TOWARDS ACOUSTIC CRITERIA FOR INCLUSION IN MAINSTREAM CLASSROOMS

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1 INTRODUCTION

The Department for Education's (DfE) new Offsite Framework[1] will shape the design of schools in England for 15 years which presents an opportunity to review acoustic criteria for mainstream classrooms via the EFSA Output Specification[2]. This paper analyses the acoustic criteria for mainstream classrooms[2,3,4] against a thorough review of the evidence base for speech perception by typical and SEND children. Reasonable adjustments to the acoustic criteria to improve access to learning, within the available funding budget, are proposed. Classroom management and the use of communication aids to restore intelligibility are also considered, to ensure that people with additional listening needs are not placed at a disadvantage.

2 REQUIREMENTS, CRITERIA AND STRATEGY

2.1 Acoustic Criteria

In order to comply with the Building Regulations[3], a summary of the allowable acoustic criteria for naturally ventilated mainstream classrooms in Building Bulletin 93[4] is presented in Table 1. Natural ventilation remains a priority for both new build and refurbished classrooms for sustainability.

Rooms intended specifically for children with Special Hearing and Communication Needs (SHCN) include SEN rooms and Designated Units or Specialist Resource Provision, where there is a recognised need for lower ambient noise levels and shorter reverberation times to achieve better speech intelligibility. These enhanced acoustic criteria are practicable for smaller rooms with low occupancy and high staff to student ratios, which are typical in SEN rooms. Ambient noise level criteria are based on an assumed teacher voice level and communication distance to obtain sufficient signal-to-noise ratio (SNR). SNR is also stipulated in the BATOD[5] and ASHA[6] Guidelines.

Table 1: BB93 Acoustic criteria for naturally ventilated classrooms

Space	Maximum IANL $L_{Aeq,30min}$ (dB)	Maximum Reverberation Time, T_{mf} (s)	
		Primary	Secondary
Mainstream Classroom			
New build	≤ 40 dB	Primary: 0.6 s[a)]	0.8 s
Refurbished/APS[a)]	≤ 45 dB	0.8 s	1.0 s
Rooms intended specifically for children with SHCN			
New Build	≤ 35 dB[b), c)]	0.4 s $_{(125\text{-}4kHz)}$[b), c)] ; 0.6 s maximum at any frequency	
Refurbished/APS[a)]	≤ 40 dB	0.4 s[c)]	

Notes:
a) APS = Alternative Performance Standard
b) BATOD[5] compliant. BATOD also recommends 20 dB SNR at 125-750 Hz, and 15 dB SNR at 750-4000 Hz
c) ASHA[6] compliant. ASHA also recommends 15 dB SNR.

2.2 Inclusion Requirements and Strategies for Schools

In accordance with The Equality Act 2010[7] schools are required to make 'reasonable adjustments' to put children with disabilities on a more level footing. The Education and Skills Funding Agency (ESFA) Output Specification[5], requires that *'People with disabilities, including those with a hearing impairment, must not be placed at a disadvantage by the design of the Building'*.

Guidance supporting the School Premises Regulations (SPRs)[8] states that *'pupils with special needs may need to be taught in spaces with lower noise levels and shorter reverberation times than in mainstream classrooms',* acknowledging that SEN units in mainstream schools require designing to a higher acoustic standard. Acoustics of Schools: A Design Guide[9] states that pupils with SHCN should be taught in rooms which meet BB93[4] acoustic criteria for SHCN rooms and that '*occasionally specialised provision may be directly attached to a mainstream class in the form of a 'quiet room' leading from the classroom'.* The ESFA Output Specification[2] requires the school design to *'ensure and demonstrate that all layouts allow for disabled pupils to be able to access all activities on offer in at least one space of each type or within each suite'.* This suggests that it would be acceptable to provide a quiet room or SEN room achieving the BB93[4] enhanced SHCN criteria within each teaching suite, and to send children with SHCN to these rooms to access the majority of their teaching and learning. However, whether this practice is inclusive is questionable[10]. The SPR guidance[8] states that *"where pupils with special needs are taught in mainstream schools, the acoustics of the spaces where they are taught may need to be enhanced to the same standards as those special units*", and "*provision will usually be required to teach these pupils in smaller groups so that noise from other pupils is lower and the distance between teacher and pupil is minimised"*.

The acoustic strategy for inclusion in mainstream classrooms is complicated by the following:

a) The current funding crisis in schools[11] has resulted in diminishing resource to teach students with SHCN in small groups as desired by School Premises Regulations.
b) It is difficult to achieve the enhanced reverberation time criteria in mainstream classrooms, particularly control of reverberation time at low frequencies, given available wall space, and trends for exposed soffits.
c) The ESFA budget does not allow for the enhanced BB93 acoustic criteria for pupils with SHCN in mainstream classrooms.
b) Natural ventilation remains a priority, resulting in indoor ambient noise levels of 40 to 45 dBA in some new and refurbished classrooms.
d) Provision of communication aids is not part of the Generic Brief of the Output Specification[2], the school may only list these in a School-Specific Brief[12], *'where there is a Designated Unit or Special Resource Provision for SEND'* (Special Educational Needs Disability).
e) Given the current prevalence, all mainstream primary classrooms and 1 in 2 secondary classrooms need to anticipate the presence children with SHCN (see below).

