Building a Sound Future for Students: Considering the Acoustics in Occupied Active Classrooms

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Acoustics in occupied active classrooms should be carefully considered because they may relate more to student achievement than unoccupied conditions.

Children all over the world spend a majority of their time in built environments, spaces constructed for humans to occupy such as homes or classrooms at schools. Although there is certainly evidence that points to the impact of the home environment on development, there is less scientific research showing the effects of the classroom's built environment on student learning outcomes. However, recent research both in the United States and abroad (including by our group) shows that the acoustic environment of classrooms has a profound effect on learning.

Surveying 220 K-12 classrooms over the course of two years of measurements has provided a unique opportunity for us to reflect on the acoustic standards that guide the design of these classrooms. The purpose of specifying acoustic conditions in classrooms is to ensure that the spaces are appropriate learning environments. Standards on classroom acoustics typically set recommendations for unoccupied spaces based on a goal of attaining clear communication through increased speech intelligibility. Such standards, however, are not commonly enforced in the United States. Furthermore, meeting current recommendations for unoccupied classrooms may not result in appropriate acoustic environments when those rooms are occupied and in active use, which is how students typically experience classrooms.

Background

Researchers have taken a keen interest in characterizing the acoustic attributes of classrooms and their effects on both students and teachers. Studies have observed and measured the effects of room acoustics on both speech intelligibility and student academic achievement as well as on vocal health of teachers (Hunter and Titze, 2010; Bottalico et al., 2017; Puglisi et al., 2017). In this article, we focus on the impact of classroom acoustics on students.

Initial studies related to classroom acoustics centered on speech intelligibility or the degree to which speech is clear and recognizable. Speech intelligibility, often measured in the form of word, phrase, or sentence recognition, depends on the sound level of the talker, the level of the background noise, and the room acoustic characteristics (Bradley, 1986). When the ratio of the signal level from the talker to the noise level from background sources (signal-to-noise ratio) is low, the speech intelligibility scores of children and those with hearing impairments are consistently found to be worse than for adults or those with normal hearing (Crandell and Smaldino, 2000; Shield and Dockrell, 2003; Klatte et al., 2013).

Using an amplification system for teacher's voices can dramatically improve the signal-to-noise ratio, leading to better speech intelligibility (Rosenberg et al., 1999). Although amplified solutions remain viable, most consultants in architectural acoustics will shy away from an amplified solution to mitigate inadequate signal-to-noise ratios in classrooms. Amplified systems require more substantial partition construction to ensure sufficient isolation between classrooms. Increasing the signal-to-noise ratio beyond those achievable with natural room acoustics can be counterproductive without considering isolation.

Other studies have focused on how the interaction between a classroom's volume, geometry, and materials can result in overly reverberant conditions that negatively affect the speech intelligibility. Sounds produced in a more reverberant environment will linger longer than in less reverberant environments, increasing the overall average noise level within the space. Researchers have investigated the impact of reverberation time on speech intelligibility, often in combination with varying background noise levels (Bistafa and Bradley, 2000; Hodgson and Nosal, 2002; Wroblewski et al., 2012). For a constant signal-to-noise ratio, higher reverberation times do result in poorer speech intelligibility. Though limiting excessive reverberation is important for optimal speech intelligibility, Yang and Bradley (2009) caution that reverberation should not be eliminated because early arriving reflections from room boundaries are found to improve intelligibility by supporting the sound energy that arrives directly from the source to listeners.

Starting in the late 1990s, a growing number of measurement campaigns were undertaken to gauge the state of classroom acoustics. Acoustic conditions were documented in university lecture halls (Hodgson, 1999), preschools (Yang and Hodgson, 2005), elementary or primary schools (Picard and Bradley, 2001; Shield and Dockrell, 2004; Nelson et al., 2008), and secondary schools (Astolfi and Pellerey, 2008; Shield et al., 2015). Many of these investigations found that existing conditions did not exhibit appropriate noise levels and/or reverberation times for optimal speech intelligibility.

