SPEECH INTELLIGIBILITY IN CLASSROOMS: SPECIFIC ACOUSTICAL NEEDS FOR PRIMARY SCHOOL CHILDREN

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ABSTRACT

Classrooms for primary school children should be built to criteria based on children's speech intelligibility needs which in some respects – e.g. reverberation time - differ markedly from the traditional criteria for adults. To further identify why the needs of children and adults for speech perception are so different we have measured the 'integration time' of speech for adults and children using a novel technique to obviate the complicating effects of differing language. The results for children are significantly different than for adults (35ms c.f. 50ms) and recommendations for classroom design based on the children's requirements have been made. When groups of children engage in 'co-operative learning' activities in the classroom, the "cafe effect" produces a rising activity noise level. We suggest the Lombard Effect is responsible for this. Measurements show children are more susceptible to the effect and we have developed a prediction model for activity noise in a classroom.

1. INTRODUCTION

This paper outlines investigations into speech intelligibility requirements of New Zealand children in primary school classrooms[1]. It follows on, and attempts to answer questions posed by the work conducted by the New Zealand Classroom Acoustics Research Group (NZCRG)[2] which involved an extensive study into subjective and objective ratings of primary school classrooms, in some cases before and after acoustic treatment. As in the NZCRG study, the outcomes of this work strengthen the hypothesis that children's speech intelligibility requirements ought to be the controlling factor in classroom acoustical design and that some existing design standards for reverberation time (RT) may not be appropriate. For example, the ANSI S12.60-2002 standard[3] suggests that RTs up to 0.6 seconds are appropriate for primary school classrooms, whereas the NZCRG found such classrooms were generally rated as poor, and suggests 0.4 seconds is a more suitable value. This finding is also supported by the work of Neuman & Hochberg[4] and Bradley & Picard[5].

We hypothesise that a reason why young children benefit from a lower RT than is appropriate for adults, is that their hearing systems are not fully mature[6] so their ability to utilise the speech cues in early reflections is reduced. In particular we suggest that this might be evidenced by a shorter 'integration time of speech' in children than in adults.

In addition to heightening the presence of late-energy i.e. outside the integration time of speech, excessive reverberation also exacerbates background noise via the café effect. In simple terms, the café effect is the tendency for noise to 'breed' noise where the noise is generated by conversations of separate groups of occupants of a room. Subconsciously each group competes with the reverberant noise from other groups and voices are raised instinctively. This is not only so that they can be heard and understood by members of their own group, but also it is an automatic effect (i.e. the Lombard Effect) resulting from the fact that hearing one's own voice is a necessary part of normal voice production.

The NZCRG found in their teacher survey that group work is the most common method of classroom activity, accounting for 38% of teaching styles utilised. It is during these group work sessions, where students communicate with one another through so called "incidental learning"[7] that the café effect occurs. When taking account of the café effect, it is common to assume the phenomenon is wholly governed by one's perceived requirements for social interaction i.e. "I must speak louder so my friends can hear and understand me." However we hypothesise a second motivation, which is that the speaker raises their voice level in order to hear themselves. The Lombard Effect[8] is a well documented phenomenon, though not previously connected to the café effect.

Thus our research was carried out to answer the following questions:

1. Could the Lombard Effect be the key to predicting the café effect,
2. can the Lombard Effect be suppressed through astute acoustic design, and
3. can the café effect during classroom activity be eliminated?

2. INTEGRATION TIME OF SPEECH

'Integration time of speech' is used to denote the point in time after which reflections of a speech signal no longer have the effect of fully adding their energy to that of the direct signal. Reflections arriving outside the integration time contribute less and less usefully and – especially when overlapping with subsequent speech phonemes – will interfere with speech perception and hence reduce intelligibility. For adults, this point is generally taken as being 50 milliseconds[9,10,11,12] but we hypothesise a shorter value is required for children.

