Describing levels of speech privacy in open-plan offices
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Summary

The primary goal of the acoustical design of conventional open-plan offices (cubicle style) is to achieve an acceptable level of acoustical or speech privacy. That is, we would like to make it more difficult for occupants to hear and understand speech sounds from adjacent workstations. We can therefore measure speech privacy by measuring the intelligibility of speech sounds from adjacent workstations.

Speech privacy or speech intelligibility ratings can be related to signal-to-noise ratio type measures that indicate how much louder the speech signal is relative to the ambient noise. The most common objective measures of speech privacy in open-plan offices are the Articulation Index (AI) and its more recent replacement the Speech Intelligibility Index (SII). Both are frequency-weighted signal-to-noise-ratio type measures. That is, they include measures of signal-to-noise ratios at a range of frequencies and sum them according to the relative importance of each frequency band. Both AI and SII have values varying between 0 and 1. A value close to 1 indicates near-perfect speech intelligibility. A value close to 0 indicates very low intelligibility, which would correspond to a high degree of speech privacy.

Criterion values of AI=0.15 (equivalent to SII=0.20) have been suggested as a maximum value for achieving 'acceptable' or 'normal' speech privacy in open-plan offices. However, these criteria are not based on experimental studies and seem to have been estimated from practical experience. The literature contains several descriptions of the meaning of 'normal' or 'acceptable' speech privacy as well as different criteria for achieving them other than those given above.

The present work included controlled experiments in which subjects evaluated a wide range of simulated acoustical conditions in open offices. In one experiment subjects performed speech intelligibility tests for conditions of varied AI and SII. In a second experiment, subjects rated the speech privacy and the degree of distraction of the conditions while working on representative office work tasks.

At the criterion values of AI and SII, the median subject could understand 88% of the words in phonetically balanced test sentences. For these criterion values they rated speech privacy as a little less than 'acceptable' and the degree of distraction as almost 'moderate'.

These AI and SII criteria are a good choice for design goals because they are practically achievable while representing a significant amount of speech privacy. They represent the point at which speech privacy starts to substantially improve with decreasing SII or AI value. Higher values of AI or SII would indicate that the office design has provided no improvement in speech privacy relative to doing nothing. However, slightly lower AI or SII values than these criterion values would correspond to significant further improvements in speech privacy.

These results support the recommendation that conventional open-plan offices be designed to achieve an SII rating of 0.20 or less (or equivalently an AI $\leq$ 0.15). The results of the experiments given in this report give a clear description of how these conditions would be perceived by occupants of open-plan offices. Careful design to meet these criteria can produce more acceptable working conditions in open-plan offices.

Contents

1. Introduction

The primary goal of the acoustical design of an open-plan office is to achieve an adequate level of acoustical or speech privacy [1]. Speech Privacy is essentially the opposite of speech intelligibility. That is, for good speech privacy, intruding speech sounds should not be intelligible. Speech privacy can be related to physical measurements of speech-to-noise ratios. When speech levels are low relative to the ambient noise levels, then the speech will not be very intelligible and hence speech privacy should be high. In the past speech privacy in open-plan offices has been related to measures of the Articulation index (AI) [2], which is a frequency-weighted signal-to-noise-ratio type of measure with values between 0 and 1. Values close to 1 represent situations where high speech intelligibility is expected and values close to zero indicate that intelligibility will be low, corresponding to high speech privacy.

Various levels of speech privacy have been described verbally, but usually have not been related to specific values of objective measures such as the AI. 'Normal' or 'acceptable' privacy has often been suggested as a requirement for open-plan offices. 'Normal' privacy has been described in many ways including: as where conditions are not too distracting or where effort is required to understand intruding speech. In some cases an AI of about 0.15 has been suggested as a maximum AI for achieving 'normal' or 'acceptable' acoustical privacy [3]. In other cases only verbal descriptions of 'normal' privacy are given [1]. Although acceptable levels of speech privacy are often specified in terms of corresponding AI values, there is very little experimental evidence to support the particular values. They seem to be mostly sensible values estimated from practical experience. It is not at all clear to what perceptual experience these values relate. For example, how intelligible or how distracting would intruding speech be? How much acoustical privacy would occupants experience in situations with these particular AI ratings?

To complicate matters, the Articulation Index measure [2] has now been replaced by the newer Speech Intelligibility Index (SII) [4], and hence levels of speech privacy should now be related to measured SII values. Calculated AI and SII values for open-office situations have been shown to have values that are a little different but that are systematically related to each other [5]. An AI value of 0.15 corresponds approximately to an SII value of 0.20.

2. Previous Investigations

The most significant study to relate perceived speech privacy to objective measures is the pioneering work of Cavanaugh et al. [6]. Although their work focussed on acoustical privacy for closed offices, they carried out tests in which subjects rated the acoustical privacy of a range of situations. They showed that judged acoustical privacy is related to speech-to-noise ratios rather than to absolute levels of either the speech or the noise. 'Confidential' privacy was defined as a situation where speech from an adjacent area is generally not intelligible and they concluded that 'confidential' privacy occurs when the AI is 0.05 or less. They also described a lesser level of privacy that they referred to as 'normal' privacy that would correspond to 'freedom from distraction' from speech sounds arriving from adjacent spaces. Finally, a higher level of privacy, referred to as 'truly secret', where no speech sounds could be understood, was also mentioned. Neither of these other two levels of privacy was related to particular AI values or to any other objective measure in their work.

In 1970 Pirn [7] published a study of the various parameters influencing the acoustical performance of open-plan offices. He included 'tentative relationships' between AI values and descriptions of various degrees of acoustical privacy. These included 'normal' privacy as the range of AI values from 0.05 to 0.20. However, these values seem to be the author's personal estimates from consulting experience and no experimental evidence is cited to support the choice of these values.

Warnock [3] published the results of a number of studies of acoustical privacy in open-plan offices. His work included subjective evaluations of acoustical conditions in actual open-plan offices. From his studies, he concluded that background noise and masking noise levels should not exceed 48 dBA. He also pointed out that simple word intelligibility tests were not effective in low intelligibility situations because respondents could guess the answers about 20% correctly. He described the range of AI from 0.05 to 0.15 as corresponding to 'normal' acoustical privacy for an open-plan office.

An ASTM task group produced a document describing the important factors in the acoustical design and evaluation of open-plan offices [1]. It states that achieving the desired level of acoustical privacy is the primary problem of open-plan offices. 'Confidential' privacy is described as, "…zero phrase intelligibility with some words being intelligible". The document is quite vague about other levels of privacy. The ASTM E1374 document [8] explains the use of various ASTM standards with respect to open office situations. In this standard 'confidential' privacy is described as where speech is detected but not understood. 'Normal' privacy is described as when effort is required to understand intruding speech or as corresponding to the absence of distraction. The standard states that additional research is required to better establish the relationship between AI values and subjective judgments of 'normal' privacy.