Recent computational developments in software and hardware have led to studies aimed at understanding classroom acoustic effects using auralization techniques (Yang and Hodgson, 2006; Hodgson et al., 2008; Neuman et al., 2010; Valente et al., 2012). Auralization refers to rendering the sound field of a built environment through modeling and simulation. For example, a recording of a teacher's voice can be auralized in different classroom environments so that listeners can understand how different rooms affect that listening experience. Auralization has been particularly useful for subjective testing because it allows researchers to test the effects of different acoustic environments in a more controlled laboratory environment.

Some of these laboratory studies on classroom acoustics have been shifting toward the measurement of speech comprehension that involves higher levels of cognition rather than simply recognizing words, phrases, or sentences (Klatte et al., 2010; Valente et al., 2012; Lewis et al., 2014). Results from those studies indicate that background noise and room reverberation have more detrimental effects on comprehension than on speech recognition. Work has also branched into characterizing how classroom acoustic conditions influence occupant listening effort or listening difficulty (Howard et al., 2010). Building on this concept, Prodi's research group has focused further on quantifying "listening efficiency" as a measure of both the accuracy of speech intelligibility and listening effort (Prodi et al., 2010, 2013; Prodi and Visentin, 2015).

The American National Standards Institute/Acoustical Society of America S12.60 Classroom Acoustic Standard

In 2002, the American National Standards Institute (ANSI) published the first classroom acoustics standard in the United States, ANSI S12.60 (ANSI, 2002): *Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools*. The current standard recommends that the A-weighted sound level measured in an unoccupied classroom with ventilation (mechanical) systems on should not exceed 35 dB(A) (ANSI/Acoustical Society of America [ASA], 2010). This standard also states that the maximum reverberation time averaged over the 500, 1,000, and 2,000 Hz octave bands should be less than or equal to 0.6 second in classrooms with an enclosed volume less than 10,000 feet^3 (283 meters^3) or less than or equal to 0.7 second for classrooms larger than 10,000 feet^3 but smaller than 20,000 feet^3. The first edition of this standard provided the perceptual, educational, and developmental rationale for the recommended criteria as well as the empirical evidence from which the criteria were derived (ANSI, 2002). The rationale was that verbal communication is essential to learning, developing language proficiency, and developing cognitive skills. Verbal communication can only successfully occur when there is a high degree of speech intelligibility. Minimizing the background noise level and controlling room reverberation helps to create a clear communication channel between