2.1 Survey

To test our hypothesis it was important that we use a speech test signal. For other signals e.g. music, the integration phenomenon can be significantly different. We recognised from our experience in the earlier NZCRG work[2] that speech perception testing with children can be complicated by difficulties with choosing appropriate material, and the corresponding poor resolution of the tests. Therefore, a novel technique is proposed, based on an effect demonstrated by Saberi and Perrott[13]. The technique is based on using reversed-segmented speech. If the integration phenomenon is viewed as one of a simple summing of the sound energy entering the ear over a period of time, then it is possible to "chop" a speech train into segments equal to, or less than the integration time of speech and, providing the order of the segments is maintained, reverse each segment without losing the intelligibility of the speech. The sentences with a long segment length have longer periods of reversed speech and are therefore more difficult to understand, whereas the speech information in the sentences with shorter reversed segments can be more easily interpreted. This is quite a dramatic effect when experienced for the first time. Figure 1 illustrates a speech signal prior to processing, and Figure 2 illustrates the processed signal.

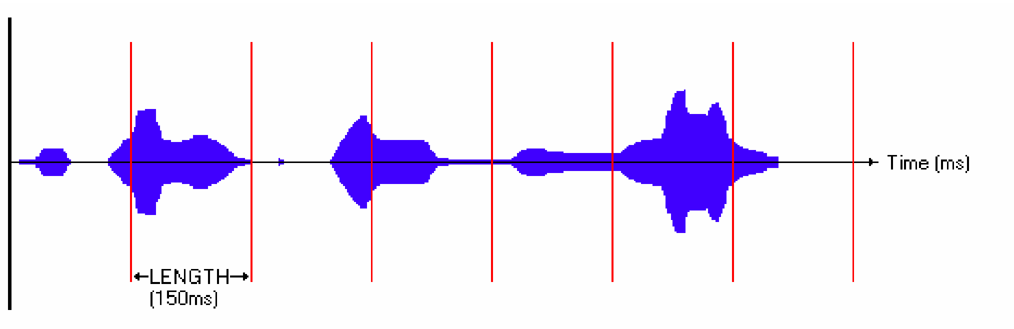

Figure 1.- Unprocessed Speech Stream, showing segment divisions of 150ms (for example)

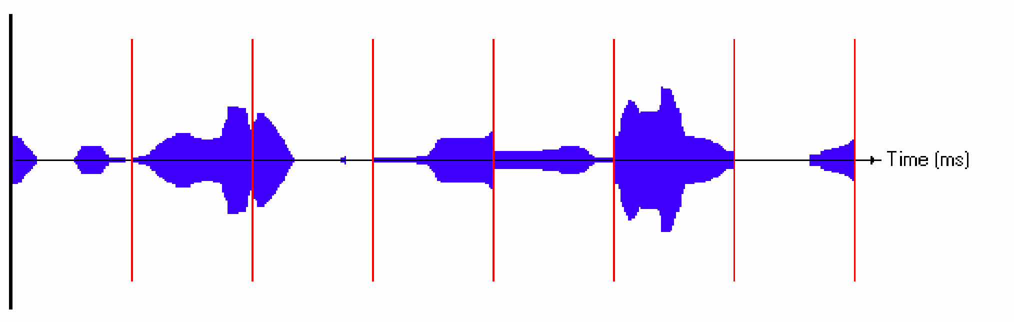

Figure 2.- Reversed segmented speech stream. Each segment locally reversed in time

A group of 15 adults and another of 18 children (7-9½ years) were individually presented in an anechoic room with BKB sentence lists[14] which had been segmented and reversed using a range of segmentation times (20-220ms). Sixteen sentences were randomly delivered via standard computer loudspeakers placed at a distance of 1.5 metres from the subjects' ear-height. The subjects repeated the sounds they heard and the percentage of correctly-perceived phonemes were scored by the experimenter.

Figure 3 shows curve-fitted results for the child and adult groups. There is a clear difference between the groups which is significant at the 5% level (except for segmentation times at the extremes where no difference is to be expected). Because of the asymptotic nature of the fitted curves at the extremes it is not possible to ascribe relative integration times to the children and adult cohorts based on a criterion of when they drop below 100%. However, taking the 98% correct score as an appropriate boundary between full and partial integration, values of 35ms and 50ms for children, and adults, respectively, appear to confirm the hypothesis that the integration times for speech in children and adults are significantly different. That is, children of this age have an integration time approximately 70% of the adult value. This suggests that a classroom should be designed to ensure reflections reach a child listener within 35ms if they are to be of maximum value.