2.2.1 Prevalence of SHCN

As defined by BB93[4], children with SHCN includes several special needs, including those with mild hearing impairment, permanent hearing impairment, speech language and communication needs, attention deficit hyperactivity disorder (ADHD), Autistic Spectrum Disorder and Auditory Processing Disorder. BB93 states "*In order to fulfil their duties under the Equality Act 2010, school client bodies should anticipate the needs of deaf and other disabled children as current and potential future users of the school".* The Equality Act also covers age discrimination (for example young children) and children with English as an additional (EAL)[7]. Both of these groups may be disadvantaged by poor acoustic conditions in the classroom and may also be considered as having SHCN.

Whilst the attainment gap for hearing impaired students has begun to slowly reduce since 2015, it is reported that deaf children continue to underachieve significantly (the proportion of hearing-impaired children achieving expected grades at GCSE is 13% below the proportion for all children)[13]. This learning gap is significantly smaller than that reported for other forms of SHCN. National progress scores for English and Maths reveal a gap of up to 10% for hearing impaired children, compared to 25% for ASD and 30% for SLCN[14]. Furthermore, the prevalence of ASD and Specific Learning Disorder (ADHD and SLCN) is far higher than hearing impairment in mainstream schools[15].

An assessment of the prevalence of children with SHCN in mainstream classrooms was undertaken following detailed analysis of DfE Statistics[15,16]. The average number of children with SHCN (all needs combined) is 0.5 in a secondary classroom of 26 pupils, and 1 in a primary classroom of 30 pupils. Whilst the use of averages should be treated with caution, the analysis shows that the need to provide appropriate acoustic conditions for children with SHCN should be anticipated in every primary classroom, and in 1 in 2 secondary classrooms. It also shows that, given the low numbers of children with SCHN in typical mainstream classrooms, preferential seating and use of personal listening aids may be feasible management strategies to help improve acoustic conditions and hence access to learning. Where there is a significantly larger proportion of children with SHCN in a school cohort, this may suggest the need a Specialist Resource Provision or Designated Unit.

Children with English as an additional language (EAL) are considerably more prevalent than those with SHCN in both primary and secondary classrooms in England, with a predicted national average of 7 per classroom in mainstream primary schools and 3.5 per classroom in secondary schools[15], and it is important to consider any enhanced acoustic criteria for this group. Clearly primary schools will also need to consider enhanced acoustic criteria which may apply to younger children who are more impacted by poor acoustics.

Schools also need to anticipate the prevalence of children with mild and temporary impairments in the classroom. Studies have discovered incidence rates of around 15% for children with mild or minimal hearing loss[17](nominally around 4 per classroom). Therefore the acoustic conditions for this need have been included in this review.

2.3 Classroom management and responsibility for inclusion

The major effect of poor acoustics in classroom is the reduction of speech intelligibility. Acoustics of Schools: A Design Guide[9] recognises that ‘effective classroom management by the teacher is critical in ensuring that the pupils can have access to all that is spoken’, but ‘classroom management alone cannot ensure adequate speech communication’. It identifies types of assistive listening systems which may be used to ensure pupils with SHCN are able to hear the teacher and peers. BATOD[5] also recognises the importance of classroom management. It can be concluded that provision of good listening conditions for children with SHCN in mainstream classrooms is the combined responsibility of the acoustic design plus provision of assistive listening systems, as well as classroom management. In an attempt to identify acoustic design responsibility, Table 2 assigns the responsibilities for each Listening Scenario[18], with common classroom management strategies. This exercise reveals that the primary responsibility of the acoustic design is to ensure teacher-to-student speech communication in quiet. Good control of noise reverberation time as required to support this listening mode for SHCN will also help to control buildup of classroom activity noise to support other listening scenarios, and other non-spoken learning modes.

Personal listening systems are normally made available to hearing impaired children but are not normally provided for children with other forms of SHCN (although they may be beneficial for those with Auditory Processing Disorder, ASD/ADHD). Sound field systems can be more inclusive as they benefit the entire class. Whilst induction loops are a cheap and readily available form of assistive listening system and are listed by the DfE as an ‘auxiliary aid’ in its advice to schools[7], they are not recommended in classrooms[9] as they don’t deal with noise in active classrooms.

Table 2: Proposed classroom design and management responsibilities by listening scenario

Listening Inventories For Education (LIFE) Listening Scenario[18]	Design solution responsibility?		Classroom management responsibility?
	Acoustic design?	Listening system?	
Teacher speaking in quiet	✓	✓Personal aid or SFS	support[a)]
Teacher facing away	support	✓Personal aid or SFS	✓
Class is active/ others talking	support	support Personal aid	✓[b)]
Teacher moving around	support	✓Personal aid or SFS	✓[c)]
Other pupils answering	support	support (conference mic)	✓[d)]
Working in groups	support	✓conference mic	✓
Noise from multimedia (projector)	✓	support	support