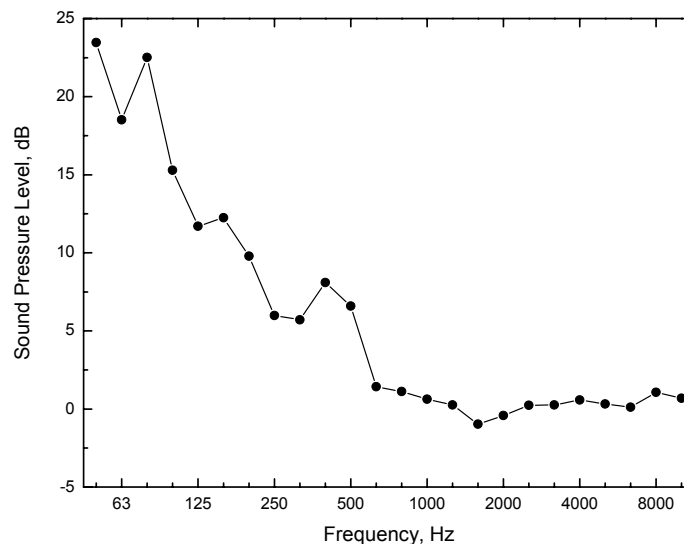Other documents suggest an AI value of 0.15 or less as a criterion for 'normal' or 'acceptable' speech privacy in open-plan offices [9] but no supporting studies have been found. More recent work indicates that an AI value of 0.15 (or equivalently an SII value of 0.20) in practice represents about the maximum level of acoustical privacy that is easily achievable in a well-designed conventional open-plan office [5, 10].

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The purpose of the present work was to carry out subjective evaluations of speech privacy in simulated open office conditions to more satisfactorily describe the significance of speech privacy criteria for open-plan offices. It was hoped to more precisely describe the conditions that open office occupants would experience in these particular conditions. It was also hoped to provide further evidence to support the use of the criteria for 'normal' privacy (AI=0.15 or SII=0.20) or alternatively to propose the use of new criteria.

This report describes the results of controlled experiments in which subjects evaluated simulated open-plan office conditions. The major experiment was based on the usual assumption that increased speech privacy is related to reduced intelligibility of intruding speech sounds and it related speech intelligibility scores to objective measures of simulated open-office conditions. A second experiment obtained subjective ratings of a range of simulated open office conditions by subjects engaged in various tasks. The results provide a credible description of the subjective experience related to the acoustical criteria and provide more substantial meaning to the terms 'normal' and 'acceptable' speech privacy.

3. Experimental Test Facility

All experiments were carried out with single subjects responding to simulated open-plan office conditions. The open office simulations were performed in the Room Acoustics Test Space in building M59 at the National Research Council. This is a sound-isolated test room that makes it possible for the experimenters to completely control the sounds heard inside the room. Figure 1 shows a plot of the measured levels in the room with the simulation system turned off. These measured background levels corresponded to an overall level of 13.7 dBA. The room is 9.2 m long by 4.7 m wide and 3.6 m high and is constructed of concrete and vibrationaly isolated from the rest of the building. For these experiments the walls were lined with 10 cm thick sound absorbing foam covered by curtains. This created an acoustically dead environment in which sounds could be produced in a more controlled manner. The floor was carpeted and there was a conventional T-bar ceiling with 25 mm thick glass fibre ceiling tiles. The glass fibre tiles were chosen because they are more sound absorptive than other materials and at the same time are more acoustically transparent to sounds from above the ceiling. This was important because loudspeakers reproducing simulated ambient noise were located above the ceiling.
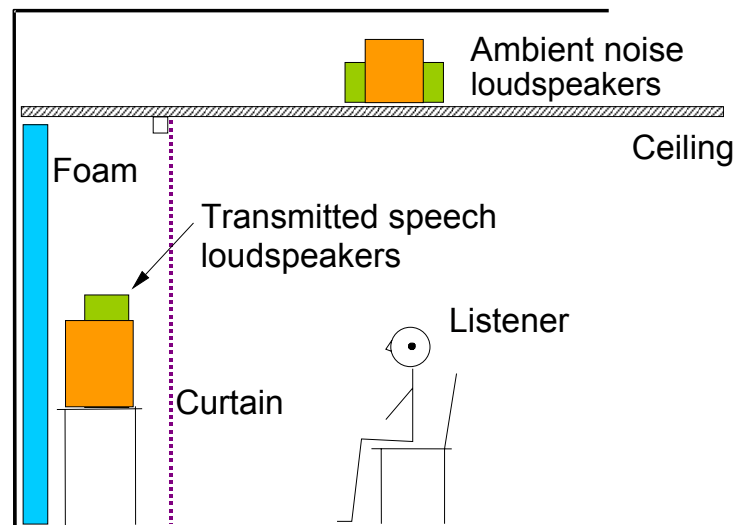

Figure 1. Measured background noise levels in the Room Acoustics Test Space with the simulation system turned off and corresponding to an overall level of 13.7 dBA.

Figure 2 is a sketch showing a cross-section of the test room with the listener located immediately below the loudspeakers that were mounted above the ceiling and that reproduced the simulated ambient noises. A second set of loudspeakers was located behind the curtain 2 m in front of the subject and was used to reproduce the sounds of simulated speech from an adjacent workstation.

Figure 3 is a block diagram of the electro-acoustic system used to produce the simulated speech and noise sounds. The blocks labelled DME32 are Yamaha Digital Mixing Engines that are signal processing boxes that can be configured to function as interconnected devices such as various equalizers, mixers and reverberators. They make
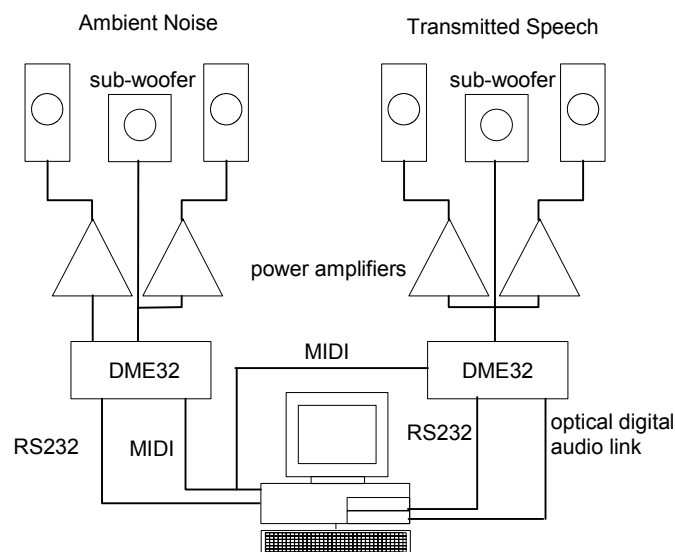
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it possible to modify the level and spectrum shape of the speech sounds and noises to create those sounds required for the experiment, and they operate under computer control.

Figure 2. Cross-section through the Room Acoustics Test Space showing the location of the listener and the loudspeakers used to reproduce simulated office sounds.

The outputs of each DME32 were fed to separate loudspeaker systems. Both consisted of a pair of high quality bookshelf sized loudspeakers (Paradigm Compact Monitor) supplemented by a sub-woofer unit (Paradigm PW). One component of each DME32 was used to equalize the response of each loudspeaker system to be flat from 60 to 12,000 Hz ±1 dB at the location of the listener's head.

Figure 3. Block diagram of the computer controlled electro-acoustics system used to create simulated speech and noise sounds.

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One of the DME32 units was used to create the desired ambient noise spectra. The DME32 includes a noise generator and additional components were used to create equalizers to filter the noise to have the desired spectrum shape. The same noise signals were fed to both left and right loudspeakers except one channel was delayed by 300 ms so that the two signals were subjectively uncorrelated. This creates a more diffuse sound that doesn't vary unnaturally with small movements of the listener's head.