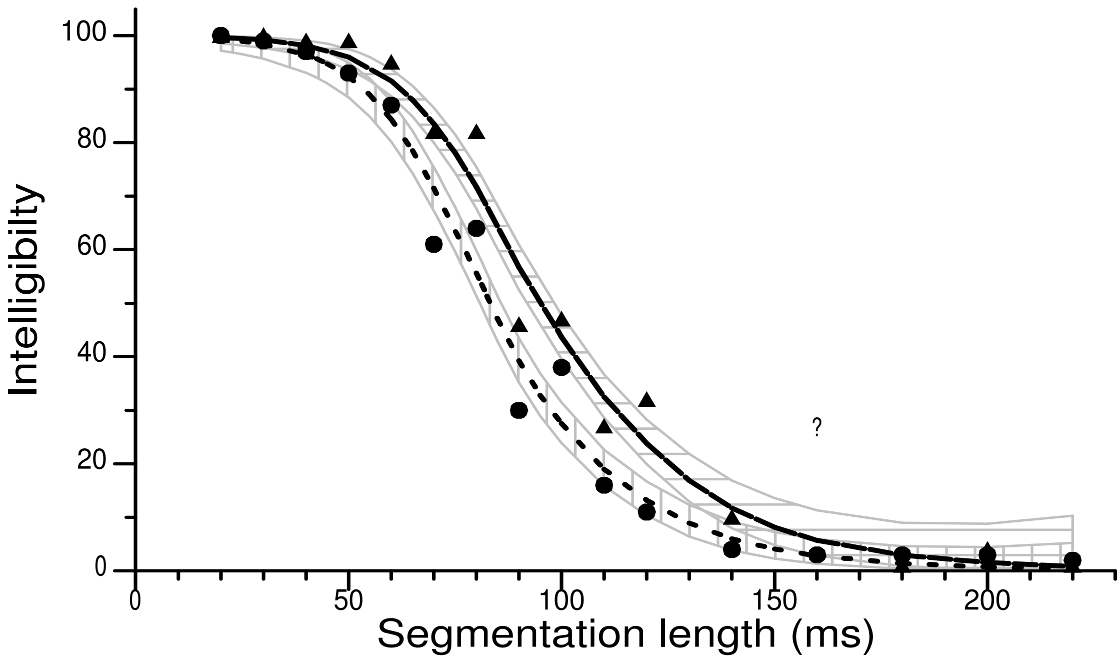

Figure 3.- Intelligibility scores for the children (circles) and adults (triangles)

2.2 Implications for Classroom Design

The implications for classroom design are predominantly with regard to reverberation time and the arrival times of early reflections. A room with a long reverberation time will cause individual phonemes to become masked by the persistence of previous phonemes and intelligibility will be degraded. If the time period over which reflections occur is reduced such that reflections only occur within the integration time of speech (i.e. early reflections), then the clarity of speech will be maximised. However, if a room were to have no reflections beyond 35ms it would subjectively have a zero RT and, as experience in anechoic chambers supports, this may not be the optimum for comfort or intelligibility. A room with a low RT will obviously have less unwanted reverberant sound energy (i.e. occurring outside the integration time) so a crucial design feature of a primary school classroom should therefore be a low RT, as our earlier work suggests, around 0.4 seconds[2,4,5]. This then provides the 'neutral basis' upon which the acoustical environment can be developed by way of harnessing early reflections. This approach could be seen as analogous to concert hall design, where the RT is designed to suit the intended use of the space, followed by ray tracing to ensure optimum coverage from reflectors etc.

There is evidence that low RT also suppresses child activity noise. Whitlock[15] and Lubman & Sutherland[16] both recorded a reduction in classroom activity noise level well in excess of that predicted by the difference in RT before and after treatment. Whitlock recorded a reduction in day-long class activity noise of 6 dB in a classroom after installation of acoustic ceiling tiles,

which reduced the RT by 16% (0.62 to 0.52 seconds) – the associated increase in room absorption only predicts 1 dB reduction. Lubman & Sutherland reported a reduction of 12 dB for a 48% reduction in RT (1.92 to 1 second) – the increase in room absorption predicts 3 dB reduction. A low RT therefore also suppresses the café effect inherent in classroom group activities as well as improving speech intelligibility.
An integration time of 35 ms corresponds to a distance travelled by sound of approximately 12 metres (compared with 17 metres for the 50 ms adult integration time). This therefore is the ideal maximum path length difference for any receiver between a direct sound and a fully useful reflection, and the classroom geometry should ideally be constrained accordingly.