Notes:

a) Teacher to gather younger children on carpet/mat for critical listening scenarios
b) Teacher to use visual cues to quieten and active class before critical listening
c) Address small groups/individuals and roaming tactics around classroom.
d) Teacher to repeat children's answer to secure speech intelligibility of answer

The detrimental impact of noise on aspects of children's learning performance other than speech communication (for example reading ability, attention and memory tasks) in noisy conditions (such as 65 dBA babble) are well studied, and it is generally agreed that children with SEN are significantly more affected than their typically developing peers[19]. Whatsmore, occupied classroom noise levels of 50-70 dBA have been shown to be associated with higher average occurrences of repetitive behaviours by children with ASD, compared to quieter classrooms[29]. Results are not reported in the scope of this paper, which focuses on the impact of acoustics on children's speech perception in critical listening scenarios. However, this work does highlight the need to consider classroom management carefully when children with SHCN are working on tasks in mainstream classrooms.

2.4 Factors affecting speech communication and learning

It is well known that the most important parameter affecting speech intelligibility is the signal-to-noise ratio (SNR), and that this parameter is more important than reverberation time, although both factors affect speech intelligibility[19]. Whilst some laboratory studies have suggested that speech intelligibility improves as reverberation time decreases to zero, this is not the case in real settings where the presence of early reflections (short reverberation times) are necessary to support the received signal (teacher's voice) level. Yang and Bradley[20] showed that near ideal conditions for speech communication can be achieved over the range 0.2-0.5 s for normal hearing children in elementary school classrooms given sufficient SNR, with acceptable conditions for normal hearing children achieved in reverberation times up to 0.9 s, and very short reverberation times should be avoided.

Control of reverberation time at low frequency is also cited as being important for hearing impaired listeners[5] who may be reliant on their residual hearing at low frequency, although it has proved difficult to find experimental speech perception data to support this or derive any specific criteria for low frequency reverberation based on experimental evidence.

Ambient noise level criteria for classrooms are commonly derived based on the required signal-to-noise ratio for certain listeners, and assumptions about the teacher's voice level and communication distance to the listener[21,22]. However it is important to make sure these assumptions account for classroom management strategies and available assistive listening systems.

2.5 Strategic Approach

In order to help establish appropriate acoustic criteria for children with SLCN to ensure that the acoustic design of mainstream classrooms *does not place people with disabilities at a disadvantage*, a detailed review of the seminal research studies on speech perception, by children with various different listening needs, has been undertaken.

In a novel approach which directly addresses the ESFA's inclusion policy, it is proposed to examine the listening gap, ie the difference in % speech perception scores between the impaired group and non-impaired group for each type of SLCN. This reveals the inherent % listening gap of the impaired groups (under ideal acoustic conditions), and the additional % listening gap caused by non-ideal conditions. This approach also helps to reveal consistencies between studies, as systematic errors/variations between studies are reduced.

It is also important to examine the variation (standard deviation) within the impaired group, which is often significantly greater than the non-impaired group, and to test for significance between different acoustic test conditions. This will help to establish reasonably adjusted acoustic criteria which are robust, practicable and improve access to the mainstream classroom by disabled children.

3 REVIEW OF SPEECH PERCEPTION BY CHILDREN

A review of the experimental studies which investigated the effects of reverberation time and/or noise on the speech perception scores of children with additional listening needs and their typically developing peers was undertaken. The review was screened for those studies which quantified speech perception by subjective testing and included acoustic conditions which are realisable in classroom environments during quiet activities, to reflect speech perception for teacher to student speech communication in critical listening scenarios. Findings are summarized in Tables 4-7. Notably, all studies used a wide range of ages in both HI and typical groups, however results were not analysed by age or controlled for age.

It is interesting to note that many studies tested at low signal-to-noise ratio conditions, which would not represent teacher-to-student communication in critical listening scenarios where teachers use visual cues to gain attention, and in long reverberation times exceeding any limits for mainstream classrooms set in BB93. Not surprisingly, test conditions of 1.2 seconds RT as tested by Finitzo-Hieber & Tillman[23] revealed average word-recognition deficits (compared to 0.4 s RT) of 15-20% for both hearing impaired children and their normal hearing peers[23]. Interestingly, Igelhart[24] found a similar sentence recognition deficit by Cochlear implant users of 15-17%, when changing between conditions of 0.3 s RT and 0.9 s, although their normal hearing peers were not affected by this change in reverberation condition at good SNRs (which is possibly explained by the extra understanding available to normal hearing listeners for the sentential speech test material compared to individual words).These results suggest that reverberation times of around 1.0 s and above are unsuitable for hearing impaired children, and also normal hearing children who may not be familiar with the speech material (young children, EAL, auditory processing disorder). They also support the recommended reverberation time range suggested by Bradley[20,21] for normal hearing children.

3.1 Hearing impairment

Results for children with hearing impairments are split into mild-to moderate hearing loss (Table 4), and effects of severe-to-profound hearing loss including cochlear implant users (Table 6). Whilst in early studies the test material was presented monaurally and without hearing aids, later studies examined the advantage of listening binaurally and with hearing aids.