Figure 4 plots the measured spectra of the two simulated ambient noises. One approximates a 'neutral' spectrum with levels decreasing approximately 5 dB/octave and is similar to many indoor ventilation noises[11,12]. The other has deliberately increased low frequency levels to approximate a more 'rumbly' ventilation noise.
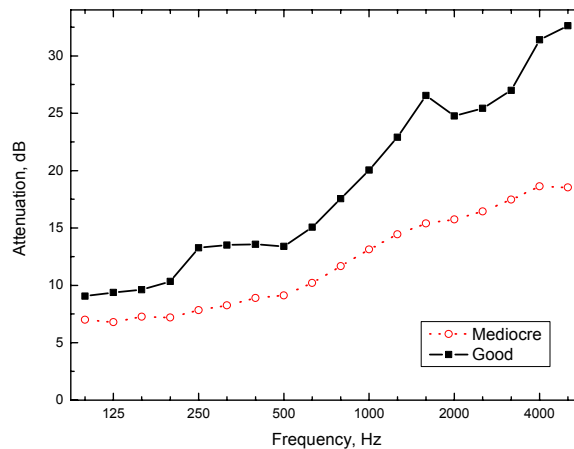

Figure 4. Measured spectra of the two types of simulated ambient noise, both having an overall A-weighted level of 45 dBA.

The speech material was stored as *.wav format files on the computer and transferred digitally to the other DME32 unit. This DME32 was configured to include equalizers to filter the speech sounds to represent the attenuation of the speech in propagating from one workstation to another. The details of the attenuations versus frequency were determined using the COPE-Calc software. This is a program that implements an image sources model of propagation between workstations [13-16]. Calculated attenuations were determined for a range of workstation conditions. Two representatively different attenuations were used and are plotted in Figure 5. Exactly the same filtered speech signal was fed to both the left and right channels of loudspeakers.

The stored settings of both DME32 units were changed under computer control using a MIDI interface. It was therefore a simple procedure to step through the various combinations of simulated ambient noise and speech according to particular play lists.

It is important to reproduce the speech and noise sounds from different directions to be as realistic as possible. The amount of masking or interference with the speech sounds by the noise is less when the two types of sounds come from different directions [17], as is most common in most real situations. Typically occupants of workstations would experience speech sounds arriving from the adjacent workstation and ventilation noise from ceiling grills or some other location than the source of the speech. Thus, the

configuration of the test set up was intended to model the expected spatial effects found in typical open-plan offices.

Figure 5. Inter-workstation attenuations used to produce simulated speech sounds from adjacent workstations.

All subjects were NRC employees who volunteered to participate by responding to a general email request for subjects. Each was given a hearing threshold test. Because the subjects were intended to represent typical occupants of open-plan offices, they were not selected according to the sensitivity of their hearing. However, 2 subjects were excluded from the analyses because they had quite significant hearing loss. A total of 29 subjects were included in the analyses of both experiments. Figure 6 plots their average hearing level values ±1 standard deviation.

Figure 6. Average measured hearing level, ±1 standard deviation, for the 29 subjects.

All other details of the experiments are described separately for each experiment in the following sections.

4. Speech Intelligibility in Simulated Open-Plan Office Conditions

(a) Experimental Procedure

Speech privacy is usually related to the reduction in intelligibility of unwanted intruding speech sounds. If speech intelligibility, SI, is the fraction of the words understood, then speech privacy, SP, is the fraction of words not understood and the two are simply related as follows,

$$SP = 1 - SI$$

It is therefore possible to directly assess the degree of speech privacy for particular situations using speech intelligibility tests in which the fraction of correctly understood words is determined.

There are many types of speech intelligibility tests. One of the simplest types is a rhyme test where only the first letter of each test word must be identified by the listener [18]. Such tests have the advantage that they are easy for subjects to learn how to do, but are not suitable for low intelligibility conditions because subjects can easily get scores of 20-25% by guessing. Therefore, these tests cannot accurately assess conditions of low intelligibility that would correspond to reasonable speech privacy. There are also speech intelligibility tests where the listener is presented with complete sentences. For these sentence intelligibility tests to function well in low intelligibility conditions, they should be material of 'low predictability'. That is, the second half of the sentence should not be obviously predictable from the first part.

In this work the Harvard test sentences were used [19]. These are phonetically balanced and of low predictability. There are also a large number of them (720) so that many tests can be carried out without each subject hearing the same sentence more than once. This is very important for low intelligibility conditions in which one can often identify repeated material by the rhythm or cadence of the sentence even though the words are not intelligible to the listener. In related studies of speech security for closed offices and meeting rooms[20], the influence of the particular talker on intelligibility scores was considered. Slightly higher intelligibility scores were obtained for a male talker in a well -enunciated recording in high quality 16-bit audio at a 44.1 kHz sampling rate. These slightly more intelligible recordings were used in the current experiment.
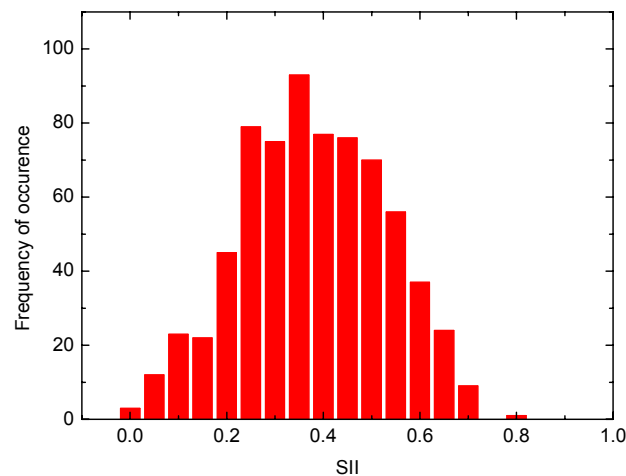
Each sentence was played back to the listener once in the presence of ambient noise. The speech was filtered to simulate the attenuation of sound propagating from one workstation to another (see Figure 5). The subject simply repeated back the words that they had understood. A microphone near the subject picked up their response so that the experimenter, who was outside the test room, could record the correctly understood words. The subject's responses were later scored as the fraction of the words in each sentence that were correctly understood. It took subjects approximately 20 minutes to complete this test.

The goal of the experiment was to have subjects rate the intelligibility (or privacy) of a wide range of conditions representing typical open-plan offices. It was intended to include varied level and spectrum of ambient noise as well as varied simulated speech propagation conditions from the adjacent workstation. Since intelligibility is primarily related to speech-to-noise ratios, it was particularly important to include variations of this

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parameter. It is also important to evaluate each physical condition with several test sentences to get a result that is more generally representative of all speech material. Although it would be ideal to include many levels of each of these important parameters, this would have lead to very long experiments and perhaps to making it impossible to find subjects.

The final experimental design had subjects listening to 100 test sentences. These consisted of the combinations of: 5 different sentences, by 2 inter-workstation attenuations of the speech sounds, by 2 ambient noise spectra, by 5 signal-to-noise ratios.

Speech privacy has usually been measured using the Articulation Index (AI) [2], which has more recently been replaced with the Speech Intelligibility Index (SII) [4]. Figure 7 shows the distribution of SII values from measurements of 702 pairs of conventional workstations obtained in another recent project [21]. These were calculated assuming an Intermediate Office Speech Level (IOSL) intended to be representative of speech levels in open-plan office environments [5]. The mean SII for these measurements was 0.35 with a standard deviation of ±0.15. Figure 7 suggest that most SII values are between about 0.2 and 0.6. Figure 7 gives a good indication of the range of conditions that should be included in the simulations of the current experiment.

Figure 7. Distribution of measured SII values in 702 workstation pairs [21] calculated using an Intermediate Office Speech Level [5].