If the physical size of the classroom cannot be designed such that the boundary surfaces (i.e. walls and ceilings) provide these desired early reflections, there is the potential to add reflectors to do so, as well as absorbers to reduce later energy. The placement of these may depend on the activity or teaching style used. For instance:

- For group work where children need to hear one another, an array of reflectors could be placed above their work space, similar in nature to overhead reflectors placed above the stage in concert halls to allow performers to better hear themselves.
- For styles where the teacher is addressing the class from the front of the room (didactic and mat-work), a possible problem may occur from late sound (arriving at listeners near the front of the room) from reflections off the back wall, therefore absorption material could be placed on this surface.

With this 12 metre 'first reflection restriction', new classroom designs can be investigated - and (where necessary) modified - using ray-tracing techniques. Ray tracing software programs such as Odeon[17 and Ecotect[18] would be an tools to explore the possibilities. Some simplified ray-tracing examples are shown, for a hypothetical square classroom with dimensions of 8 x 8 x 3 metres (similar in volume to a typical New Zealand relocatable classroom, but dimensions are non-typical) in which there is no furniture and all surfaces are non-diffusing. The worst-case scenario in terms of path length difference has been used, whereby both the teacher and child are effectively in the same position in the room.

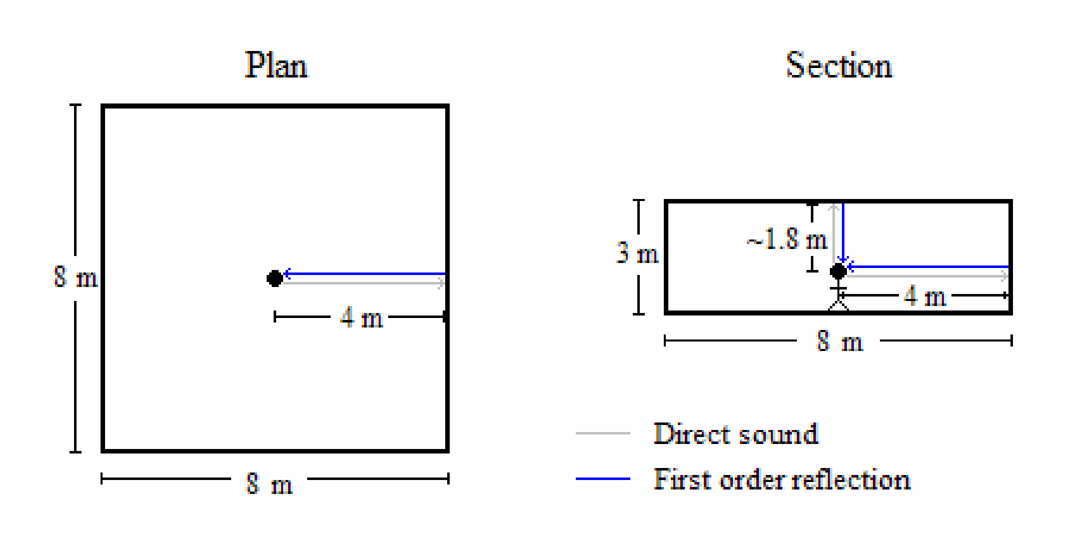

Figure 4: Example of ray-tracing of first order reflection with source and receiver in centre of room

In Figure 4 the speaker and receiver are in the centre of the room at a height of approx. 1.2 metres (a typical height of an adult whilst seated, or young child whilst standing). The direct sound is received instantaneously by the receiver because of the negligible distance from the speaker, but the first order reflection is received after travelling a distance of 8 metres (4 metres to and from the wall). This distance is less than the critical 12 metres, so reflected sound via this path will arrive within the receiver's 35 millisecond integration time of speech. Only one ray has been shown, but a similar path will be travelled by rays in other directions, including upwards and downwards (off the ceiling and floor, if reflective), so there may be up to 6 useful first order reflections in this case.