None of the studies examined listening via a personal listening aid (such as an FM system) which is now commonplace for children with a significant impairment listening in the classroom. The Design Guide[9] states that "*personal listening aids enhance the signal-to-noise ratio, reduce the impact of* *unhelpful reverberation (particularly when a headset is used by the speaker), and maintain a constant signal level irrespective of communication distance"*. BATOD[5] recommends that "*if ambient noise level* [ie signal-to-noise ratio] *is controlled then apparently high RT has a minimal effect when a personal listening aid is in skilled use and set up properly*". Benefits of FM systems are also realizable by Cochlear implant technology[24].

All studies used multitalker babble (meaningful speech) as the noise source, ostensibly chosen *'since it is the most disruptive type of interference in a noisy classroom".* Whilst babble noise was matched to the speech spectrum which would obtain a flat SNR across the spectrum, it may represent worst-case noise masking, compared to stationary or environmental ambient noise sources in the classroom during critical listening in quiet.

3.1.1 Mild to Moderate Hearing Loss

Despite variations in the presentation of the speech testing material, results are remarkably consistent between studies. An inherent listening gap of around 7% was measured for children with mild-to-moderate hearing loss in ideal (near-anechoic, quiet) listening conditions. Whilst these conditions are not reproducible naturally in a classroom, use of FM listening aids with close microphone technique may help to approach these conditions by capturing direct sound in the near field (excluding reverberation) and amplifying to achieve +20 dB SNR. No significant difference was found between ≥15 dB SNR and quiet (no babble) conditions when the RT was very well controlled (nominally ≤0.2 s), however a significant difference was apparent between 10-12 dB SNR and quiet conditions. Finitzo-Hieber & Tillman[23] showed that moving from anechoic to 0.4 s RT required a corresponding increase in SNR, from +12 dB to 'quiet' conditions, in order for the hearing impaired group to maintain word score performance. Quiet conditions (SNR ∞) are shown to be effectively equivalent to +20 dB SNR, revealing no significant difference between these conditions for studies of both mild and more severe hearing loss[24,25].The listening gap for 0.4 s RT increased to 14% for perception of words in monaural conditions, according to Finitzo-Hieber & Tillman[23], however it is possible that this gap could reduce with the benefit of modern digital hearing aids, binaural listening, and sentential speech.

Uniquely, Hicks & Tharpe[26] investigated effects of fatigue and listening effort as well as word scores, for binaural, hearing-aid aided conditions. Cortisol measurements did not reveal any significant difference in fatigue between hearing impaired children and their normal hearing peers. Whilst hearing-aid aided children generally expended significantly more listening effort (as measured by difference in reaction times on a dual-task performance), there was no significant difference in listening effort revealed across listening conditions (SNR +10 dB to SNR ∞ dB)[26].

In studying children with mild hearing loss, Crandell[27] determined that at least +6 dB SNR is required under near-anechoic conditions to maintain the inherent listening gap. Given the additional +6 dB SNR required to maintain scores when moving from anechoic conditions to 0.4s RT, as demonstrated by Finitzo-Hieber[23], a minimum of +12 dB SNR is recommended for children with mild hearing loss in classrooms, to maintain the inherent listening gap in for this group, which is 4-8%.

3.1.2 Severe-to-Profound Hearing Loss

Bess Tharpe and Gibler[25] found that the inherent listening gap appeared to increase by a further 4-6% for severe-to-profound hearing loss, to around 10-12%. However, there was no significant difference in scores between mild-to-moderate and severe-to-profound groups at >20 dB SNR in near anechoic conditions, suggesting that this is an appropriate target criterion. Iglehart[24] carried out the most comprehensive speech perception study with varying acoustic conditions to date, for children with Cochlear implants. The inherent listening gap of 9-10% is remarkably consistent with Bess Tharpe and Gibler[25]. Children with cochlear implants could maintain this gap under 0.3 s RT conditions with an SNR of +21 dB. It is proposed that these conditions could be realisable with the provision of an FM system. The apparent improvement in scores when moving from 0.6 s to 0.3 s RT was only significant for children with cochlear implants at +21 dB SNR and not at other SNRs from +9 dB to + 18 dB.

Iglehart's[24] analysis of SNR-50 (the SNR required to achieve 50% correct scores), revealed that children with cochlear implants require +12-15 dB higher SNR than normal hearing children (who typically need around +5-6 dB SNR). By comparison, Finitzo-Hieber's[23] group with mild-to-moderate hearing loss needed roughly a +5 dB higher S/N than children with typical hearing.

The research studies concerning children with mild-to-moderate hearing loss support the ASHA recommendation to provide +15 dB SNR via the acoustic design of the classroom. Providing additional amplification via a personal amplification system to achieve +20 dB SNR, and further control of reverberation time in the near field, would be effective to support children with severe-to-profound hearing loss including those using cochlear implants.

3.2 English as Additional Language (EAL)

The results of a study comparing performance of children with English as a Second Language (ESL) and their native peers by Crandell and Smaldino[28]are summarised in Table 5. This study showed that there was no significant difference in scores between +6dB SNR and Quiet (SNR ∞ dB) in near anechoic conditions. That is, at ≥ 6dB SNR, the inherent listening gap of up to 4% is negligible. Based on the findings of Finitzo-Hieber & Tillman[23] discussed above, it would be reasonable to assume that a target of +12 dB SNR would ensure that the listening gap for children with EAL remains negligible with a well-controlled RT in the classroom.

