also studied using CATT-Acoustic v8.0 (Ref. 9) computer simulation. The lecture-room and ceiling-baffle configurations were modeled, octave-band EDTs and speech levels predicted, and corresponding values of SLA_N, $\mathrm{EDT}_{\mathrm{mid}}$, and C_{50} calculated. The lecture-room configuration was exactly the same as in the scale-model measurements. A sound source and nine receivers were positioned as shown in Fig. 1. The output level and directivity of the sound source were identical to the values

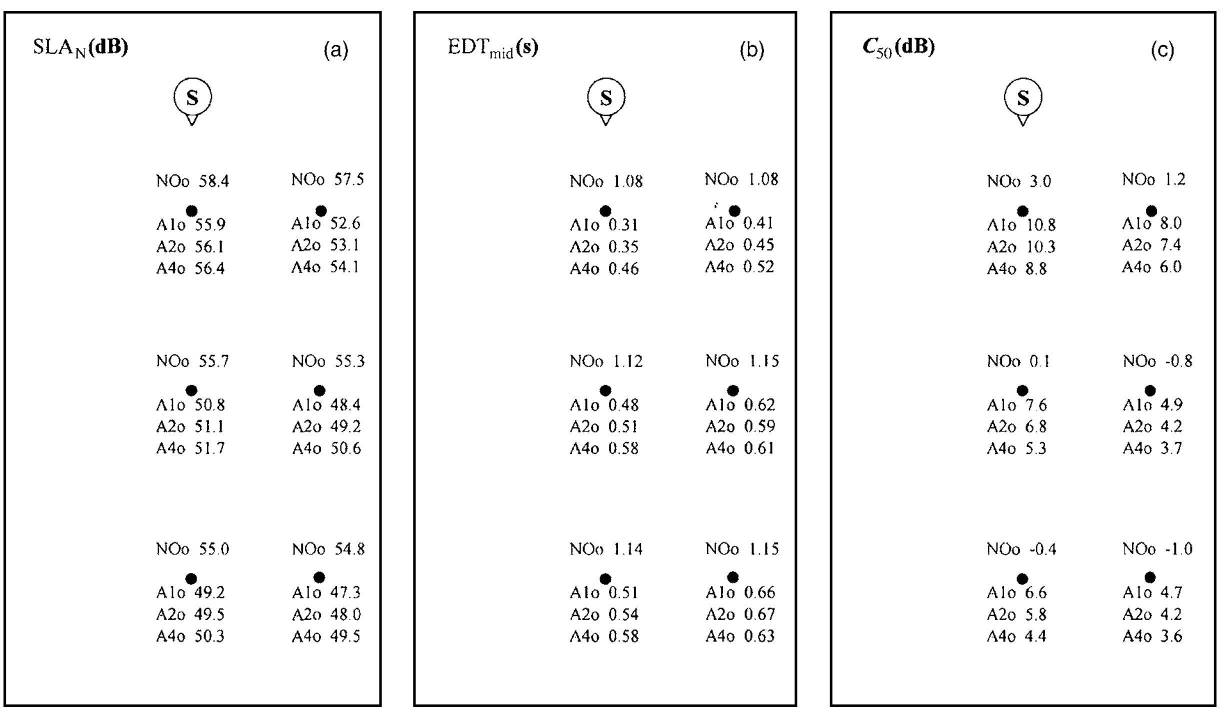

FIG. 11. Predicted variation with position of (a) SLA_N in dB, (b) $\mathrm{EDT}_{\mathrm{mid}}$ in s, and (c) C_{50} in dB without and with absorptive ceiling baffles, in the occupied virtual lecture room with the center speaker.

