1. Introduction

The assessment of the acoustical quality of schools both objectively and subjectively has been extensively investigated [1,2,3]. It has been found that speech intelligibility in rooms with poor acoustics was detrimental to learning [4,5,6], as have classrooms with high levels of background noise [7,8,9]. There were particular acoustic related learning difficulties found for bilingual children or children with additional needs in poorly performing spaces [10]. However, sound field amplification has been found to provide improve children's behaviour in cross cultural environments [11,12,13]. It has also been found that the teacher’s voice will suffer in classrooms with poor acoustics [14,15]. As such new guidance has recently been introduced to aid in the design of classrooms, particularly rooms for more than 40 students [16]

With a significant investment in new schools and a programme of refurbishment currently being undertaken in the UK under new produced guidance [17] , it is necessary to determine how to most effectively improve speech intelligibility in classrooms [18], either by reducing the room reverberation through the application of acoustic treatment, the introduction of a sound reinforcement system into room, or a combination of the two approaches. This type of comparison has not been undertaken before, as the algorithms used in sound reinforcement systems are not disclosed. To this end this paper attempts to provide a methodology to objectively quantify under what conditions such a system improves speech intelligibility considering two variables: ambient noise and reverberation both with and without the sound reinforcement system. The paper details the equipment setup, the experimental method used, and provides results in the form of a new term: effective noise reduction for the various scenarios, 50 in total. From these results an empirical model was proposed which could be used as a tool to help make informed decisions as to what approach to take in refurnishing classrooms or similar spaces.

2. Experimental Equipment, Methodology and Procedure

The selected equipment as regards the sound field amplification system (SFA) was the Phonak Digimaster 5000. It was used to demonstrate the proposed methodology and procedure to determine the effectiveness of SFA in noisy and reverberant classrooms, but could be installed in alternative spaces. All SFA systems are propritory and as such the details of how the system works are unknown.. The methodology detailed below was designed so that a comparative performance of any SFA system could be undertaken, although it would need to be tested under identical conditions in the same space.

The Digimaster 5000 does automatically monitor background noise level, in for instance a classroom setting, and adapts the gain level of the speaker’s voice dynamically. This ensures an appropriate signal to noise ratio for the teacher’s voice, independent of whether the children are quiet or whether there is a high noise level in the classroom. It shouldbe mentioned that Phonak are most famous for their hearing aid designs which do contain compression algorithms. We do not know if they were implemented in the SFA system.

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The reverberation chamber at London South Bank University was used for the tests to physically simulate typical classrooms, volume of 202 m3 and surface areaof 213 m2, very similar to that measured by Shield *et al* in 165 British secondary schools [19], see Table 1, an average volume of 217 m3. The physically simulated classroom was then setup in a number of acoustic conditions. Porous sound absorbing material (0.17 m thick hung in strips on the wall) was introduced into the space to achieve different reverberation times (T60) at 1 kHz (0.4, 0.6, 0.8, 1.0 and 1.2 s), see Figure 1. These reverberation times gave a range which was very similar to that measured by Shield *et al* [19], see Table 2. As the reverberation chamber was designed to produce a diffuse sound field, it was assumed that the location of the absorption would not affect the results.

**Table 1.** Summary of British secondary classrooms [19]

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Enclosed Classroom** | **Design Workshop** | **Music Room** | **Science Room** | **Art Room** | **Open Plan Space** |
| Number of Rooms | 13 | 86 | 10 | 33 | 7 | 16 |
| Average Room Volume (m3) | 244 | 161 | 208 | 233 | 262 | 457.5 |

**Table 2.** Summary of the acoustic condition of British Secondary School Classrooms [19]

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Enclosed Classrooms** | | **Design Workshop** | | **Music Room** | | **Science Room** | | **Art Room** | | **Open Plan Space** | |
|  | Mean | Range | Mean | Range | Mean | Range | Mean | Range | Mean | Range | Mean | Range |
| Unoccupied Background Noise (LAeq, 5min) | 33.6 | 26.8 41.6 | 38.4 | 30.3 41.7 | 36.8 | 28.2 42.4 | 36.2 | 29.5 43.4 | 36 | 30.8 39.6 | 35.4 | 31.2 43.4 |
| Reverberation Time (s) | 0.64 | 0.40 0.86 | 0.72 | 0.30 0.96 | 0.51 | 0.36 0.67 | 0.75 | 0.41 1.09 | 0.63 | 0.48 1.23 | 0.53 | 0.51 0.66 |
| Lesson Noise (dBLAeq, 45 min) | 63.5 | 62.7 66.0 | 64.5 | 62.9 69.6 | N/A | N/A | 65.6 | 64.0 68.4 | 63.1 | 47.1 64.3 | 63.2 | No Data |