3.3 Age

Sato & Bradley[22] investigated the word recognition scores of children of 6, 8 and 11 years in real elementary classrooms with occupied reverberation times of 0.4-0.5 seconds (see Table 7 for summary). Whilst there was a significant reduction in word recognition scores as age reduced, average scores of ≥90% were obtained for all age groups at +10 dB, +15 dB and +20 dB SNR. Word scores as opposed to sentence scores are particularly pertinent to younger children, who may not have the language acquisition skills to achieve improved intelligibility for sentences. The listening gaps for each age group (compared to that of adults) as reported in Table 7 suggest that the gap is negligible (<5%) for all age groups and comparable to the reported standard deviation within the group, at SNRs of +15 dB in the primary school classroom. Results for the 8 year olds and 11 year olds suggest that it would be possible to target +13 dB and +9 dB respectively in the secondary school classroom and still achieve mean scores of 95% for normal hearing children, provided that the reverberation time is well controlled to 0.4-0.5 seconds (assuming no other listening need).

3.3.1 Other listening needs

Van der Kruk's systematic review[30] found that improving SNR (including by use of FM systems) benefitted students with Autisitc Spectrum Disorder (ASD), via improved listening behaviours, increased on task behaviours, improved speech recognition and reduced listening stress, although SNR conditions were not well quantified in the studies. In a separate study, Alcantara *et al*[31] found that high functioning individuals with autism or Asperger's syndrome required 2-3.5 dB higher SNRs than their typically developing peers to achieve equivalent scores in sentence tests, when the background sound contained temporal dips such as speech babble (albeit there was no significant difference for stationary noise). Lagacé[32] showed that children with Auditory Processing Disorder (APD) had poorer overall sentence recognition scores for a babble masker at four different SNR conditions. Reynold's[33] systematic review concluded that FM aids should be considered for children with auditory processing disorder to improve children's ability to listen and attend in the classroom.

4 TEACHER VOICE LEVELS

Reverberation and noise also affect the teachers voice level (the signal) in the classroom, and there is a balance to be achieved between ensuring that reverberation time supports the teacher's vocal effort level to communicate without voice strain, and controlling reverberation time so that listeners with SHCN are not disadvantaged.

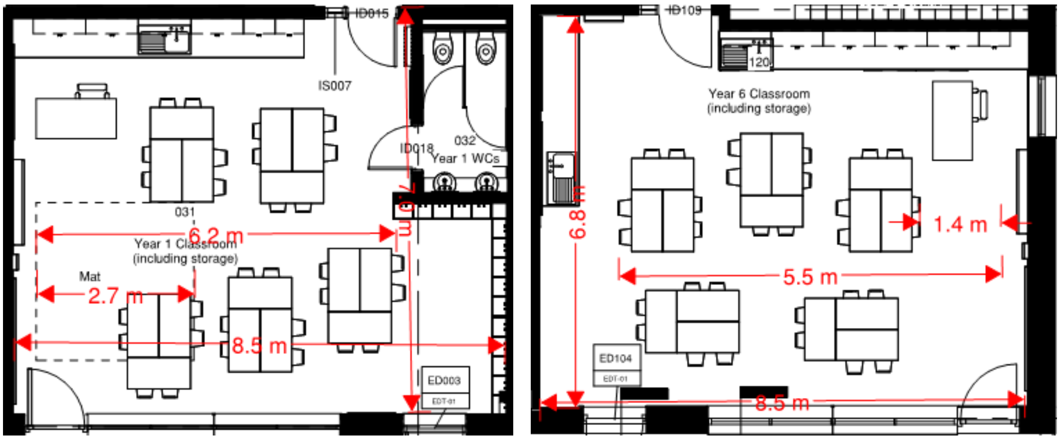
It is widely agreed that teacher's experience higher prevalence of voice problems than the general population[19] and several studies have attempted to establish objective teachers' vocal effort levels in recent years. A wide range of teacher speech levels are reported with speech levels of up to 79 dBA at 1 m, however the majority of recent studies[19, 34-37]are based on long term dose measurements. The variation of speech level with teaching activity was not investigated for the majority of studies[19, 22. 34-36] which is not useful for this current study. For those studies which *did* investigate variation of voice level with teaching activity[37-38], the average measured teacher voice levels when addressing a quiet and attentive class, in rooms with reverberation times of around 0.5-0.6 seconds, was 65 to 67 dBA at 1 m, (correcting dBZ to dBA where required[37], after Durup[35]).