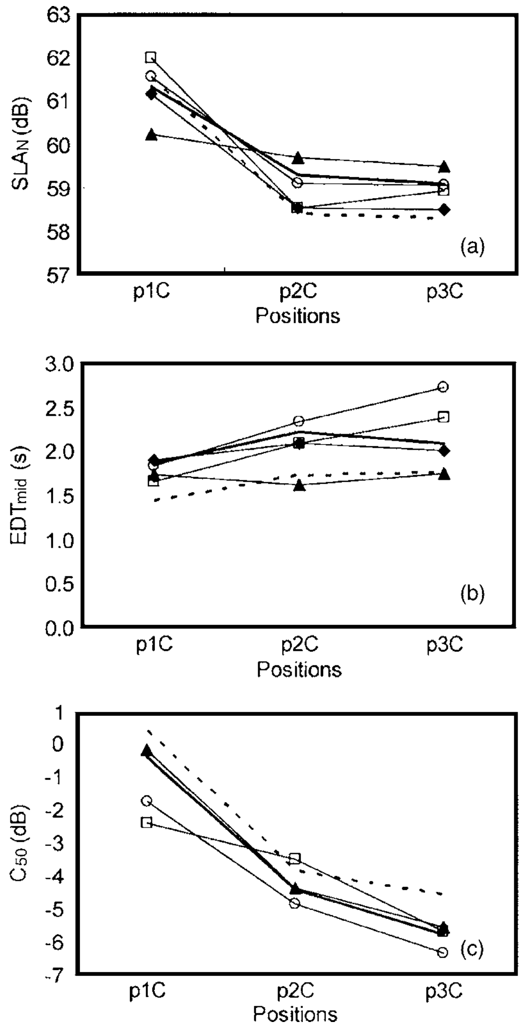

FIG. 12. Measured variation with position of (a) SLA_N in dB, (b) EDT_{mid} in s, and (c) C_{50} in dB in the unoccupied scale-model lecture room at central positions without and with ceiling baffles and reflectors: (——) no reflectors; (······)*R*4; (– ▲ –) CF; (–◆ –) CC; (– □ –) C60; (– ○ –) C30.

used in the scale-model measurements. Unoccupied seats were modeled as one large 1 m deep seat block. Figure 5 shows computer models of the virtual lecture room without and with ceiling baffles. Ceiling reflectors were not studied by computer prediction as it was not clear how to model them accurately. The absorption coefficients of the room surfaces used in the simulation were the average values measured in the scale model without ceiling baffles or reflectors. Diffuse-reflection coefficients of the surfaces were set to increase with frequency from 0.1 to 0.3, based on previous research.[10]

III. RESULTS

Two introductory remarks must be made before discussing the results. First, it was generally found that measured and predicted EDTs and C_{50}'s were strongly inversely related, as has already been reported in the literature.[1] Even though, in principle, C_{50} is a better measure of the effect of reverberation on speech intelligibility than EDT, both parameters in fact provided similar information about the effects of the baffles and reflectors. Second, discussed below are results for two key components of speech intelligibility—speech level and C_{50}. It would clearly be useful in evaluating the ceiling baffles and reflectors to calculate values of a speech-intelligibility metric—such as speech transmission index or useful-to-detrimental energy fraction (U_{50})—from these components. However, this would require choosing values for the noise level at the receiver position under consideration, which introduces significant difficulties, as discussed in Ref. [11]. To assume a uniform noise level throughout the room is not realistic. Modeling noise as emanating from localized sources is more realistic; however, the effect of such noise sources depends on their output powers and positions relative to the speech source and receiver position. Real classrooms contain many noise sources (ventilation outlets, classroom equipment, the occupants) with different output powers and positions in the classrooms. Their characteristics cannot easily be estimated or generalized in a useful, realistic manner and, therefore, neither can the effect of noise. For this reason, no attempt was made to calculate values of speech-intelligibility metrics.

A. Comparison of measurement and prediction

In order to confirm that the scale-model and virtual lecture rooms were reasonably similar, comparisons were made between measured and predicted speech levels, early-decay times, and early-to-late energy fractions in the unoccupied lecture room without ceiling baffles or reflectors, for the center source position and the three central receiver positions. Figure 6 shows the octave-band results. Predicted SL_N values were somewhat lower than those measured by about 4 dB at low frequency, decreasing with frequency to about 1.5 dB at high frequency. Predicted EDTs varied negligibly with position; measured times showed much more variation—predicted values tended to be lower than those measured, by up to about 25%. At pC2 and pC3, as was the case for EDT, measured C_{50} values also had more variation than those predicted, and predicted values tended to be higher than those measured. The imperfect agreement between measurement and prediction is interesting, given that the average absorption coefficients involved in the virtual and scale models were very similar to one another. It can partly be explained by uncertainties in the scale-model measurements, differences in the values of important room parameters (e.g., the diffuse-reflection coefficients), possible limitations of the computer simulation (for example, the seat block), and the fact that the scale model is more realistic in, for example, including modal effects. In any case, it can be concluded that the reduced-scale and virtual lecture-room models, while not identical, are sufficiently similar that both can be used to study the effects of ceiling baffles and reflectors. The two techniques have their individual advantages and disadvantages. The scale model has the advantage of physical realism (for example, including modal effects), while prediction has the advantage that the input data defining the virtual room are more precisely known.