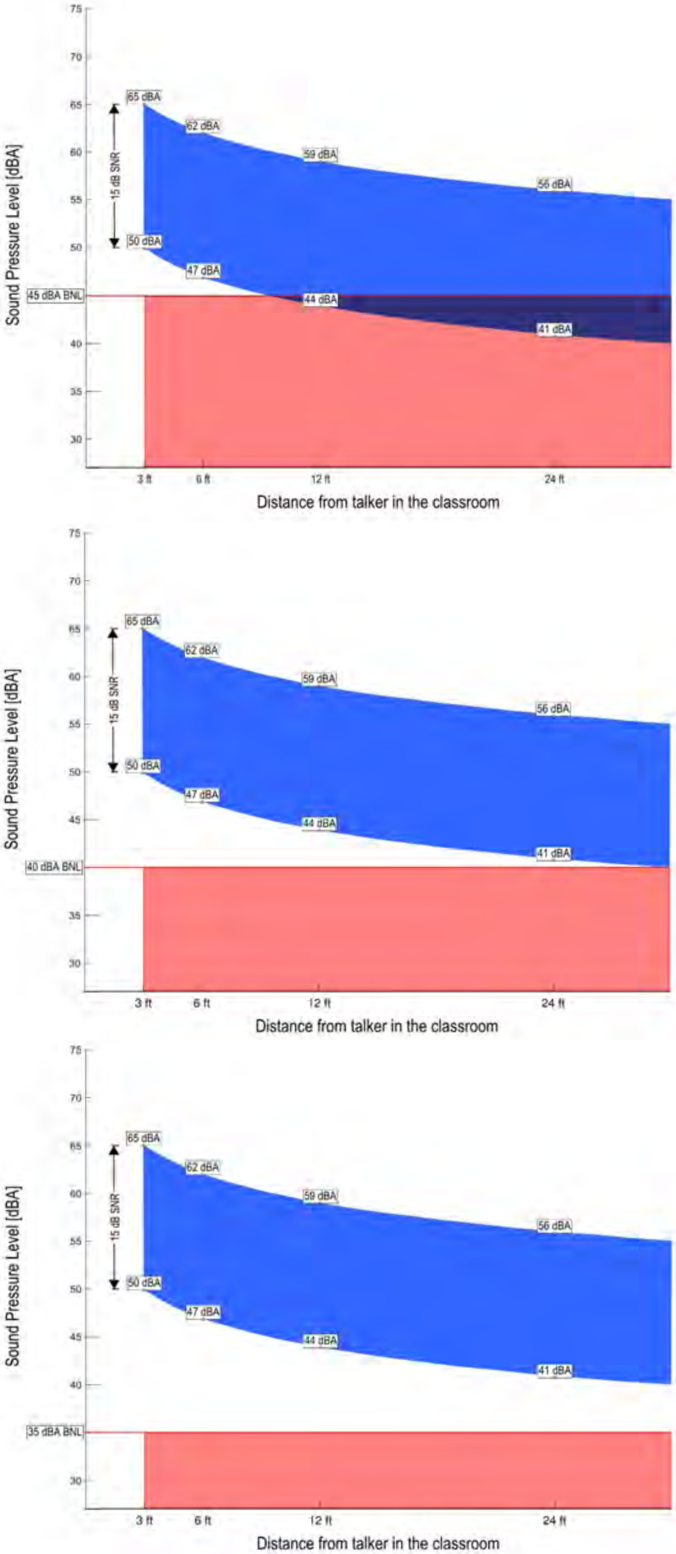

Figure 1. *The spatial decay of the sound pressure level in the reverberant field of a classroom. The sound pressure level at 3 feet (1 meter) from a talker is 65 dB(A).* ***Blue area****, region within +15 dB signal-to-noise ratio (SNR);* ***red area****, levels lower than the background noise level (BNL). Where the* ***blue and red areas*** *intersect, listeners at that distance from the talker will experience lower than +15 dB SNR.* ***Top****: When the BNL is 45 dB(A), only students sitting within 9 feet of the teacher will hear the lesson with a sufficient SNR.* ***Middle****: A 40 dB(A) background noise level can meet the desired +15 dB SNR in classrooms where the largest dimension is less than 30 feet.* ***Bottom****: Designing classroom background noise levels to be at most 35 dB(A) ensures that students sitting anywhere within a classroom will experience a SNR of at least +15 dB, even with talkers that produce slightly lower voice levels.*

teachers and their students, and doing so can be particularly important for children as they are still developing their language skills (Klatte et al., 2010).

Classroom speech levels are an important factor in determining the maximum recommended background noise levels. The American Speech-Language-Hearing Association (1995) recommends a signal-to-noise ratio of at least +15 dB to ensure high speech intelligibility for children with language and hearing impairments. Bradley and Sato (2008) found that an even higher signal-to-noise ratio of +20 dB was preferable for the youngest students in their study (grade 1) to attain near-ideal speech communication. A study by Pearsons et al. (1977) showed that the A-weighted sound level of teacher's speech is typically 67 dB(A) at a distance of 1 meter in a quiet classroom. Because sound levels are expected to decrease approximately 3 dB per doubling of distance in a classroom, the levels of the talker could diminish to be as low as 55 dB(A) in the rear of a typical classroom in the United States (**Figure 1**). To conservatively ensure a minimum +15 dB signal-to-noise ratio everywhere in the classroom, the ANSI standard set the recommended background noise level to not exceed 35 dB(A). Meeting this recommended maximum noise level achieves a suitable signal-to-noise ratio for high speech intelligibility, thereby positively influencing student learning.