This agrees with Sato & Bradley's[22] estimated mean free field teacher voice level of 65 dBA at 1 m, based on measurements in active occupied classrooms with unoccupied RTs of 0.3 to 0.7 s (albeit teaching activity not specified). It also agrees closely with the specified speech level of 66.5 dBA at 1 m (ISO 9921 'raised' vocal effort) specified by the BB93 Design Guide[9] for acoustic modelling purposes. The recent objective research[19,22,34-37] confirms Webster's[38] conclusion that *'it is neither natural nor expected for teachers to use a 'normal' voice effort'* (60 dBA at 1m), due to the Lombard effect, with teachers raising their voice by approximately 0.5-1 dB per 1 dB increase in noise. And yet the recommended ambient noise level criterion of 35 dBA is based on an assumed teacher's voice level of 55 dBA at 1 m[19, 21], equivalent to a 'relaxed', below normal vocal effort according to ISO 9921.Studies have not found any significant direct correlation between increased noise levels and teachers' voice problems, albeit associations have been found between vocal load factors and voice problems.

The relationship between reverberation times and vocal health are inconclusive or contradictory, however it is recognized that there is a balance to be achieved between control of reverberation time (to control activity noise levels as well as for good speech perception), and providing sufficient early reflections to support the teachers speech and hence reduce vocal effort. Although some studies have recommended *optimum* reverberation times of 0.7-0.8 seconds, other larger scale studies have showed that a target reverberation time of 0.5 seconds would fall within the appropriate recommended range for classroom sized rooms, and would provide sufficient support for the teachers' voice[39]. Bradley's recommended minimum occupied reverberation time to support the teacher's voice in the classroom is 0.4 s[21]. As a guide, an occupied classroom reverberation time of 0.4-0.45 seconds corresponds to an unoccupied reverberation time of 0.45-0.5 seconds[22].

Accounting for attenuation with distance and the expected increase due to room reflections with an RT of 0.4 s (as proposed by Sato and Bradley[22]), the derived voice levels at different distances in the classroom, based on an ISO 'Raised' voice level of 66 dBA at 1 m (in order to protect teachers' voice), are 63 dBA at 2 m, 62 dBA at 4 m and 59 dBA at 6 m[22] (these have also been confirmed by 3D acoustic modelling). Typically at Key Stage 1 classrooms, critical listening takes place on the mat within 3 m of the speaking teacher (see Figure 1), whereas for Key Stage 2 and beyond (8+ years), critical listening could take place at desks between 1.5 and up to 6 m from the teacher.

Figure 1: Example KS1 and KS2 classroom layouts



5 NOISE

The presence of students in a classroom increases the noise level above the unoccupied ambient noise level. 56 dBA is consistently reported when students are working quietly[19] (for example sitting at tables doing silent reading or a test, including movement of chairs and rustling of paper). This 56 dBA level was reported for mainly untreated classrooms (including Victorian buildings), where the average unoccupied ambient noise level was 45-47 dBA[19], which exceeds the limits for classrooms built post-BB93. Lower average noise levels of 47 dBA were reported in treated rooms[19]. Even lower noise levels are reported in treated classrooms when children are engaged in critical listening activity (that is, no student activity, when children are quiet, attentive and listening to the teacher), when external noise ingress is well controlled. Astolfi and Pellerey[38] measured up to 44 dBA during critical listening activity in secondary schools, and Bradley reported that the average unoccupied ambient level of 42 dBA increased to 44 dBA in occupied classrooms (with no student activity).

This implies that the average specific noise level from the quiet students alone (based on the average of 21 students present) is 40 dBA. This matches the calculated SPL for 21 students quiet and listening to the teacher, in a standard classroom with 0.45 s occupied RT, based on sound power levels referenced in the Design Guide[9]. Adjusting for average UK class sizes[16], the specific critical listening activity noise level would be 40 dBA for secondary classrooms and 41 dBA for primary classrooms.

6 DISCUSSION & RECOMMENDATIONS

This review was undertaken to explore how classroom acoustics criteria might be reasonably adjusted to ensure children with SHCN are not placed at a disadvantage in mainstream classrooms. On average, all primary, and 1 in 2 secondary classrooms, need to anticipate the presence of children with SHCN, who require improved acoustic conditions to avoid being placed at a disadvantage.
The inherent listening gap between children with hearing loss and their typical peers would be around 12-14% in BB93 rooms designed specifically for children with SHCN. Students with severe-to-profound hearing loss listening in conditions of RT 0.6-1.0 seconds may be placed at a disadvantage, even when excellent signal-to-noise ratios are achieved. When reverberation time increases from 0.3-0.4 s to around 1.0 s, the listening deficit for hearing impaired children is around 15-20%.

On balance, a reasonably adjusted criterion for reverberation time (to protect teachers' voice level whilst achieving good speech intelligibility for SHCN) is considered to be 0.5 seconds unoccupied, corresponding to around 0.45 seconds occupied. SHCN children could benefit further from even shorter effective reverberation via headset microphones and an FM aid system. Achieving this criterion would require a Class A suspended ceiling, already common in many classroom designs. It would however be more challenging to achieve this for classrooms with an exposed soffit design.

Based on the BB93 ambient noise level limits for naturally ventilated classrooms, estimates of the specific critical listening noise level, and hence occupied noise level, coupled with expected teacher's voice level under these conditions can be used to indicate the available SNR for each critical listening scenario as shown in Table 3.