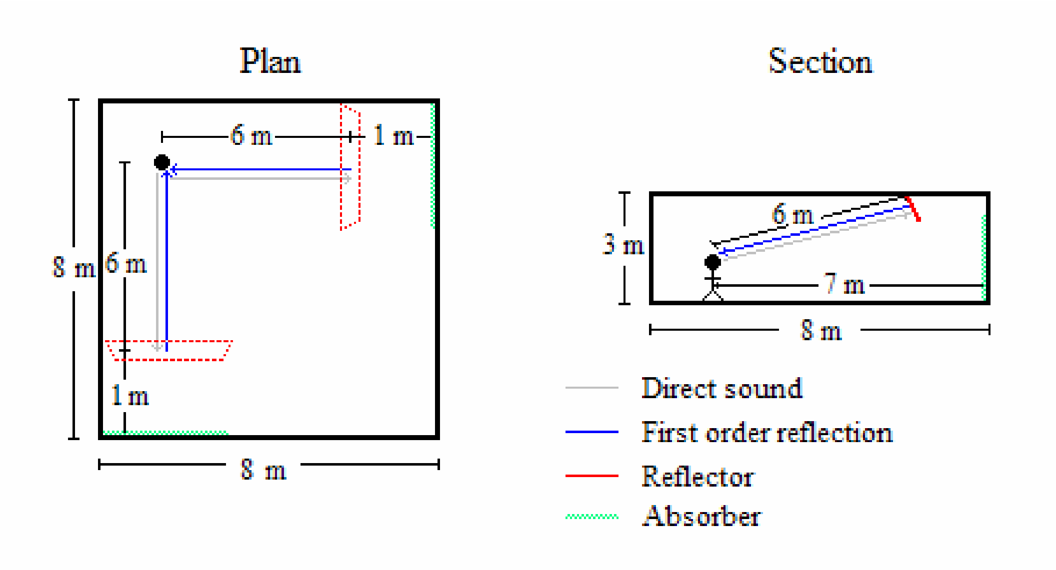

Figure 5: Example of ray-tracing of first order reflection with source and receiver off-centre.

Figure 5 shows another first order reflection example where the speaker and receiver are closer to one corner. The path length differences for the rays travelling to the two farthest walls are 14 metres (7 metres to and from the wall), which is outside the 12 metre limit. Early reflections will still be received off other surfaces (floor, ceiling and two walls behind speaker), however simply by changing the speaker/receiver position the number is reduced from six to four. In simple terms, this would equate to a 2 dB reduction in the strength of early reflections. The two less useful paths therefore ideally need to be modified by adding reflectors at distances of at least 6 metres so the path lengths are reduced to less than 12 metres. Absorption should also be placed on the two farthest walls to eliminate those unwanted reflections.

The potential complexity of predictive modelling in this way is clear, bearing in mind only one path was modelled in each case above. In practice, a multitude of paths must be considered, and for higher order reflections this may result in large numbers of paths, particularly when scattering by surfaces is considered. Moreover, only one receiver position has been considered – including more would complicate the model further as some reflections would be desirable for some receiver positions and not for others. Other complications include the variety of classroom dimensions, furniture and the restricted area available for absorptive treatment, because of the predominance of glazing, and the use of walls as pin-up areas. It is likely that only first and second order reflections need be taken into consideration, because if the classroom has a sufficiently low reverberation time (as suggested), higher order reflections are not likely to be strong enough to degrade intelligibility of speech significantly. However, further research would be beneficial to establish the relative value – or conversely the disruptive effects – of longer delayed, lower level reflections.

3. SURVEY OF THE CAFÉ AND LOMBARD EFFECT

3.1 The Café Effect

As discussed above, the primary school classroom is affected by the café effect. The phenomenon is sometimes referred to (particularly in the United States) as the Cocktail-Party Effect[19], as parties present another social situation which is highly susceptible to the effect. However, the term Cocktail-Party Effect relates to a different phenomenon, as described by Cherry[20], whereby an occupant in a busy room is able to selectively ‘tune in’ to and pick up personally relevant material in another conversation over the dominant background level, even if the speakers are not in the immediate vicinity.