An underlying assumption has been that improving speech intelligibility results in improved student achievement. However, only a few studies before the introduction of ANSI's standard in 2002 showed a direct link between noise levels and actual student learning outcomes (Bronzaft, 1981). Investigations completed after the introduction of the standard have provided more evidence that poor classroom acoustic conditions correlate to worse student performance. For example, in situ studies focusing on aircraft noise in the classroom have shown that greater exposure to such noise is related to lower reading scores for elementary students (Stansfeld et al., 2005; Klatte et al., 2017).

Moreover, Shield and Dockrell (2008) surveyed classrooms with noise sources more commonly found at elementary schools (e.g., traffic, ventilation systems) in both occupied

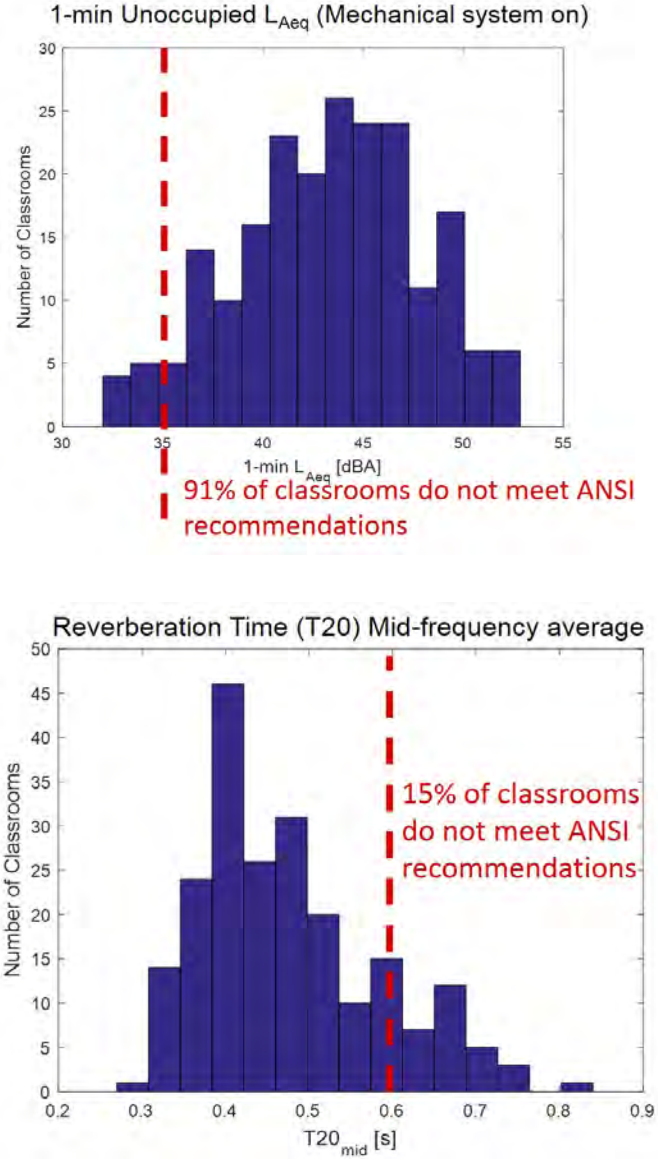

Figure 2. *Samples of the data measured from 220 K-12 classrooms in five school districts.* ***Top****: One-minute unoccupied A-weighted equivalent levels (L_{Aeq}) were recorded to characterize the BNL in the classrooms due to ventilation noise. Ninety-one percent of classrooms do not meet the American National Standards Institute (ANSI) recommended maximum of 35 dB(A).* ***Bottom****: Reverberation time was measured using a swept-sine method. Only 15% of classrooms do not meet the ANSI recommended maximum of 0.6 second.*

and unoccupied conditions. They found that lower English test scores were more strongly related to higher occupied background noise levels than to unoccupied background noise levels. It is therefore necessary to diminish the background noise level in actively occupied classrooms to mitigate this effect. One other study has found that background noise levels in unoccupied classrooms correlated to student achievement scores in reading and language subject areas (Ronsse and Wang, 2013). That study did not measure levels in the occupied active classrooms though.