(b) Results

With 29 subjects each responding to 100 test sentences, there were 2900 speech intelligibility scores. These were first plotted versus each of three signal-to-noise type measures: the Speech Intelligibility Index (SII), the Articulation Index (AI) and an A-weighted speech-to-noise ratio (S/N(A)) as shown in Figures 8, 9 and 10 respectively. These each include a sigmoidal shaped best-fit line obtained using a Boltzman equation. The associated R^2 values are included on each plot. All of the relationships are highly significant ($p < 0.001$) due to the large number of data points (N=2900). The relationships with AI and SII values are quite similar, but the intelligibility scores are less strongly related to the A-weighted signal-to-noise ratios (S/N(A)). The range of SII values in Figure 8 is seen to cover the complete range of values found in actual offices that were shown in Figure 7.
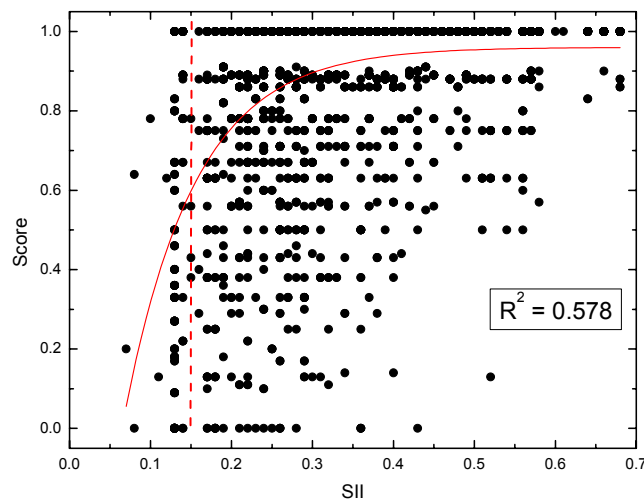

Figure 8. Individual sentence intelligibility scores for the 2900 combinations of 100 sentences and 29 subjects plotted versus measured SII values.

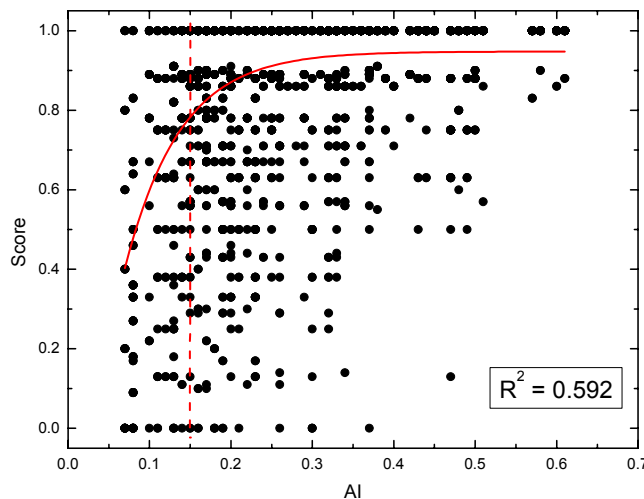*Figure 9. Individual sentence intelligibility scores for the 2900 combinations of 100 sentences and 29 subjects plotted versus measured AI values.*
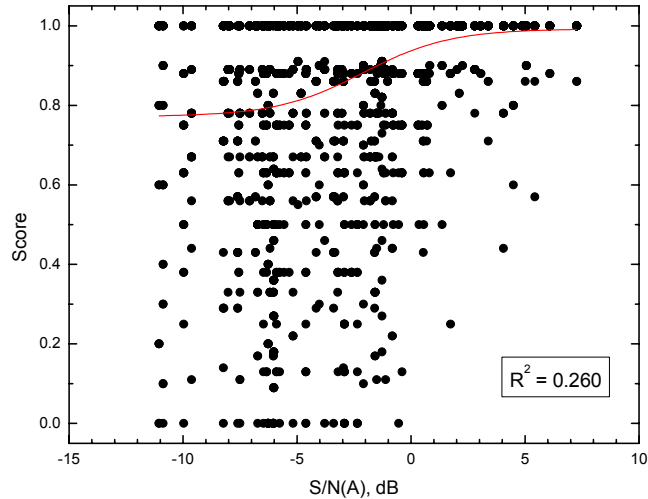
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Figure 10. Individual sentence intelligibility scores for the 2900 combinations of 100 sentences and 29 subjects plotted versus measured S/N(A) values.

These plots are deceptive because many points fall exactly on top of each other and there is actually less scatter than it might appear. For example, on the right hand two-thirds of these plots, most scores correspond to a value of 1, and only a smaller number of points correspond to lower intelligibility scores. There are other problems too in that the distribution of scores about the best fit line is not at all normal and varies systematically with variations of the x-value. It is therefore necessary to choose a better format for displaying the results of this experiment.

As a better approach, the distribution of intelligibility scores was determined in adjacent intervals of AI, SII and S/N(A). Figure 11 shows the cumulative distributions of intelligibility scores in 12 SII intervals each 0.05 wide. The lowest interval included scores with SII values between 0.10 and 0.15. The highest interval included scores with SII values between 0.65 and 0.70. The distributions are not at all normal and are mostly highly skewed to lower intelligibility scores. This is because intelligibility scores can never exceed 1.0 by their definition. As the SII values of the conditions increase, more and more scores have values of 1.0.
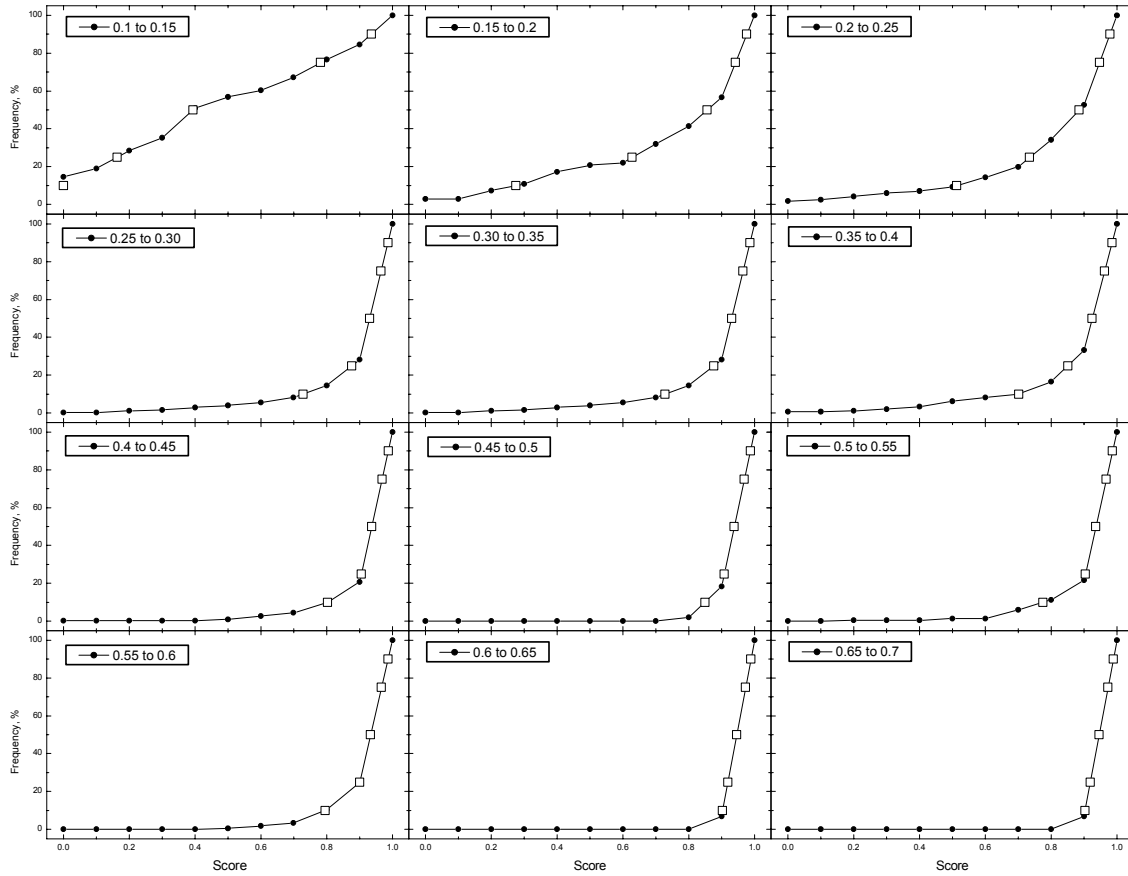
Figure 11. Cumulative distributions of intelligibility scores in each of 12 SII intervals. Open square symbols are, from left to right, the 10, 25, 50, 75 and 90th percentiles.