3.2 The Lombard Effect

First identified in the pioneering work of Etienne Lombard[8], it describes the tendency for a speaker to raise their voice if the acoustical path from their mouth to their ear is impeded, either by physiological (i.e. hearing impairment) or environmental (i.e. background noise) influences. Lombard suggests it occurs so that the speaker can (a) hear themselves and (b) feel that they are communicating adequately with a listener or listeners. It is an effect which some few people can overcome to some degree by conscious control of their voice level, but the vast majority of people are unable to succeed at this[21].

3.3 Survey

We suggest that the Lombard Effect is largely responsible for the occurrence of the café effect, a view shared by Lubman and Sutherland[16]. This effect was investigated in two recent studies, firstly in children[1] and then in adults[22]. The same group of 18 children (7-9½ years) involved in the integration time experiment, and an ancillary group of 30 adults (20-61 years) were tested in an anechoic room. Each subject was asked to read out loud a story from a book or magazine whilst broadband masking noise was delivered to them via insert earphones at incremented levels. The reading material was chosen to be unchallenging insofar as was possible, so that the subjects would be able to read without pausing due to difficulty with words. Their resulting voice level was measured at each increment. Figure 6 shows the rise in speech level with increased masking noise, with respect to the average measured base voice level i.e. no masking noise (53.4 dB(A) in children and 55 dB(A) in adults):

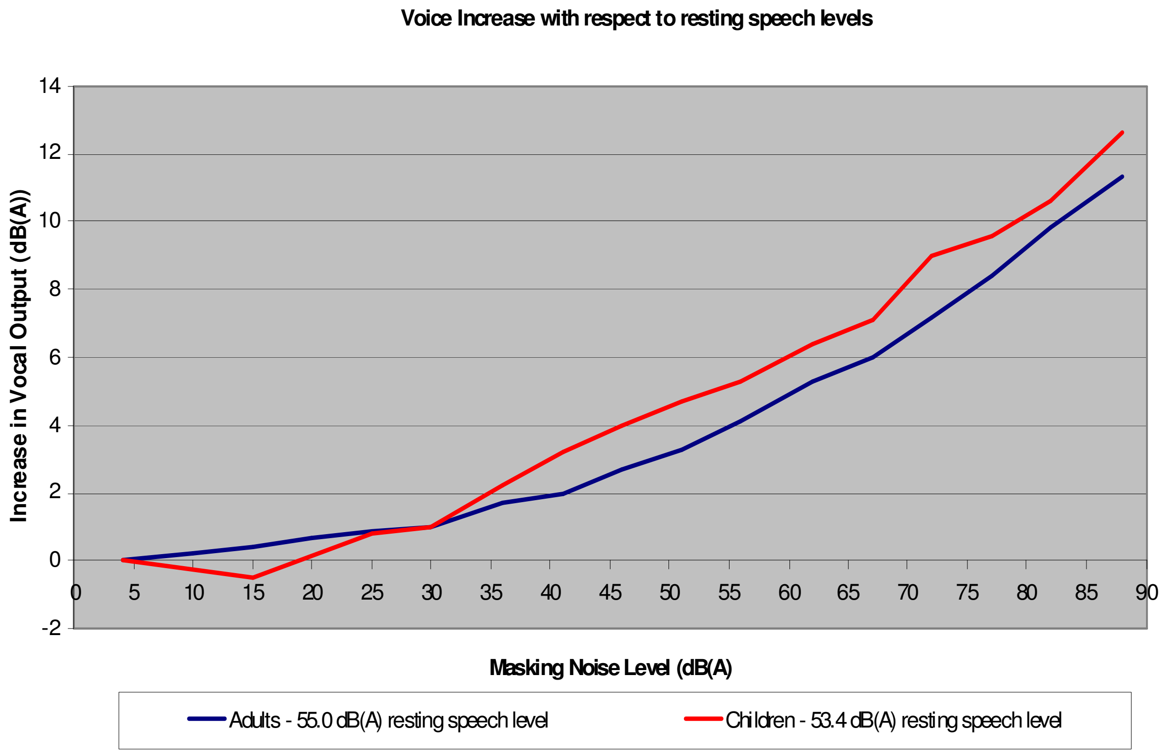

Figure 6.- Lombard Effect in Children vs Adults (with respect to base speech levels)