Limitations of American National Standards Institute/Acoustical Society of America S12.60

Many investigations have shown that although the reverberation time recommendations given in ANSI/ASA S12.60 are attainable, there are few classrooms that meet the unoccupied background noise level requirements (Knecht et al., 2002; Nelson et al., 2008; Sato and Bradley, 2008). Observations of the 220 classrooms in our study are consistent with these findings (**Figure 2**).

Most of the K-12 classrooms that we visited have acoustical ceiling tile covering the entire ceiling surface, with a ceiling height at or less than 11 feet (3.3 meters). These room characteristics lead to acceptable reverberation times. **Figure 3** shows examples of typical classroom conditions observed in our study. If a classroom is excessively reverberant, adding absorptive materials in the space is a relatively easy task postdesign. Major renovations, however, are typically required to decrease background noise levels significantly, particularly those produced by building mechanical systems for heating, ventilation, and air conditioning (HVAC).

The best way to ensure quiet background noise levels from building mechanical systems is to design for them and not rely on postdesign solutions because the cost of replacing noisy mechanical systems is far greater than designing quiet systems in the first place. Designing a loud mechanical system is easier and less expensive than designing a quiet system, but the financial cost should not be the only cost considered when it comes to our educational facilities. There is a cost associated with designing and installing quiet mechanical systems, but the benefits experienced by the occupants of the classroom far outweigh these increased costs.

Routine approaches to mechanical systems frequently utilized in classrooms are often inconsistent with the best acoustical practices. It can be challenging to disregard routine practices in favor of less utilized, more creative design solutions. Coupling this with the fact that there are not easily enforceable acoustics requirements means that appropriate classroom sound levels are not always prioritized in the building design industry.

In the United States, the ANSI classroom acoustics standard provides a guideline for background noise levels but does not prescribe enforceable requirements. The United States Green Building Council (USGBC) introduced the Leadership in Energy and Environmental Design (LEED) green building certification system in 2000. LEED certifies