These distributions allow us to directly determine the percentage of responses corresponding to a particular speech intelligibility score in each SII range. The open squares on each of the 12 distributions show the points corresponding to the 10, 25, 50, 75 and 90th percentiles of the scores going from left to right. The 10th percentile point indicates that 10% of the scores are lower than this value and 90% are higher than this value. On the second plot of Figure 11 (centre of top row corresponding to the SII range from 0.15 to 0.20) the 10th percentile point corresponds to about 28% speech intelligibility. This indicates for this SII range (0.15 to 0.20) 10% of the responses have 28% correct intelligibility scores or less and 90% have higher intelligibility scores than this. Similarly the 75th percentile point on the same graph indicates that 75% of the scores were 93% correct speech intelligibility or less. Conversely this indicates that 25% of the responses in this SII range had speech intelligibility scores higher than 93% correct.

Similar plots were produced in terms of AI values and A-weighted signal-to-noise ratios (S/N(A)). The 10, 25, 50, 75 and 90th percentile points from these plots were then plotted versus the AI, SII or S/N(A) values for each range of these measures. For example, Figure 12 plots these five percentiles versus the SII value for each of the 12 SII ranges. These give a more complete description of how the distribution of speech intelligibility scores vary with SII values. For reference, a vertical dashed line is included at an SII of

0.20 corresponding to the conventional criterion for 'acceptable' or 'normal' speech privacy. At this criterion value of SII, the 50th percentile corresponds to 85% correct or better. However, at an SII of 0.15 the median score (50th percentile) is approximately 40% correct speech intelligibility. On the other hand, by the point that SII = 0.30 the median score reached about 93% correct speech intelligibility.

The 10, 25, 50, 75 and 90th percentile values were also plotted versus the corresponding AI and S/N(A) values for each range and are included in Figures 13 and 14. The results in Figure 13 in terms of AI values are very similar to those in Figure 12 plotted in terms of SII values. In Figure 13 the generally accepted criterion for 'acceptable' or 'normal' privacy is indicated by a vertical dashed line at AI = 0.15. As in Figure 12, the median speech intelligibility at the criterion value of AI is about 85% correct. When the percentiles are plotted versus the S/N(A) values the results are quite different. Speech intelligibility scores are less well related to this measure and hence it is less useful for describing acoustical conditions in open-plan offices.
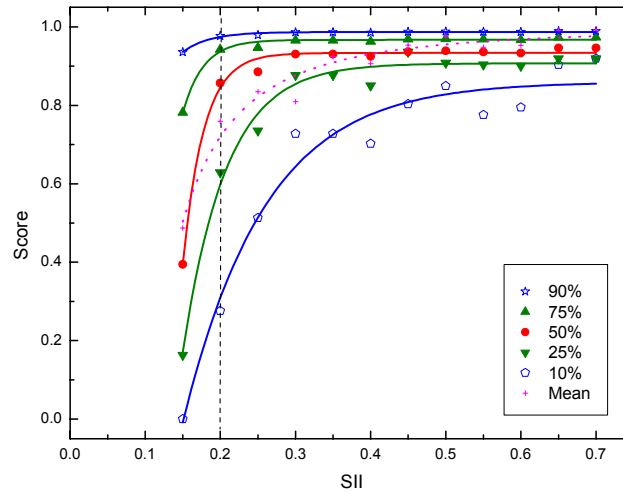

Figure 12. Percentile (10, 25, 50, 75 and 90) scores versus SII value for each SII interval. Mean values are also shown for comparison.
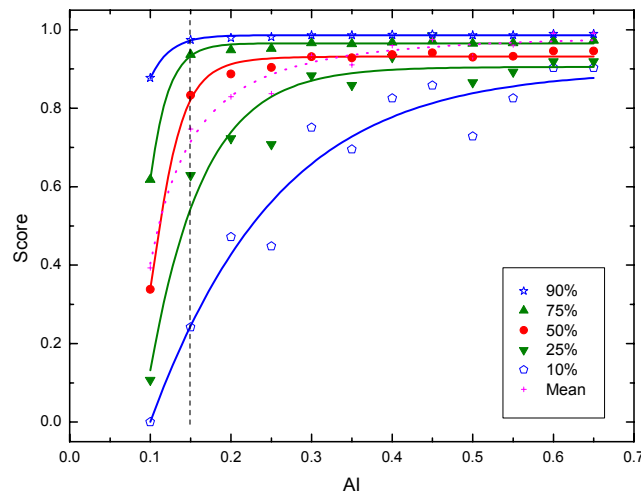

Figure 13. Percentile (10, 25, 50, 75 and 90) scores versus AI value for each AI interval. Mean values are also shown for comparison.
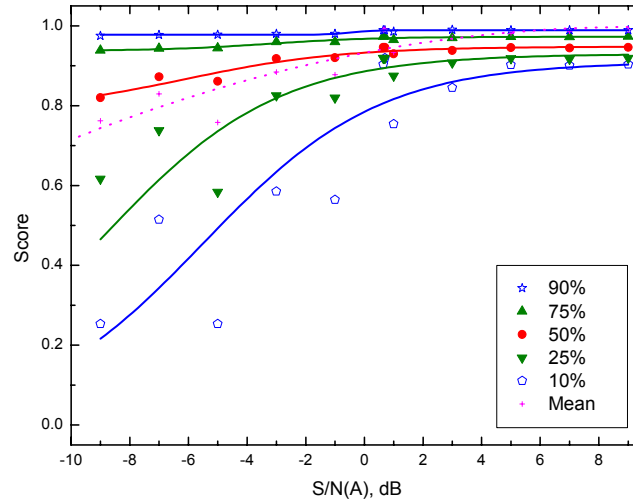
Figure 14. Percentile (10, 25, 50, 75 and 90) scores versus S/N(A) value for each S/N(A) interval. Mean values are also shown for comparison.

