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EFFECT OF DESIGN AND RENOVATION ON THE SPEECH CONDITIONS IN UNIVERSITY CLASSROOMS

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ABSTRACT
The acoustical characteristics of new and renovated university classrooms have been determined. Details of each design or renovation were related to the results, in order to determine how various new-design and renovation features relate to acoustical quality. Since the quality of verbal communication was the focus, room-average speech intelligibility was used as the quality measure. Speech intelligibility is affected by two main factors − the speech-signal to background-noise level difference and the reverberation. The results show that some designs and renovations were effective, but others were not. They have put too much emphasis on adding sound absorption to control reverberation, at the expense of lower speech levels, particularly at the backs of rooms. Future design must prioritize: 1) limiting background noise; 2) promoting high speech levels; and, 3) controlling reverberation.

1 - INTRODUCTION
The objective of the work reported here was to use the MLSSA measurement system, and theoretical considerations, to determine the acoustical characteristics of a number of university classrooms. Of particular interest were new classrooms with special acoustical designs, and those that had recently been renovated and had been measured before renovation. The results were related to the details of the design or renovation and used to generate guidelines for classroom design and renovation.

2 - BACKGROUND
Improving the acoustical quality of UBC classrooms is the ultimate objective of this work. The most important acoustical aspect of classrooms is verbal communication. Thus, speech intelligibility was used to quantify quality. Speech intelligibility is the percentage of speech material that is correctly identified by the average listener. Speech intelligibility is affected by two factors: speech-signal to background-noise level difference (SN) and reverberation, quantified here by the early decay time (EDT).
As described in detail in [1], classroom measurements were made in the 125 to 8000 Hz octave bands, and total A-weighted levels were calculated, as appropriate. At each receiver position, the following acoustical quantities were measured or calculated:

- **Early decay time (EDT)** − EDT1 is the value at 1000 Hz. The optimum value for a quiet, occupied classroom varies from around 0.3 to 0.7 s, increasing with room size [2];
- **Average surface absorption coefficient** (a) − This was calculated from the measured EDT, using the Eyring reverberation formula. At 1 kHz, the value is a1, calculated from EDT1; it values vary from about 0.1 in classrooms with no acoustical features, to 0.4 or higher in classrooms with carpets, wall or ceiling absorption and upholstered seating [1];
- **A-weighted speech level (SLA)** − SLA is the typical total A-weighted speech level. It is calculated from the measured sound pressure levels, the known sound-power levels of the test source, and the sound-power levels for a typical person speaking at midway between normal and raised vocal effort [3]. In this case, the range of SLA's found in occupied classrooms is approximately 50 − 65 dBA [1];

- **SLA slope (sA)** – SLA slope sA is a measure of the rate of decrease of the magnitude of SLA with distance from the sound source, in dB per distance doubling (dB/dd). The range of SLA slope's found in occupied classrooms is approximately 0.5-4 dB/dd, with an average of about 2 dB/dd [1];

- **Background-noise level (BGN)** – BGN includes noise coming from the ventilation system (VN), and noise due to student activity (SAN). Noise which diffuses into the room from outside may also contribute, but is assumed negligible here. BGNA (related to VNA and SANA) is the total A-weighted background noise level. The range of VNA's found in occupied classrooms is about 30-52 dBA, with an average of about 41 dBA [1]. SANA prediction was done empirically [4] and must be considered tentative;

- **A-weighted speech-signal to background-noise level difference (SNA)** – Values were calculated without and with the contribution of student activity to the background noise. The optimal value of this level difference is 14 dBA. Even if the level difference becomes higher than 14 dBA, there will be no further improvement of speech intelligibility. The range of SNA's found in occupied classrooms is about -2 to 15 dBA, with an average of about 10 dBA [1];

- **Speech intelligibility (SI)** – Speech intelligibility (SI) is a measure of the combined effects of speech level, early decay time, background noise and signal-to-noise level difference. Values were calculated without and with the contribution of student activity to the background noise. Subjective quality ratings were assigned to ranges of SI values as follows: SI $\geq$98%, excellent; 96% $\leq$SI<98%, very good; 93% $\leq$SI<96%, good; 88% $\leq$SI<93%, fair; 80% $\leq$SI<88%, poor; SI<80%, bad quality [6, 7].

Experiments were performed at typical instructor and student positions. A speech source was placed at the typical instructor lecturing position, usually at the front center of the classroom. Three to ten receiver positions, distributed over the student seating area were tested and room-average SI's were calculated. Measurements were performed in the unoccupied classrooms. Unoccupied-room results were corrected to the 70%-occupied condition using techniques described elsewhere [5]. Three new and ten renovated classrooms were involved in the study. Indicative results are discussed here.

3 - RESULTS AND ANALYSIS

HEBB THEATRE and LASR 104/102 – HEBB THEATRE is a huge room with a capacity of 375 people. It was renovated by adding side-wall and ceiling absorption. This doubled the average surface absorption coefficient to 0.28 and decreased EDT1 from 1.24s to 0.78 s, which is a good value for such a large room. SLA decreased slightly to 53.5 dBA, which is low due to the large volume and high absorption. It drops off at an average rate, surprisingly for a room of this size, presumable due to the room shape and reflectors which direct sound to the back. The background noise in this room is quite low (38.0 dBA), resulting in an optimal SNA at all positions. The reduction of reverberation caused a significant increase in quality, with SI increasing from 89.5 ('fair' quality) to 93.4 ('good' quality). Predicted student-activity noise is high in this classroom, so including it significantly reduced quality, with SI after renovation decreasing to 89 % ('poor' quality).