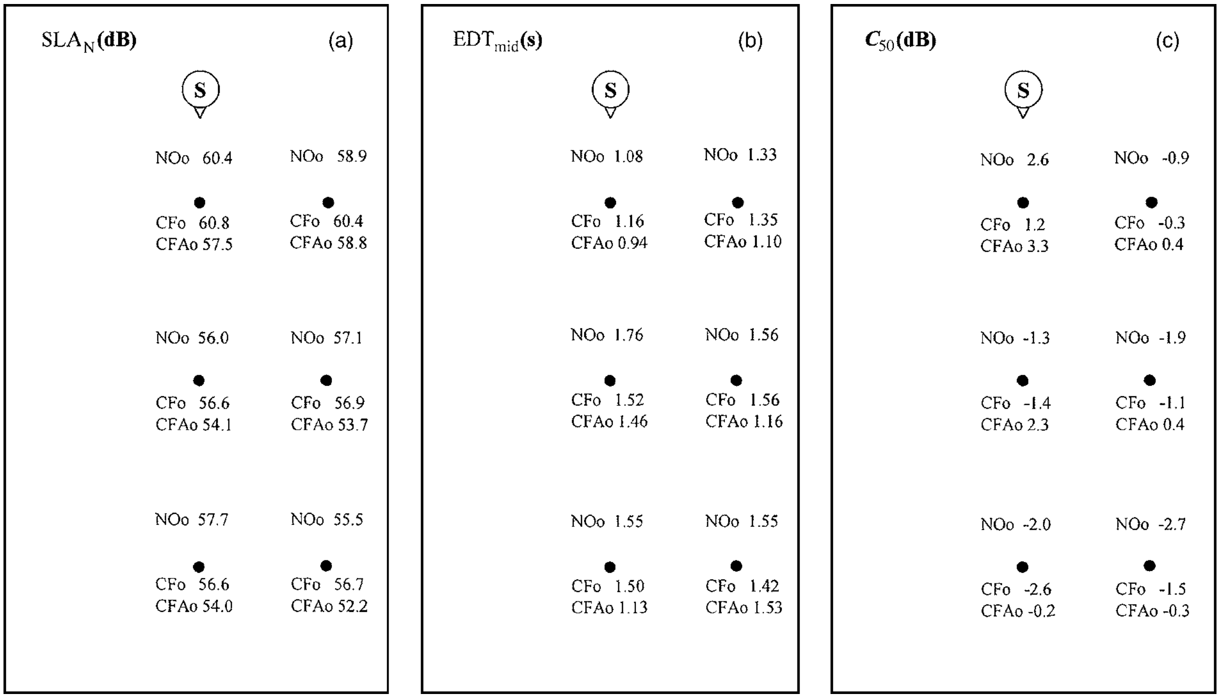

FIG. 13. Measured variation with position of (a) SLA_N in dB, (b) EDT_{mid} in s, (c) C_{50} in dB with the center speaker without and with ceiling reflectors, in the occupied scale-model lecture room.

B. Ceiling baffles

Figure 7 compares speech levels, early-decay times and early-to-late energy fractions measured and predicted in the unoccupied room with the six reflective and absorptive ceiling-baffle configurations, with the results for no baffles for the three receivers along the centerline and the center speaker. SLA_N is highest with no baffles, decreasing by about 2 dBA from the front to the back of the room. With the reflective ceiling baffles, as the number of baffles increased, predicted SLA_N remained virtually unchanged at the front of the room, but decreased by up to about 1.5 dBA at the back. Measured levels showed more variability, but similar trends, especially at p3C. With the absorptive ceiling baffles, and increasingly with the number of baffles, levels decreased more rapidly with distance relative to levels with the reflective baffles-by up to between 4 and 6 dBA at the front and back of the room, respectively. Ceiling baffles decreased the EDT_{mid} in all cases. With the reflective ceiling baffles, predicted EDT_{mid} values decreased progressively with increased number of baffles by up to about 50%—the decreases were similar at all three receiver positions. With absorptive baffles, EDT_{mid} varied little with baffle spacing and was very low. Again, measured results were similar, but showed less clear trends, and baffles resulted in smaller decreases in EDT_{mid}. C_{50} increased with an increasing number of baffles, and with baffle absorption.