Although the criterion values were shown on Figures 12 and 13, in each case the actual criterion value falls at the edge of one of the ranges of the AI or SII values. To better describe speech intelligibility scores in the neighbourhood of these criterion value, the distributions of the two adjacent ranges were combined and the cumulative distributions of the combined distributions determined. These are shown for SII values in Figure 15 and for AI values in Figure 16. These plots are very similar, confirming that an AI value of 0.15 and an SII value of 0.20 are very equivalent. Figure 15 shows that in the range of conditions near to SII=0.20 the median (50th percentile) intelligibility score is about 88%. That is, half of the responses lead to a score of at least 88% correct. The 90th percentile value indicates that 90% of the scores correspond to 98% speech intelligibility or less. These are virtually the same as found in Figure 16 for the range of AI values about the 0.15 criterion value.
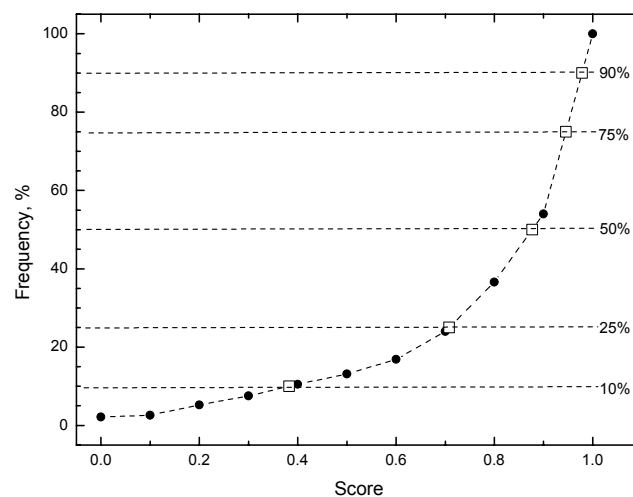

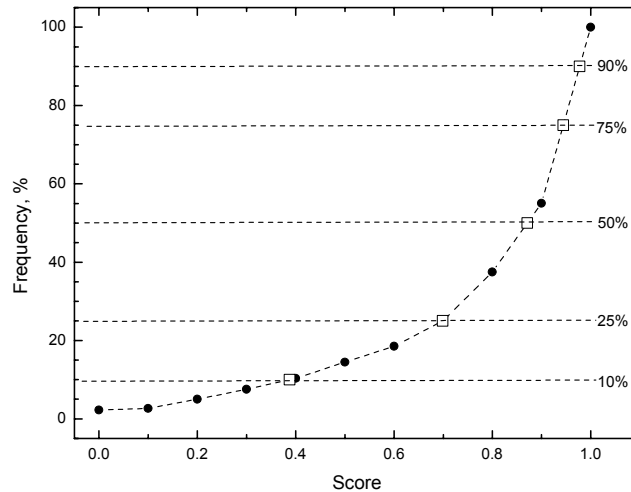*Figure 15. Cumulative distribution of scores for the SII interval centred on the criterion value of SII=0.20.*

Figure 16. Cumulative distribution of scores for the AI interval centred on the criterion value of AI=0.15.

These results give a quite precise description of the degree of speech privacy at the criterion values of AI and SII. The plots of Figures 12 and 13 indicate that the criterion values of AI and SII correspond to the start of improved speech privacy for the median (50th percentile) response. That is, a little to the right of these criterion values the median scores reach a plateau and do not increase for higher AI or SII values. One could describe AI=0.15 and SII=0.20 as the first point where the median privacy rating is much better than the result of doing nothing to improve speech privacy. From this point, even small further reductions in AI or SII lead to substantial increases in speech privacy. These criterion values seem ideally located to be achievable goals for speech privacy in open-plan offices.

Although some subjects with less than ideal hearing were included in these experiments, they did not respond equally to those with more sensitive hearing. To illustrate this the data were divided into two groups according to their measured hearing levels. Subjects were divided based on a frequency-averaged hearing level (F-HL). This was the average of the measured hearing level at both ears for the frequencies 0.5, 1, 2, 3, and 6 kHz. Over all subjects the average F-HL was 6.6 dB. This is about the same as the median value for 50-year-old, otologically normal, female listeners [22]. The 22 subjects with the least hearing loss had an average F-HL of 4.1 dB and the 7 others having greater hearing loss had an average F-HL of 14.4 dB. These values are approximately similar to those for the median 45 year old and 65 year old female respectively. Figure 17 plots mean HL versus frequency for each group as well as the overall average repeated from Figure 6**.** The individual intelligibility scores are plotted versus SII values in Figure 18 separately for the two hearing level categories. The results are similar to those in Figure 8 for the complete data and again do not reveal the true distribution of the data. However, the two mean trend lines in Figure 18 show that the subjects with more hearing loss did have, on average, lower intelligibility scores and so would apparently experience higher speech privacy in open offices. There is not enough data for subjects with increased hearing loss to show how intelligibility ratings vary with measured hearing level.
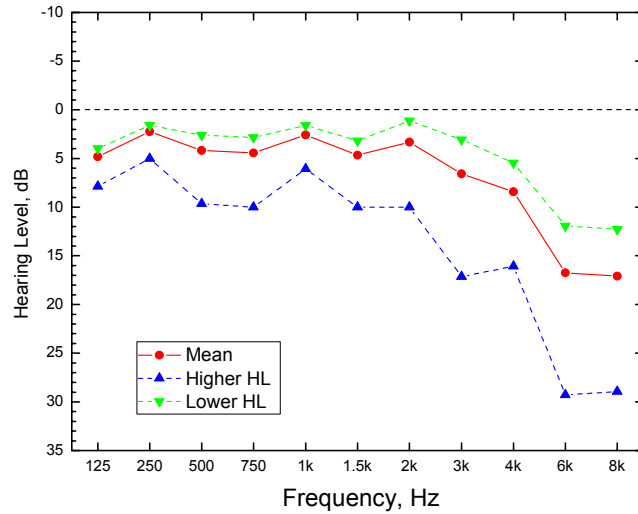
Figure 17. Comparison of mean measured hearing loss versus frequency for lower hearing loss and the higher hearing loss group of subjects compared to the overall mean values.
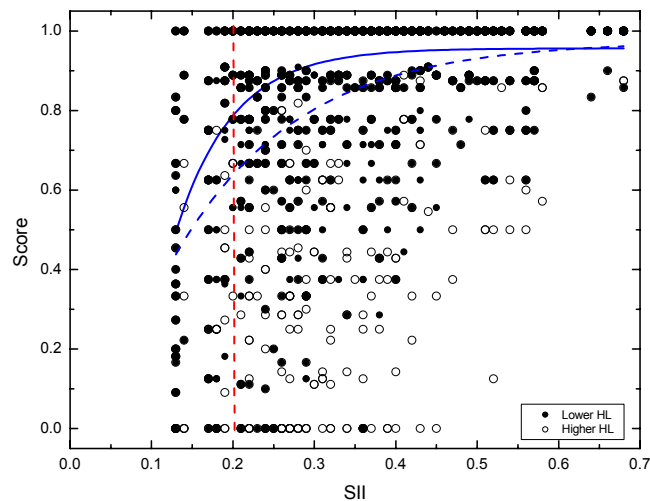

Figure 18. Individual sentence intelligibility scores for responses to 100 sentences by 22 lower hearing loss subjects and 7 higher hearing loss subjects versus measured SII values.

5. Subjective Rating of Simulated Open-Plan Office Conditions

(a) Experimental Procedure

The second experiment was intended to develop a better understanding of people's perceptions of acoustical conditions in open-plan offices by directly asking them to rate a range of conditions. Specifically, they were asked to rate the perceived degree of speech privacy and how distracting they found each condition. It was felt that such ratings would be strongly influenced by the activity with which the subject was occupied immediately prior to responding to the question. That is, if subjects had no task and were asked to subjectively rate each condition, they might find conditions less acceptable because they were so focussed on listening to them. However, if they were busy with some task, they might not notice the various conditions so much. Pilot tests suggested that it was much more difficult to remember how distracting conditions had been when occupied with various tasks. Thus, to some extent the rating of the conditions can be expected to vary with the tasks that the subjects are doing.