**Figure 1** The reverberation chamber showing the measurement setup including absorption,T60=0.4 s

A mouth simulator (Berhinger B205D loudspeaker) was positioned at the front of the room at a height of 1.5 m. A STIPA signal, set at 65 dBLAeq, 15s at 1 m in the free field, was used to determine the speech transmission index using the STIPA method [22], in the worst case reverberant field position 2.5 m from the loudspeaker 61.2 dBLAeq,15s in the physically simulated classroom. In addition, two loudspeakers (Yahama HS50M), positioned 2.5 m from the measurement microphone, see Figure 2, generated competing filtered random noise with the same spectral envelope as the STIPA signal, but without modulation at five levels to give a controlled signal to noise ratio, see Table 3.

Figure 3 - LSBU Phonak Room Figure

**Figure 2.** Shows the position of the mouth simulator (SA), the sound field amplification system (SB), and two noise generating sound sources (NA and NB)

For each T60 value, a baseline STIPA measurement was made for each competing noise level (40,50, 55, 60, 70 dBA) chosen, see Table 3, again similar to that found by Shield *et al* [19], see Table 2. Once the baseline was determined the SFA boom microphone was placed on axis at a distance of 0.05 m, and the system activated and allowed to acclimatize to the noise for 20s before the measurement was taken. Based on this measurement, the introduced competing noise was adjusted until the original STIPA value was again achieved (within 0.02 over an average of three 15 s measurements).

**Table 3.** Measurement conditions showing the combinations of achieved reverberation times (T60 at 1 kHz) and competing noise levels used for the individual measurement trials.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| T60 (s) | Background  noise level (dBA) | Competing noise levels (dBLAeq,15s) | | | | |
| 0.4 | 24.8 | 40.4 | 50.2 | N/A | 60.2 | 70.3 |
| 0.6 | 24.8 | 40.1 | 50.3 | N/A | 60.1 | 70.1 |
| 0.8 | 30.4 | 40.0 | 50.1 | 54.9 | 60.0 | 70.0 |
| 1.0 | N/A | N/A | 50.1 | 55.0 | 60.0 | 70.0 |
| 1.2 | N/A | N/A | N/A | 55.1 | 60.0 | 70.0 |

Next, the SFA system was turned off and the ambient noise level was measured. The difference between the noise levels with and without SFA that produced the same criterion STIPA was taken as a new metric, termed the equivalent noise reduction (ENR) achieved by the system.

Finally, the room impulse responses were measured under background noise level conditions and at each of the five noise levels using eSweeps in winMLS 2004 [20] in accordance to ISO 3382-1:2009 [21]. This was used to measure and verify the physically simulated classroom's reverberation times, Figure 3. Due to the dynamic nature of the SFA system, it was not possible to measure impulse responses (which requires linear time invariance) when SFA system active.

Figure 2 - Reverberation Times 3

**Figure 3.** Shows the measured frequency dependence of the reverberation times (T60) for the 5 different room setups (T60, 1kHz = 0.4, 0.6, 0.8 1.0 1.2).

3. Results and Analysis

The STIPA measurement results were plotted against competing noise levels and this data was fitted experimentally to determine the following equation:

 (1)

where *x* representing competing noise in terms of pressure, *Pa*rms, (not dB SPL). The two free variables, *A* and α (governing the y-axis intercept and curvature) were calculated using a Nelder-Mead search method to minimize the local sum of the squared error between the model and the data.

R2 was calculated and used to evaluate the goodness of fit between the model and measured data. Of course, equation (1) is only a model for the Phonak sound field amplification system under investigation, and of course could theoretically give an STI outside of the 0 to 1 range [22].

Activating the SFA system increased the STIPA by an amount equivalent to the increase one could achieve by reducing the competing noise, Figure 4. The amount of this ‘equivalent noise reduction’ or ENR was found to depend on the level of noise, the room’s reverberation time and presumably the placement of the system relative to the listener. This new simpler parameter is easier for non-acousticians to understand, as it is in units of decibels, it is does not require a modulated signal and hence works even if the SFA system compresses the signal.