For both children and adults, the results of this experiment show a strong Lombard reflex and a consistent rise in speech level for masking noise above 15 dB(A) in children, and above 4 dB(A) (i.e. for all masking levels presented) in adults. From the starting level for the Lombard reflex to the maximum 88 dB(A) level, there was an average rise in speech level of 13.9 dB(A) in children and 11.3 dB(A) in adults. Or alternatively, a 'Lombard Coefficient' (i.e. rise in voice level per decibel of background noise level) of 0.19 dB/dB in children, and 0.13 dB/dB in adults. These values for the Lombard Coefficient are rather low in comparison to other studies [23]. This may be due to experiments being conducted in the controlled environment of an anechoic chamber, and in an incremental manner. The child-to-adult margin of 68% is similar to the 70% found in the Integration Time of Speech experiment.

3.4 Prediction Model

Using the Lombard Coefficient data obtained for the child experiment we propose the following prediction for activity noise in a classroom:

$$F = \frac{B - S.L + 10\log N - R}{(1 - L)} \qquad (1)$$

$$R = 20\log\left(0.057\sqrt{V/T}\right) \qquad (2)$$

Where:

B = the base (i.e. no noise) voice level in dB(A)

N = the number of children speaking

S = the starting level for the Lombard effect in dB(A)

L = the Lombard Coefficient in dB/dB

V = the volume of the classroom in m^3,

T = the reverberation time of the classroom in seconds, and

R = the difference between speech level at 1m, and the level at the reverberation radius of the room L_{Prev} for one speaker (see eqn (2))

As an example, we will assume a classroom with a volume of $200m^3$ and reverberation time of 0.6s, containing 30 students, in which activity noise is the *only* source of background noise. For a group work activity in which the students are working in pairs, and only one of the pair is talking at any one time, there would be 15 students generating the activity noise. If the students on average have a base voice level of 53.4 dB(A), then (by eqn (1)), the generated noise level would be approximately 74 dB(A). This value correlates with activity noise levels of between 72 and 77 dB(A) measured in other recent classroom acoustics studies[2,16,24,25]. Therefore this may be a valid prediction model for classroom activity noise, albeit in its fledgling state.

Furthermore, this correlation suggests that the Lombard Effect may be wholly responsible for the Café Effect. However as the trigger level in both groups is low, it seems unlikely that the onset of the Café Effect can be avoided altogether by controlling background noise.

3.5 Implications for Classroom Design

The NZCRG, The American ANSI Standard ANSI S12.60:2002[3] and the Australian and New Zealand standard AS/NZS 2107:2000[26] recommend an unoccupied background level of 35 dB(A) for teaching spaces. It can be seen from Figure 6 that the findings of this work support this value, as it ensures a negligible café effect due to intrusive noise.

Results also indicate that the Lombard Effect occurs to some degree even at very low background noise levels. However the relationship has an exponential form so the higher the background noise, the higher the Lombard reflex. A possible method, therefore, of controlling the activity noise in the classroom is to implement a 'warning system' of some kind to alert the children when they begin to create too much noise. This role is traditionally left to the teacher of the class, but maintaining quiet, or trying to speak above classroom noise can be very taxing on teachers. The NZCRG found that 33% of teachers said they always or often had to elevate their voices to be heard, and Sapienza et al (cited in Wilson et al.) reported that 80% of teachers experience vocal fatigue compared with 5% of the general population.

In an unpublished study Hygge et al. carried out experiments involving the use of Brüel and Kjær SoundEar 2000s[27] – wall-mounted devices which give warning light indicators at preset trigger levels i.e. predetermined levels deemed to be too loud. The results showed less than half the number of activity noise peaks greater than 70 dB(A) for periods, at the beginning of which, the pupils (7-8 year olds) were reminded to monitor their activity noise.