Table 3: Calculated available signal-to-noise ratio by mainstream classroom listening scenario

		Available signal-to-noise ratio, SNR (dB)	
Scenario	Distance	Ambient noise level 40 dBA (occupied 44 dBA primary, 43 dBA secondary)	Ambient noise level 45 dBA (occupied 46 dBA primary, 46 dBA secondary)
KS1 (on the mat)	1.5 m*	+20 dB	+18 dB
	3 m**	+16 dB	+14 dB
KS2 (at tables)	1.5 m*	+20 dB	+18 dB
	6 m**	+15 dB	+13 dB
Secondary (at tables)	1.5 m*	+21 dB	+18 dB
	6 m**	+16 dB	+13 dB

*Preferential seat; **Worst-case location

The above analysis suggests that, for a 40 dB ambient noise level, the recommended target of +15 dB SNR via the acoustic design of the classroom is expected to be available for all listening scenarios, and +20 dB SNR is also available at preferential seating locations for children with SCHN, albeit headset microphones and personal amplification systems are still recommended to benefit from additional reverberation control.

For higher ambient noise levels of 45 dB such as in naturally ventilated refurbished classrooms, it would be necessary to rely on headset microphones and a personal amplification system for children with SHCN to receive +20 dB SNR (and further control the effective reverberation time). Personal amplification systems should also be explored for those children with listening needs such as APD and SLCN. A sound field system would be beneficial for younger KS1 children to access listening on the mat at the recommended SNR. For older KS2+ children (including those with EAL), it may still be possible to access the recommended SNR of +12-13 dB without the need for a sound field system.

6.1 Next steps

The reasonably adjusted acoustic criteria for mainstream classrooms proposed in this paper should be further investigated and developed to explore the following:

- Practicality/cost of achieving criteria within budget and against other design constraints.
- Effect of low frequency reverberation time variation
- Peer review with BATOD, Educational Audiologists, Speech and Language Therapists
- Ensure classroom management strategies are practicable
- Practical use of headset and amplification systems to achieve +20 dB SNR
- Explore use of whole class sound field systems
- Classroom management for non-critical listening scenarios

7 REFERENCES

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Table 4: Results of speech perception studies for children with mild-to-moderate hearing loss

Ref	Subjects	Test type	Listening gap (%) and σ of impaired group where reported (%)	Commentary
Finitzo-Hieber & Tillman (1978)[23]	Mild-to-moderate (35-50 dB loss, unaided*) 12 NH, 12 HI 8-13 Years *Aided results not presented here as users did not benefit from modern digital hearing aids &CI	Monosyllabic Words monaurally via loudspeakers at 3.6 m (at 25 dB above hearing threshold) in anechoic room and sound treated reverberation chamber.	7% (SNR ∞ dB, 0.0s RT) 11% (SNR +12 dB, 0.0s RT) 14% (SNR +6 dB, 0.0s RT) 14% (SNR ∞ dB, 0.4 s RT) 14% (SNR +12 dB, 0.4 s RT) 17% (SNR +6 dB, 0.4s RT) 19% (SNR 0 dB, 0.4 s RT) 15% (SNR∞ dB, 1.2 s RT) 19% (SNR +12 dB, 1.2 s RT) 15% (SNR +6 dB, 1.2s RT) 14% (SNR 0 dB, 1.2s RT)	Inherent listening gap between Mild to moderate HI and NH in good classroom conditions (0.4 s RT) is 14%. The HI group's %score under anechoic conditions at +12 dB SNR was matched at 0.4 s RT when the SNR increased to ∞ dB). However There does not appear to be a significant gap between +12 dB and Quiet (∞ dB) in good acoustic conditions. Whilst normal listeners scored 69% under reasonable listening conditions (1.2 s RT, + 12 dB SNR), the HI group required the 0.4 s RT condition to match this performance. *Note: SNR conditions between +12 dB and* ∞ dB require further investigation.
Hicks & Tharpe (2002)[26]	Mild to moderate (Hearing-aid aided) 14 NH, 14 HI 6-11 years	Words binaurally (with a secondary task to investigate listening effort) via loudspeaker at 1.07 m (75 dB) in sound treated room *(assume ≤0.2s RT)*	7% (SNR ∞ dB, σ = 6%) 8% (SNR + 20 dB, σ = 4%) 6% (SNR +15 dB, σ = 5%) 7% (SNR +10 dB, σ = 10%)	Mean scores were all at or above 85% correct, which are considered good speech-recognition scores clinically. No significant difference across SNR conditions from 10 dB SNR to ∞ dB (in near-anechoic conditions) ***– possibly achieved by binaural advantage and hearing-aid aided conditions.***
Bess Tharpe & Gibler (1986)[25]	Mild to moderate (40-60 dB loss) 25 NH, 9 NH unaided 6-13 years	Syllables monaurally via loudspeakers at 1.8 m (65 dB) in sound treated room *(assume ≤0.2 s RT)*	*6% (SNR ∞ dB) 6% (SNR +20 dB) *11% (SNR +10 dB) *σ not reported*	No apparent performance difference between the SNR ∞ dB condition (no babble present) and the +20 dB SNR condition. However the difference between +20 dB and +10 dB SNR was significant, ***suggesting that more than +10 dB and up to 20 dB SNR may be required to maintain listening gap. Note that gap may reduce when impaired group use hearing aids.***
Crandell (1993)[27]	Minimal (15-30 dB loss) 20 NH, 20 HI 5-15 years	Sentences monaurally via headphone (65 dB) in sound treated room *(assume ≤0.1 s RT)*	4% (SNR ∞ dB, σ = 7%) 8% (SNR +6 dB, σ = 15%) 20% (SNR +3 dB, σ = 21%)	No significant difference between +6 dB SNR and Quiet (SNR ∞ dB). Suggests that +6 dB SNR is sufficient for minimal hearing impaired in anechoic conditions to ensure listening gap is not significant.