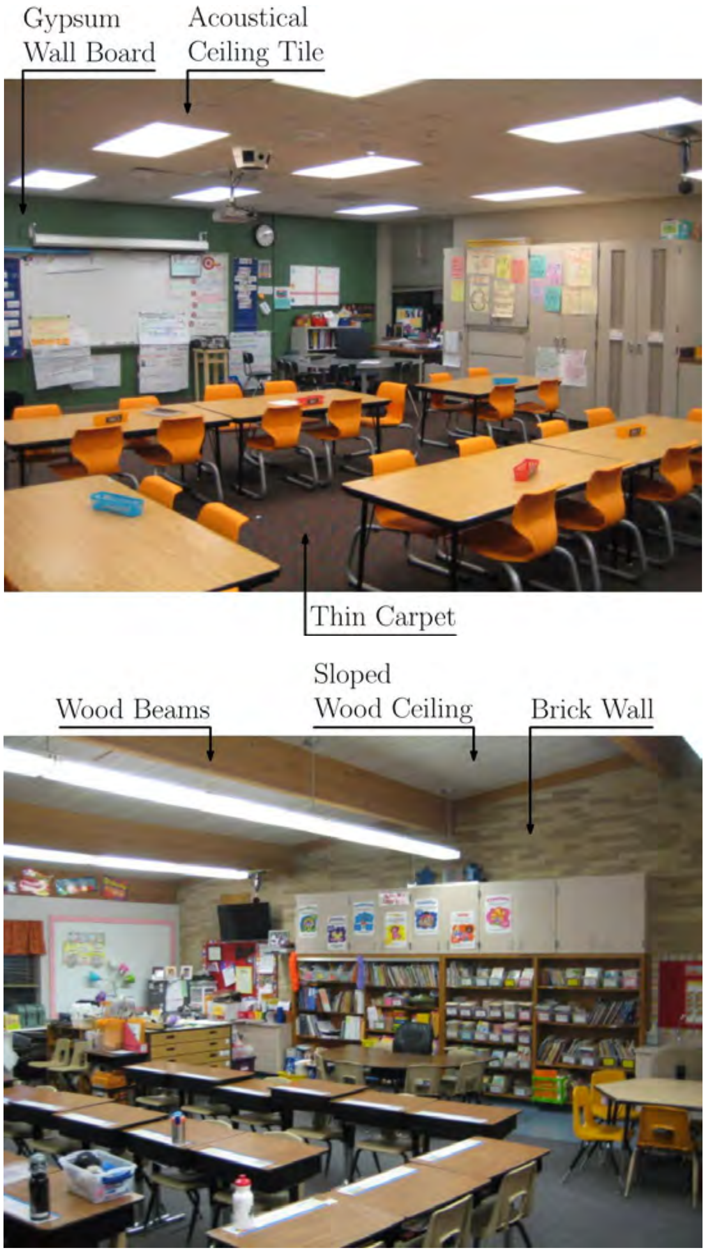

Figure 3. *Typical (**top**) and unique (**bottom**) features characteristic of the 220 classrooms measured in the central midwestern United States. **Top**: Many classrooms in the United States use acoustical ceiling tile to add absorption to classrooms to limit reverberation time as well as to create easy access points to building systems above the tiles. **Bottom**: Some classrooms have unique features like those shown. Although this room's ceiling is more sound reflective than acoustical ceiling tile, the brick walls are more diffusive and less reflective than gypsum wall board. Those considerations combined with a relatively small volume meant that this classroom's reverberation time met the ANSI S12.60 guidelines.*

that a building meets certain qualifications for sustainability. A building must meet prerequisite design criteria to obtain LEED certification but can add levels of distinction through earning credits associated with meeting more stringent design criteria. Unoccupied background noise level is one of the LEED design criteria. In previous versions of LEED for building design and construction, the prerequisite background noise level was 45 dB(A), and a distinction credit was awarded to schools that met a background noise level of 40 dB(A) or lower. These levels are noticeably louder than the 35 dB(A) recommended by ANSI S12.60. Although 45 dB(A) is quieter than some of the unoccupied noise floors in classrooms observed in our study, it does not necessarily meet the needs of its occupants. In the most recent revision of LEED (v4), the prerequisite background noise level was adjusted to 40 dB(A), and the unoccupied background noise level requirement for the credit was adjusted to 35 dB(A) (USGBC, 2013), the level recommended in ANSI S12.60. LEED is one of the only programs in the United States that provides a means of incentivizing the achievement of acceptable background noise levels in classrooms, but buildings are not required to adopt LEED standards.

In contrast, the United Kingdom has implemented enforceable building regulations for classrooms to guide the design and construction of classrooms, published in *Building Bulletin 93* (BB93) that was first issued in 2003 and last revised in 2015 (United Kingdom Department for Education and Skills, 2015). The requirements of BB93 for unoccupied noise levels are similar to those recommended by ANSI S12.60. Maximum limits for the indoor ambient noise levels (IANLs) are set to 35 dB(A) for new primary and secondary school classrooms designed as core learning spaces that are not open plan and to 40 dB(A) for refurbished classrooms redesigned for the same purposes. IANLs are A-weighted equivalent levels measured over 30 minutes during normal teaching hours, excluding noise contributions from instructional equipment and instructional activities. Noise contributions from adjacent classrooms are considered and mitigated with appropriately substantial wall construction between classrooms, deemed appropriate by the type of activities and noise sensitivities in the adjacent rooms.