The results of our study can assist in refining the trigger levels in order to optimise control of the activity noise. From Figure 6, a background level of around 40 dB(A) is required to elicit a 3 dB(A) (barely subjectively significant) rise in subject voice level. We believe this is a suitable warning level setting for quiet activities as there should be no *significant* presence of the Lombard Effect. The warning setting for louder activities will depend more on the preferences of the teacher, but we suggest a level around 60 – 65 dB(A) as appropriate. There are other devices available e.g. the Talk Light[28] whose effectiveness may also be optimised if adjusted according to these settings.

The long-term benefit of a device such as this could go beyond the suppression of activity noise in the classroom. It may help to develop the children's awareness of how their actions influence the acoustic environment, and the important ramifications of this. This is likely to continue into later life, and a greater awareness of noise and its impact on society will result amongst the population in general, as they will have learnt the basic skills from early childhood.

4. CONCLUSIONS

Two physiological phenomena have been investigated, related to the auditory sensitivity of reverberation in a space, with a particular focus on primary school children in the classroom.

In both the Integration Time of Speech and the Lombard Effect experiments, children were found to have significantly different responses to that of adults. Reverberation in a space is shown to be potentially more damaging to children in the areas of speech intelligibility and response to background noise.

Suggestions are made for optimising classroom design in terms of reducing late reflected speech energy which would be detrimental to children's speech intelligibility, but not adults'. Furthermore, setting levels are recommended for noise indicator devices which can, to some degree, control the café effect during periods of high classroom activity i.e. group work.

The work takes a step closer to designing an optimum acoustic environment for primary school children, such that speech intelligibility is maximised, which is a clear prerequisite if their full learning potential is to be realised.

4.1 Further investigations

Further research could be conducted on the Lombard reflex using various types of masking noises (pure tones, speech babble), and in different test rooms. The present tests were conducted in a quiet anechoic chamber, and similar tests in more typical conditions may elicit more relevant results for speech in classroom applications.

Performing these same experiments on hearing impaired children is essential in future research, since hearing impaired students are mainstreamed in New Zealand and the needs of these students *must* be provided for. It is for this reason that the NZCRG supported the provision of FM aids for all hearing impaired children. Designing classrooms for their more critical speech intelligibility needs will further improve things for normally hearing children also.

Whilst a classroom's acoustics should be designed to support the voice of the various occupants and suppress undesirable background noise, a teacher with a clear, robust speaking voice would optimise the didactic teaching situation dramatically and obviate the move towards controversial teacher voice amplification systems.

Vocal factors such as loudness, pitch, clarity, articulation, timbre and metre could be measured and the identification of the relative importance of these – and other factors – could be used to shape voice training or speech production techniques for teachers, which could be incorporated as part of teacher training and education.

Perhaps an objective measure of voice quality could be developed to identify desirable features in the voices of teachers who command a high degree of class control.

A developing trend for achieving higher S/N ratios is the introduction of so-called sound-field amplification or teacher voice amplification systems (TVAS) into classrooms, where the teacher wears a wireless microphone and his or her voice is amplified and delivered to the class via an array of loudspeakers fixed to the walls or corners of the room. Although this approach increases signal-to-noise ratio, it fails to address the central issue of poor room acoustics and only aids the communication of teacher to student, neglecting both the student-teacher and the crucial student-student communication during group work. If students were to experience a system like this from early on in their schooling, they may have the development of essential listening skills (such as localization & discrimination) hindered, as the amplification system removes the need for really 'attending' to the speaker. Students who change schools or classes from one fitted with a TVA system to one without may also experience disruption to their learning. The noise levels produced by a system such as this may also significantly increase the daily noise dose of a child and potentially create intrusive noise problems for near-by classrooms. Furthermore, teachers may come to depend on such a system for communication and use it overmuch, out of convenience, without fully recognising the impact on pupils.

It is suggested that the natural acoustics of the room should be improved as much as possible so that the environment lends itself to good speech communication without the need for aids i.e. the noise should be decreased, rather than the signal increased. This means that the resolution of background noise issues and the reinforcement of speech intelligibility for both student-teacher and student-student interaction through good acoustic design is paramount.

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