From Figure 4, no increase in the STI metric was observed for background noise below 40 dBA, confirming the field measurement results of Dockrell and Shield [23]. The STI metric monotonically increased with increasing competing noise, but eventually saturated at 7.7 dBA ENR at the measurement microphone position.

Figure 4 - Equivalent Noise Reduction (black and white)

**Figure 4.** Shows the effect of adding the sound-field reinforcement system on STIPA terms of an equivalent noise reduction for 5 different room configurations (curves).

The same data was re-plotted as the measured STI metric vs. the measured competing noise (dBA), see Figure 5. The same two parameter model was used to fit both SFA and no-SFA datasets with excellent correlation found, all R2 values > 0.97, see Figures 5A and 5B, respectively.

Figure 5 - Phonak soundfield data vs model2 (black and white)

**Figure 5**. Panel A shows how STIPA changed with competing noise for various room reverberation times (curves) without sound-field amplification. Data points (solid) are overlaid with a two parameter mathematical model (dashed lines). Panel B shows the same type of plot with sound-field amplification. Panel C is a comparison of the model fits extracted from B.

4. Discussion

For room reverberation times ≥ 1.0 s, adding sound-field amplification increased STIPA values for competing noise levels above 50 dBA, see Figure 5C. For reverberation times ≤ 0.6 s this threshold was 38 dBA and for T60= 0.8 s it was 44 dBA. Below these thresholds the modeled data indicate that adding SFA would actually reduce STIPA and that this deterioration would be larger for more reverberant rooms, for example modeled STIPA was reduced by 0.05 for T60=1.2 s, see Figure 5C for 30 dBA background noise.

Table 4 shows the coefficients A and α (alpha) from equation (1) and the correlation to the measured STIPA values based on competing background noise levels. From Figure 6 it can be seen that both A and α (alpha) coefficients were affected by activating the SFA, but only parameter A was sensitive to room reverberation time. Taken together these parameters suggest that just by taking account of room reverberation a simple model can capture the effects of SFA in noisy environments in terms of speech intelligibility.

Figure 6 - Phonak soundfield model parameters

Figure 6. Shows how model parameters controlling the model's curvature (parameter alpha) and y-intercept (parameter A) are affected by reverberation time and activating the SFA.

Table 4. Model parameter values and goodness of fit, R2 values, of the empirical model with SFA.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Model Parameters** | | | | | |
|  | **No sound field amplification** | | | **With sound field amplification** | | |
| **T60 (s)** | **A** | **** | **R2** | **A** | **** | **R2** |
| 0.4 | 0.8124 | 26.13 | 0.9973 | 0.7989 | 12.2 | 0.9960 |
| 0.6 | 0.7686 | 27.28 | 0.9950 | 0.7466 | 12.68 | 0.9993 |
| 0.8 | 0.7155 | 22.78 | 0.9815 | 0.6823 | 9.93 | 0.9731 |
| 1.0 | 0.6875 | 23.34 | 1.0000 | 0.6277 | 9.47 | 0.9979 |
| 1.2 | 0.6621 | 23.28 | 0.9986 | 0.5974 | 8.72 | 0.9949 |

5. Conclusions

A new methodology to evaluate the performance of sound-field amplification systems has been detailed, demonstrated using a physically simulated classroom. After a series of laboratory based measurements in the simulated classroom, using a combination of different reverberant and competing noise levels, the effective noise reduction (ENR) parameter was developed to indicate the potential benefit of sound-field amplification systems. Although the specific benefit is limited to one type of SFA, the methodology could be applied to any room based system and any system whether linear or non-linear based, e.g. using compression algorithms.

Based on these measurements an empirical model was developed to predict the expected speech intelligibility performance improvement when using a sound amplification system in noisy environments under a range of reverberant conditions. The ENR parameter provided a method by which the value (performance/cost) of adding a sound-field amplification system to a room could be compared with the more traditional room acoustic treatment solutions.

**Conflicts of Interest:**  For clarity Phonak offered no inducement to use their products. The research team had access to the Phonak system for a period of 3 months to undertake any experiment of their chosing, and had the right to publish any and all of the results doscovered.

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