The requirements of BB93 for reverberation time are also similar to those recommended by ANSI S12.60. There are, however, different requirements for primary school classrooms and secondary school classrooms. Reverberation times in general classrooms must not exceed 0.6 second in new primary schools and 0.8 second in refurbished primary schools. For secondary schools, the upper limits are slightly higher: 0.8 second for new construction and 1.0 second for refurbished. The stricter requirement for primary school classrooms acknowledges that younger students require more favorable listening conditions because they are still developing their language skills.

Considering Conditions in Occupied Active Classrooms

A great deal of work has gone into the development of ANSI/ASA S12.60, LEED certification requirements, BB93, and other classroom acoustics standards around the globe. They have filled an important void and provided a much needed basis of acoustic design, but their recommendations do not tell the whole story; they do not encompass the entire range of acoustic experiences found within occupied active classrooms.

Many studies evaluating the effects of background noise on speech levels refer to the Lombard effect. The Lombard effect is the involuntary increase in vocal level to compensate for higher background noise levels, originally observed by French otolaryngologist Etienne Lombard (1911; Brumm and Zollinger, 2011). The Lombard effect is often cited as the reason occupied noise levels in classrooms should be strongly correlated to the unoccupied noise levels. An assumption is made that the background noise level in a classroom is consistent, regardless of occupancy and primarily the result of HVAC systems. Therefore, unoccupied background noise levels should significantly relate to the signal-to-noise ratios experienced by students in occupied conditions due to the Lombard effect. That is, higher unoccupied background noise conditions should result in proportionally higher talker levels in the occupied classroom. However, students in modern K-12 occupied active classrooms experience background noises that stem from more than the HVAC systems.

Our observations from visiting classrooms for our study confirm that assorted instructional equipment is in common, though not constant, use. Such equipment should not be discounted in guidelines recommended in standards. Video projectors are still staples in most classrooms in the United States. Some classrooms use interactive whiteboards, like SMART Boards, but many of these interactive whiteboards still use projector technology (**Figure 4**). These projectors have fans to dissipate heat, but the fans radiate noise that contributes to the background noise level in the classroom. We have also observed numerous laptop/tablet charging carts in classrooms with whirring fans that ultimately interfere with speech levels in the room (**Figure 5**). Instructional equipment can and does contribute to the background noise levels teachers must compete with to communicate with their students.

Figure 4. *Many classrooms still use video projector technologies. This is an example of a typical interactive whiteboard that uses a video projector. Video projectors can contribute to the BNLs that teachers must compete against.*

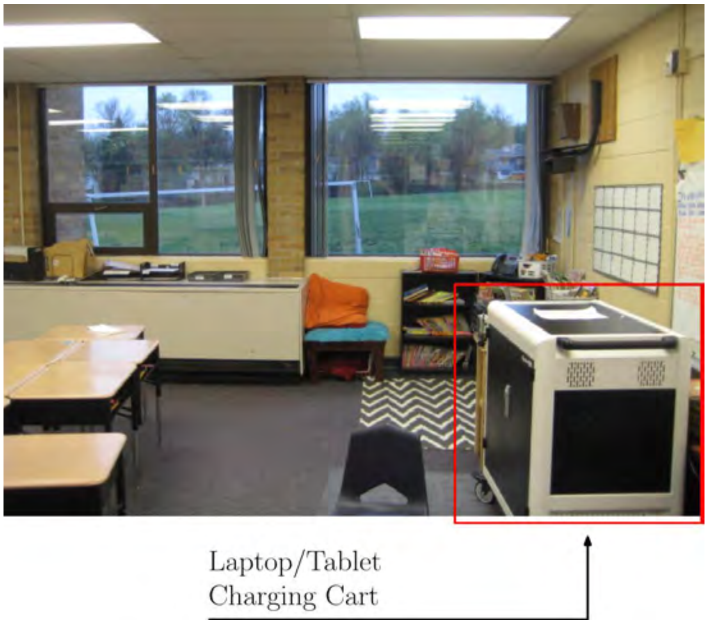

Figure 5. *The integration of computers into the curriculum necessitates charging stations for laptops and tablets provided by the school. These charging stations, like the one shown here, have fans that dissipate heat through vents. This is a source of operational noise that can interfere with a teacher's speech levels.*