LASR 104 and 102 are two classrooms with capacities of 95 people which are identical, except that LASR 102 is a renovated version of LASR 104. Renovation involved adding sound absorbers to the side-walls and adding a suspended acoustical ceiling. This extensive treatment, which increased a1 from the very low value of 0.08 to the high value of 0.39, decreased EDT1 significantly to 0.29 s, which is too low for a mid-size room. Thus, SLA is below average, particularly at the back of the classroom, as it drops off at a high rate due to the sound absorption. The background noise in this room is quite high (45.3 dBA), particularly at the back of the room where SLA is lowest. Thus, SNA decreases rapidly, from 21 to 1.8 dBA, from front to back, with an average value of 11.4 dBA, which is less than optimal, unlike prior to renovation. SI increased slightly from 92.7 ('fair' quality) to 93.4 % ('good' quality). The extensive renovation has had little benefit. Considering student-activity noise does not change the conclusions.

In both of the above cases, renovation involved adding extensive sound absorption in order to reduce reverberation. In HEBB Theatre, with relatively low background-noise levels (if student-activity noise is ignored), this was beneficial. It significantly reduced reverberation, but did not worsen SNA's since these remained optimal. In LASR 102/104, with high background-noise levels, the renovation was ineffective. A beneficial reduction of reverberation was counteracted by a detrimental reduction of speech-to-noise difference.

WESB 100 − WESB 100 is a big classroom with a capacity of 325 people. The renovation done to this classroom included redoing the ceiling absorption, adding carpet in the aisles, removing absorbent wall patches and adding slot resonators absorbers in reflectors on the lower side walls, adding upholstered seats and, apparently, an HVAC upgrade. The surface absorption coefficient doubled to 0.29. EDT1 decreased from 0.52 to 0.34 s, which is too low for a large room. SLA decreased from an average to a very low value, its slope increasing from 1.6 to 2.4 dB/dd, slightly above average. VNA decreased from a very high value of 50.6 dBA to a near optimal value of 37.4 dBA. SNA increased significantly from a very low 6.5 dBA to an optimal value. Thus, SI increased from 90.0 % ('fair' quality) to 97.1 % ('very good' quality). The renovation done to this room − in particular, the reduction of ventilation noise − was very effective. It is likely that the room-acoustical renovations had little effect. Including student-activity noise reduces SI slightly before renovation, and more significantly after.
AMPEL 311 − AMPEL 311 is a small, new classroom with a capacity of 40 people. In this classroom, industrial carpet and suspended acoustical ceiling were installed. No special acoustical expertise was involved in its design. The acoustical ceiling and the carpet lead to a1 being above average, keeping the reverberation low; EDT1 is 0.45 s, which is a bit high for a small room. SLA is 58.5 dBA, which is average. It decreases with distance at an average rate. This is explained by the narrow shape, hard side-walls and the small size. The ventilation noise level is quite low at 38.2 dBA. Thus, SNA has an optimal value of 14 dBA at all positions, and the overall SI is quite high at 97 % ('very good' quality). Including student-activity noise in the analysis does not change the conclusions.
FSC 1005 − FSC 1005 is a big room with a capacity of 250 people. An acoustical consultant was involved in the design. The acoustical features in this room include industrial carpet, curved hardwood reflectors below the structural ceiling, sound absorbers on the upper back walls and upholstered seating. EDT1 is only 0.29 s, due to a very high a1 of 0.45, and is much too low for such a large room. SLA is just 53.3 dBA, which is low due to the room's size and surface absorption. It is particularly low at the back of the room; that it only decreases with distance at a rate which is slightly greater than average (2.5 dB/dd) may be due to the ceiling reflectors. VNA is quite low (except at one position) and, thus, SNA is generally optimal. The overall speech intelligibility is 97.1 % ('very good' quality). However, the predicted student-activity noise in this room is high; thus, its inclusion decreases quality significantly, to SI = 92.7% ('fair').

4 - CONCLUSION

The results of this study suggest that new acoustical designs and renovation of university classrooms may or may not be effective. They have often focussed on adding sound absorption to reduce reverberation. The considerable absorption contributed by the occupants of a classroom was not considered, leading to too low reverberation in the occupied rooms. Also not considered is that the classroom occupants can generate significant noise. It can be concluded that, for high acoustical quality, a small classroom size is preferred, a quiet ventilation system is required, classrooms should be used when well−occupied and an appropriate amount of sound absorption is needed. The required amount of sound absorption depends on the room size, must consider that the occupants contribute sound absorption and must achieve a balance between promoting high speech level and controlling reverberation. Future design must prioritize: 1) limiting background noise; 2) promoting high speech levels; and 3) controlling reverberation.
This work assumed a 'typical' speaker. However, the variability of instructor voice levels can be high [3, 4]. Had a quiet speaker been assumed (as was done in [5]), resulting speech intelligibilities and associated classroom qualities would have been much lower. Similarly, classrooms were assumed to be 70% occupied; different occupancies would result in different conclusions regarding acoustical quality. Finally, the results of [4] suggest that student-activity noise can be high, and can significantly reduce speech intelligibility, in large, absorptive classrooms; this result requires further validation.

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