Figure 8 to 11 show the SLA_N, EDT_{mid}, and C_{50} results at all receiver positions in the occupied room with ceiling baffles. Figure 8 shows that adding reflective ceiling baffles was predicted to have little effect on SLA_N along the centerline, tending to increase it slightly at the front, leave it unchanged in the middle, and decreasing it slightly at the back. At the side receiver positions, reflective baffles were predicted to decrease levels by up to 2.4 dB, the effects increasing with the number of baffles. The addition of baffles caused the decrease of SLA_N from the front to the back of the room to increase from 3.6 dB without baffles to as much as 6.4 dB. Adding reflective baffles was predicted to decrease EDT_{mid} by 10–45%. C_{50} increased by up to 3.5 dB. Both effects increased with the number of baffles, and decreased with distance from the source and, therefore, were greater at the central receivers than to the side. The effects of adding reflective ceiling baffles measured in the scale model (see Fig. 9) were more variable than as predicted, and smaller in magnitude. Figure 10 shows the SLA_N, EDT_{mid} and C_{50} values measured in the scale model with reflective ceiling baffles for the nine receiver positions and the side speaker. SLA_N tended to decrease by up to 2.6 dB at receiver positions on the same side as the speaker, but increased by about the same amount on the far side of the room. The effects were slightly greater than with the central speaker. Increasing the number of baffles resulted in lower levels. In side seats, EDT_{mid} decreased by up to 40%; C_{50} decreased slightly at the position nearest the source and at the room center, but otherwise increased by up to 1.9 dB. Figure 11 shows the predicted effects of adding absorptive ceiling baffles with the central speaker. They decreased SLA_N by 2.0–7.5 dBA, the effect increasing with the number of baffles, with source/receiver distance, and to the side of the room; front-back level differences increased to up to 8.6 dB. Adding absorbent baffles resulted in trends that were similar to those with the reflective baffles, but which were greater in magnitude; EDT_{mid} decreased by 42–71% and C_{50} increased significantly—by up to 7.8 dB.

The absorptive ceiling baffles do not achieve the desired objective since, as well as beneficially reducing early decay

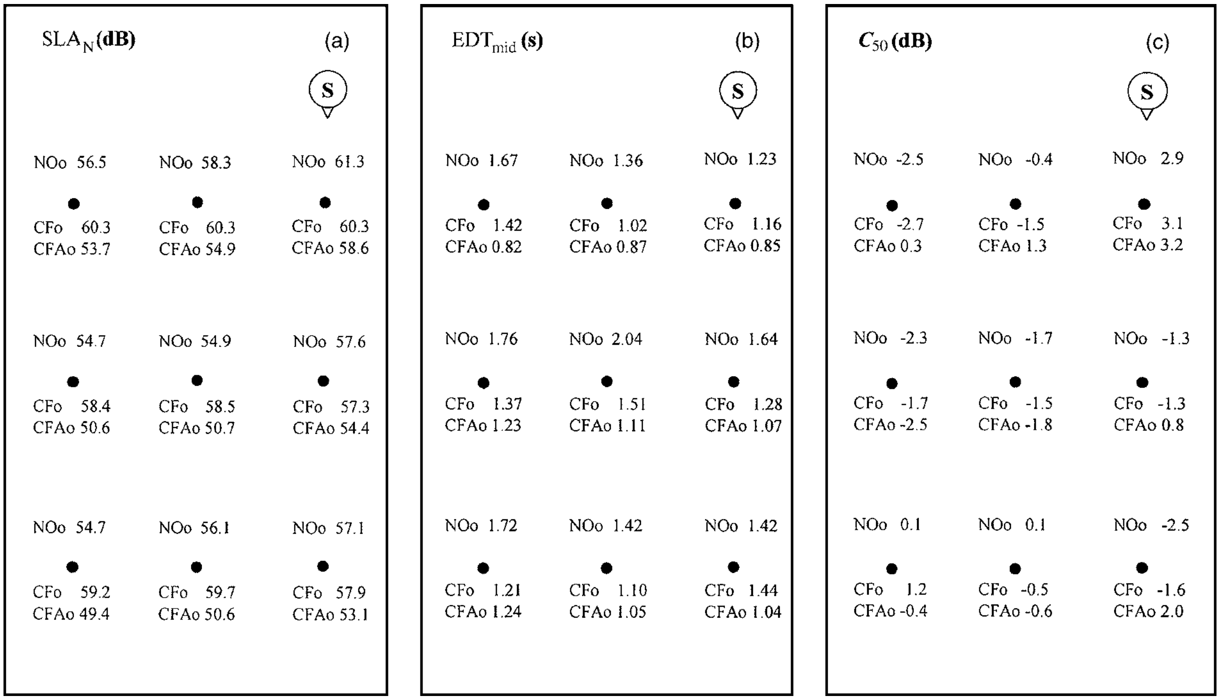

FIG. 14. Variation with position of (a) speech levels SLA_N, (b) early-decay times $\mathrm{EDT}_{\mathrm{mid}}$, (c) early-to-late energy fraction C_{50} with the side speaker without and with ceiling reflectors, as measured in the occupied scale-model lecture room.