The sound levels created by the occupants themselves should also not be disregarded. Picard and Bradley (2001) summarized levels of noise in occupied classrooms for students in assorted grades and found the highest levels in the classrooms of the youngest children. K-12 classrooms are complex learning environments in which a number of teaching modalities are used, ranging from single instructor to individual work to small group activities. Each of these types of activity in an occupied active classroom results in varying noise levels produced by the occupants themselves.

Shield et al. (2015) have analyzed the relationship between occupied and unoccupied noise levels in secondary classrooms. They conducted an acoustic survey of 185 unoccupied secondary school classrooms in England and performed continuous monitoring during 247 occupied core subject lessons in 80 of those classrooms. Results confirmed that the observed noise levels during these lessons in the occupied active classroom increased with the number of students and was greater for rooms with younger students. Consistent with the Shield and Dockrell (2008) study, a significant relationship was found between the sound levels gathered during lessons (occupied active) and those gathered in unoccupied conditions. Data on student learning outcomes are not shown in the Shield et al. (2015) paper though. More analyses comparing student achievement against occupied versus unoccupied noise levels are needed, as presented by Shield and Dockrell (2008). If the levels in occupied active classrooms more strongly predict student learning outcomes than in unoccupied levels, then design standards should include some guidance, perhaps for noise levels in occupied active classrooms as well as for ways to achieve those recommendations to optimize student learning.

Steady-state noise sources like HVAC noise can be easy to quantify, predict, and measure, but it is important to acknowledge that other, often times less predictable, sources of sound and noise exist in occupied active classrooms and can detrimentally interfere with communication between teacher and student. Considerations for occupied active conditions in classrooms and how they differ from unoccupied conditions need to be thought of holistically. Ongoing research in this area will hopefully give us a better understanding of how all of the environmental conditions work together to affect student achievement.

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BioSketches

Laura C. Brill integrates her diverse intellectual and artistic pursuits at Threshold Acoustics in Chicago, IL. Some of her current projects include renovations to the Kennedy Center Concert Hall in Washington, DC and The Perelman Center, a new performing arts center at the World Trade Center in NYC. She holds a BS in physics and a BA in theater arts from Nebraska Wesleyan University. She received her MS in architectural engineering from the University of Nebraska-Lincoln, where she was the lead graduate student researcher managing the large-scale measurement campaign of 220 K-12 classrooms.

Kieren Smith is currently pursuing her PhD in architectural engineering at the University of Nebraska-Lincoln, with a focus on building acoustics. She holds a bachelor's degree in commercial music with minors in physics and mathematics from Brigham Young University, Provo, UT. She is actively involved in her school chapters of the Acoustical Society of America (ASA) and the Society of Women Engineers. She is the most recent recipient of the ASA Leo and Gabriella Beranek Scholarship in Architectural Acoustics and Noise Control and currently serves as the ASA student council representative on the Technical Committee on Noise.

Lily M. Wang is a professor in the Durham School of Architectural Engineering and Construction and an associate dean in the College of Engineering at the University of Nebraska-Lincoln. She received her BS in civil engineering from Princeton University, NJ, and her PhD in acoustics from Pennsylvania State University, State College. Her research focuses on a variety of room acoustic and noise control topics. She is a Fellow of the Acoustical Society of America (ASA), a recipient of the ASA Hunt Postdoctoral Fellowship, R. Bruce Lindsay Award, and Student Council Mentoring Award and is currently serving as ASA president (2018-2019).