There are many studies in the literature reporting the effects of noise on the performance of various types of tasks and a recent review by Banbury et al. [23] summarises the results of many studies. Frequently these have focussed on understanding the basic psychological mechanisms of the task interference and often the acoustical conditions in the experiment are either not well defined or are quite unrelated to conditions in an open office. Banbury and Berry studied the disruption of office related tasks [24]. They used relatively loud speech and noise (65 dBA) and did not specify clearly the details of the playback system and listening room. In their work the details of the disturbance varied with the combination of disturbing sound and the nature of the task. Several authors have shown that tasks involving serial recall are more disrupted by speech and noise [23] and disruption tends to be greatest for more complex tasks. Relationships between performance of various office tasks and acoustical conditions have not been clearly established. This is a complex area that requires extensive further research.

Various tasks were tried in several pilot tests. Tasks selected were intended to be representative of office work and likely to be influenced by noise. The choice of tasks was limited by the need to include a range of levels of speech privacy in a reasonably short experiment. That is, relatively short duration tasks were essential to avoid an experiment that would become too long in duration. It was also not possible to automate the administration of many types of tasks within the practical confines of this project. In several pilot tests there was no indication of significant variations of performance of any of the tasks related to varying speech and noise levels. Longer duration tasks are probably required to create more realistic simulations of office working conditions. In spite of this it was felt that subjects should perform such tasks to insure that their ratings of speech privacy and distraction were as representative as possible and so that the subjects did not focus unrealistically on the speech and noise conditions.

It was also thought essential to use speech material that had more interesting content and hence could be more distracting. The Harvard sentences used in the speech intelligibility tests were found to be easily ignored because of their somewhat obscure content and almost arbitrary combinations of words. In this experiment, the speech was a commercial recording of CBC radio interviews by the late Peter Gzowski. Separate segments of

interviews were used for each part of the experiment so that the subject did not hear the same material more than once.

Item	Sounds	Task	Duration
1	Speech and noise	Text editing task	2 minutes
2	Chime and noise	Stop task	3 seconds
3	Noise	Subjective ratings	20 seconds
4	Speech and noise	Math task	1 minute
5	Chime and noise	Stop task	3 seconds
6	Noise	Subjective ratings	20seconds
7	Noise	Recall of text questions	Open ended

Table 1. Order of activities in the subjective rating test.

Table 1 shows the order of activities that the subject performed in this experiment. While the first combination of speech and noise was playing the subject spent 2 minutes editing a text passage to find spelling and contextual errors. The texts were unrelated passages from a novel by Agatha Christie. They were then asked the two questions listed in Table 2. This was followed by another 1 minute of speech and noise during which the subjects had to perform additions of columns of three two-digit numbers. At the end of this task they were again asked to respond to the same two questions in Table 2. After this they were asked to recall information from the text that they had read during the editing task.

If you were doing this task in an open office…	
How would you rate the SPEECH PRIVACY?	
1. None 2. A Little 3. Acceptable 4. Moderately Good 5. Confidential	
How DISTRACTING would the speech be?	
1. Not at all 2. A Little 3. Moderately 4. Very 5. Extremely	

Table 2. Questions used to evaluate the perceived speech privacy and degree of distraction of each simulated situation.

This same series of tasks and questions was repeated 6 times corresponding to different combinations of speech and noise. The complete test took about 25 minutes for each subject. One condition had only simulated ambient noise and no speech. The other 5 had a range of speech levels corresponding to those likely to be found in open-plan offices.

(b) Results

Figures 19, 20 and 21 plot the mean scores of the 29 subjects on the ratings of the speech privacy of the 6 conditions versus SII, AI and S/N(A) values respectively. The mean scores after the text editing and also after the math task are shown separately as well as

the overall averages. Both sets of results closely follow each other. The subjective ratings of the overall mean speech privacy scores are most strongly related to SII values ($R^2=0.773$) and a little less strongly related to AI values ($R^2=0.669$). These responses were less well related to S/N(A) values ($R^2=0.460$). At the criterion values of SII=0.20 or AI=0.15, the mean response is between 'A little' speech privacy and 'Acceptable' speech privacy. That is on average listeners found the criterion values not quite 'Acceptable'. The mean response is 'Acceptable' for and SII of 0.15 or an AI of 0.10.
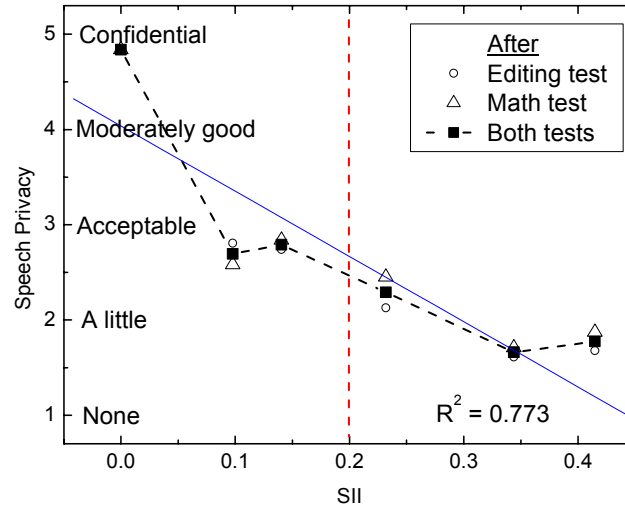

Figure 19. Mean ratings of speech privacy versus measured SII: (a) after the editing task, (b) after the math task, and (c) the average of both.
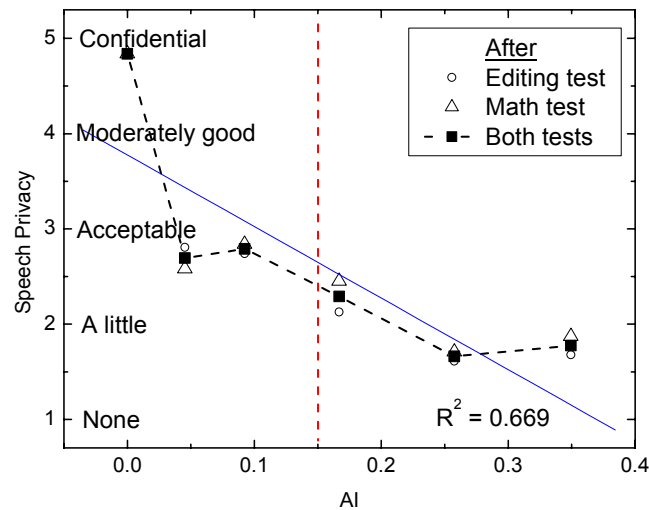

Figure 20. Mean ratings of speech privacy versus measured AI: (a) after the editing task, (b) after the math task, and (c) the average of both.
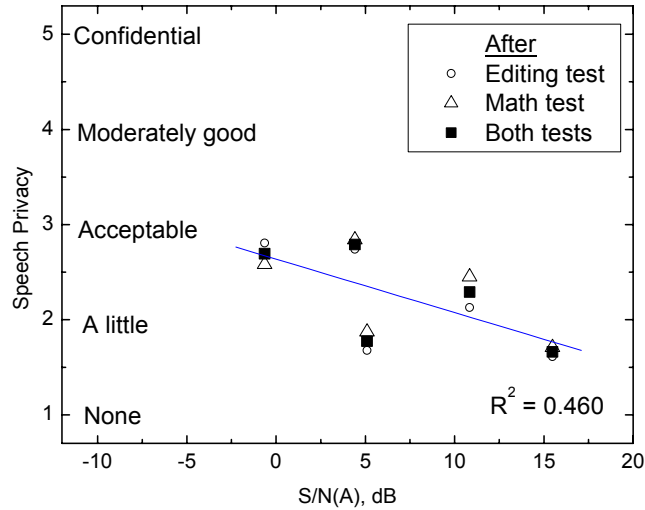
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Figure 21. Mean ratings of speech privacy versus measured S/N(A): (a) after the editing task, (b) after the math task, and (c) the average of both.