times and increasing C_{50}, they detrimentally decrease speech levels significantly. Reflective baffles, on the other hand, achieve the objective better, reducing $\mathrm{EDT}_{\mathrm{mid}}$ and increasing C_{50} significantly, while reducing speech levels little.

C. Ceiling reflectors

The ceiling-baffle results are somewhat reminiscent of those that occur when reflective scattering obstacles (fittings) are introduced into an industrial workshop.[12] Reverberation times decrease sharply; steady-state levels from a sound source increase slightly close to the source due to back-scattering, and decrease more so far from the source. Thus, an alternative ceiling-reflector concept, based on fittings and consisting of reflective scattering obstacles suspended from the ceiling, was tested. Semicircular ceiling-reflector configurations, inspired by the shapes of common light fixtures, were evaluated. Figure 12 shows the SLA_N, $\mathrm{EDT}_{\mathrm{mid}}$, and C_{50} values measured in the unoccupied scale model with the four semicircular ceiling-reflector configurations (described in Sec. II B) at the three central positions with the center speaker. Also shown are the results without baffles or reflectors, and for the $R4$ ceiling-baffle configuration which had the same baffle spacing as the CF and CC reflectors. The CF reflectors decreased SLA_N by about 1 dB at p1C, and increased them insignificantly at p2C and p3C; levels were lower than with $R4$ at the front, and higher otherwise. $\mathrm{EDT}_{\mathrm{mid}}$ decreased by between about 10 and 30%, with the largest decreases occurring at p2C; values were very close to those for configuration $R4$. C_{50}, however, remained unchanged. The CC reflectors decreased SLA_N slightly at p2C and p3C, similar to configuration $R4$. They decreased $\mathrm{EDT}_{\mathrm{mid}}$ negligibly; as with configuration CF, C_{50} remained unchanged. The short, randomly distributed ceiling reflectors (configurations CF30 and CF60) showed somewhat different results from those for the longer reflectors. The CF30 reflectors had little effect on speech levels, increasing levels slightly at p1C. Both CF30 and CF60 had little effect on $\mathrm{EDT}_{\mathrm{mid}}$ at p1C and p2C, but increased it at p3C. Their effect on C_{50} was small, resulting in decreases of about 2 dB.

In an attempt to further improve performance, measurements were made with semi-circular ceiling reflectors with sound-absorptive materials on the upper curved surfaces (configuration CFA). Figures 13 and 14 show the measured SLA_N, $\mathrm{EDT}_{\mathrm{mid}}$, and C_{50} results with the center and side speaker, respectively, in the occupied scale model. When the speaker was at the center, adding the absorption decreased SLA_N by 1.6–4.5 dB; that is, adding the CFA reflectors to the untreated room decreased levels by up to 3.4 dB. When the speaker was at the side, adding absorption decreased SLA_N at receivers along the same side by between 2.4 and 4.5 dB; the decrease increased to as much as 9.8 dB at the other receiver positions, and increased towards the back of the room. Thus, introducing the CFA reflectors decreased SLA_N by up to 5.3 dB. The added absorption decreased $\mathrm{EDT}_{\mathrm{mid}}$ and increased C_{50}. While these effects are beneficial, the strong detrimental reduction of speech levels makes the absorbent reflectors of little interest.

IV. CONCLUSION

Reflective ceiling baffles achieved the goal of decreasing reverberation and increasing early energy with minimal speech-level reduction—the effect increased with baffle density. Reflective ceiling reflectors, in the form of long reflective obstacles of semicircular cross-section, suspended below the ceiling in parallel, front-to-back lines with flat side down, were also somewhat effective. Making the baffles or reflectors sound absorptive further beneficially reduced reverberation and increased early energy, but also strongly reduced speech levels, which is highly detrimental to speech intelligibility. The shape of the semicircular ceiling reflectors was inspired by typical lighting fixtures. The results suggest that appropriately designed lighting fixtures could be effective at controlling lecture-room sound if they were made with flat, sound-reflecting (and, of course, optically transparent) bottoms, and arranged in long, parallel, front-to-back lines.

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