Table 5: results of speech perception studies for children with English as a Second Language (ESL)

Reference	Subjects & type of impairment	Test type	Inherent listening gap (%) and σ of impaired group (%)	Comments
Crandell & Smaldino (1996)[28]	20 Native English, 20 ESL 8-10 years	Sentences presented monaurally via headphone (65 dB) in sound treated room *(assumed <0.3 s)*	1% (SNR ∞ dB, σ = 4%) 4% (SNR +6 dB, σ = 9%) *5% (SNR +3 dB, σ = 10%) *12% (SNR 0 dB, σ = 18%) *22% (SNR -3 dB, σ = 24%)	No significant difference between +6dB SNR and Quiet (SNR ∞ dB). At ≥ +6dB the listening gap is negligible.

Table 6: Results of speech perception studies for children with severe-to-profound hearing loss

Reference	Subjects & type of impairment	Test type	Inherent listening gap (%) and σ of impaired group (%)	Comments
Bess Tharpe & Gibler (1986)[25]	Severe to profound (>60 dB hearing loss) 25 NH, HI unaided 6-13 years	Sentences presented monaurally via headphone (65 dB) in sound treated room *(assume <0.1 s RT)*	*10% (SNR ∞ dB) 12% (SNR +20 dB) *27% (SNR +10 dB) *σ not reported*	Listening gap is significantly greater for severe to profound than mild-to-moderate. Inherent listening gap of around 10% for severe to profound is remarkably similar to Iglehart. No significant difference between mild-to-moderate and severe-to-profound groups at +20 dB SNR.
Iglehart (2016)[24]	Severe to profound, Cochlear Implant users (no additional aids) 23 NH, 23 HI 6-16 years	Sentences presented binaurally via loudspeaker (60-66 dB at 3 m depending on hearing acuity) in classroom with varying acoustic treatment.	9% (SNR ∞ dB, 0.1 s RT, σ = 8%) *10% (SNR +21 dB, 0.3s RT, σ = 10%) 21% (SNR +18 dB, 0.3s RT, σ = 16%) 22% (SNR +15 dB, 0.3s RT, σ = 14%) 29% (SNR +12 dB, 0.3s RT, σ = 15%) 42% (SNR+9 dB, 0.3 s RT, σ = 23%) 19% (SNR+21 dB, 0.6s RT, σ = 17%) 27% (SNR +18 dB, 0.6s RT, σ = 17%) 30% (SNR +15 dB, 0.6s RT, σ = 20%) 30% (SNR +12 dB, 0.6s RT, σ = 19%) 34% (SNR+21 dB, 0.9s RT, σ = 16%) 37% (SNR +18 dB, 0.9s RT, σ = 17%) 38% (SNR +15 dB, 0.9s RT, σ = 18%) 42% (SNR +12 dB, 0.9s RT, σ = 19%)	Results are remarkably consistent with Bess and Tharpe for severe to profound. Children with Cochlear Implants required 10 dB under 0.3 s RT and 11 dB under 0.6 s to achieve 50% correct scores. Whilst the difference in scores was significant between 0.6 s and 0.3 s RT conditions, it is not a substantial increase in required SNR. Inherent listening gap is around 10%, and children with cochlear implants can maintain this performance under 0.3 s RT at +21 dB SNR.

Table 7: Results of speech perception studies for children by age

Reference	Subjects & type of impairment	Test type	Inherent listening gap* (%) and σ of impaired group (%)	Comments
Sato & Bradley (2008)[22]	11 year olds Grade 6)	Words (by picture identification) presented to 840 normal hearing children in their normal occupied classrooms (41 classrooms with average ranging from 0.4-0.5 s RT occupied) via loudspeakers at varied playback levels relative to natural ambient noise in classroom	4% (SNR +10 dB, σ = 7%) 2% (SNR +15 dB, σ = 3%) 1% (SNR +20 dB, σ = 0.5%)	Significance tests between listening conditions and between groups not reported. +8.5 dB SNR required to achieve mean score of 95%
	8 year olds (Grade 3)		5% (SNR +10 dB, σ = 3%) 3% (SNR +15 dB, σ = 2%) 2% (SNR +20 dB, σ = 1%)	Significance tests between listening conditions and between groups not reported. +12.5 dB SNR required to achieve mean score of 95%
	6 year olds (Grade 1)		8% (SNR +10 dB, σ = 7%) 4% (SNR +15 dB, σ = 3%) 3% (SNR +20 dB, σ = 2%)	Significance tests between listening conditions and between groups not reported. +15.5 dB SNR required to achieve mean score of 95%

Listening gap of each age group (compared to adults achieving 99%) reported