The ratings of the distracting nature of the 6 conditions are plotted versus SII, AI and S/N(A) values in Figures 22, 23 and 24 respectively. Again the results are shown separately for the question after the text editing task and the question after the math task. The responses after the two tasks are quite similar. For the potentially most distracting condition (highest SII value) the condition was found a little more distracting after the editing task than after the math task. The overall mean scores are again strongly correlated with SII values (R^2=0.847) and AI values (R^2=0.749) and less strongly with S/N(A) values (R^2=0.537). For this question the mean rating at the criterion values of SII=0.20 or AI=0.15 indicates subjects found this condition between 'A little' distracting and 'Moderately' distracting.
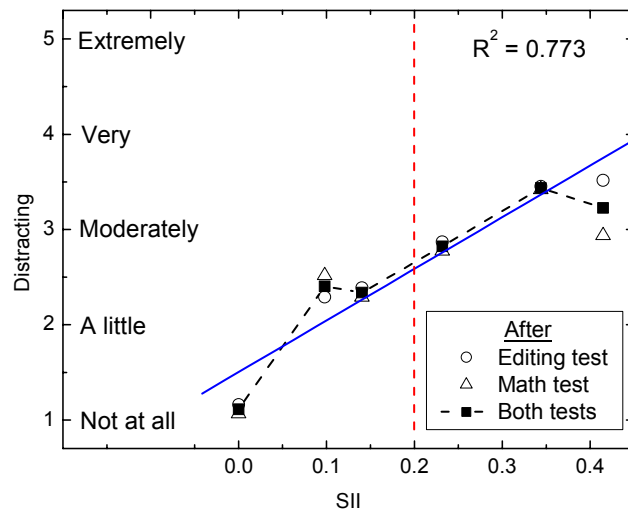

Figure 22. Mean ratings of the degree of distraction versus measured SII: (a) after the editing task, (b) after the math task and (c) the average of both.
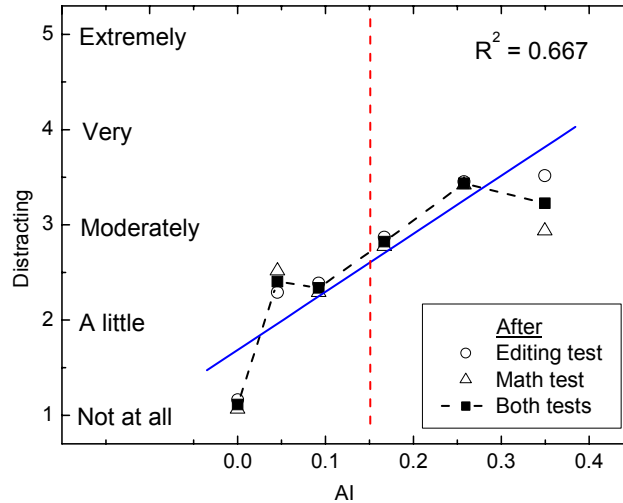
Figure 23. Mean ratings of the degree of distraction versus measured AI: (a) after the editing task, (b) after the math task, and (c) the average of both.
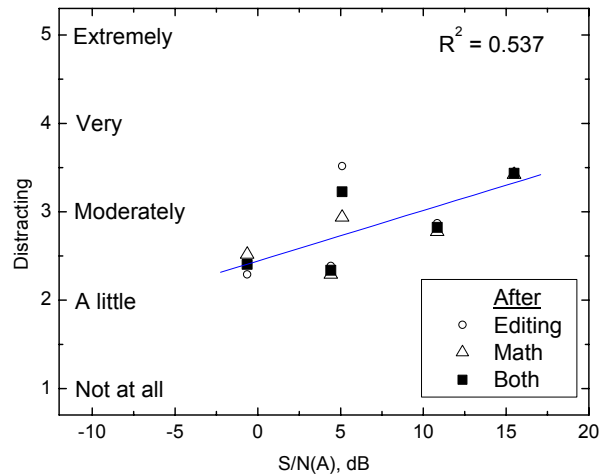

Figure 24. Mean ratings of the degree of distraction versus measured S/N(A): (a) after the editing task, (b) after the math task, and (c) the average of both.

In another recent experiment carried out in the Indoor Environment Research Facility in building M24 at the National Research Council, subjects rated speech privacy after several 15-minute exposures to various combinations of speech and noise [25]. They were more realistically engaged in computer-based office tasks than in the current experiment. The mean trend of the ratings from the current experiment (from Figure 19) are compared with the previous results in Figure 25. The current conditions extend to lower SII values than the previous results, but where the SII values of the conditions are similar the subjective ratings of privacy are also very similar. Since essentially the same question was deliberately used in both experiments, the similarity of the two results gives confidence that the tasks in the present work were adequate to create realistic distractions preventing subjects from overly focussing on the test sounds.
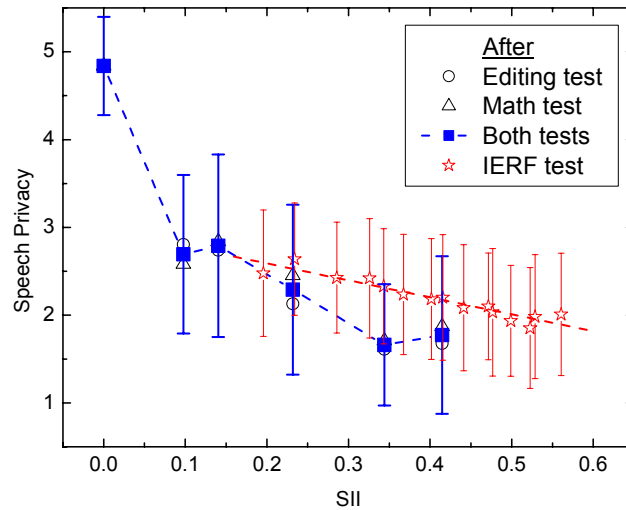
Figure 25. Comparison of mean speech privacy ratings ±1 standard deviation from Figure 19 and from a previous study [25] plotted versus measured SII values.

These results indicate that the criterion values of AI=0.15 or SII=0.20 are judged to correspond to a little less than 'Acceptable' speech privacy and between 'A little' and 'Moderately' distracting. The mean trend of the best-fit straight lines to this data suggest that 'Acceptable' speech privacy would correspond to an SII value of about 0.15 and to an AI value of approximately 0.10. The subjective ratings of speech privacy agree with previous results using the same question. Although SII and AI values are both good predictors of these subjective ratings, S/N(A) values were less satisfactory predictors of these ratings of simulated acoustical conditions in open-plan offices.

6. Conclusions

The results of these experiments give a clear description of the acoustical conditions in open-plan offices that correspond to Speech Intelligibility Index (SII) criterion ratings of 0.20 or the equivalent Articulation Index rating of 0.15. First, they correspond to a median speech intelligibility of 88% (figures 15 and 16) . That is half of the listeners can understand 88% or more of the intruding speech sounds. For the group of listeners in these experiments the actual scores at this criterion SII value varied from close to 0% to 100% intelligibility. That is, some subjects experienced no reduction in speech intelligibility and hence no apparent increase in privacy. Seventy-five percent of the subjects obtained a speech intelligibility score of 70% or better. For less well-enunciated everyday speech, intelligibility scores would likely be lower and hence would relate to greater acoustical privacy.

At these same SII or AI criterion values, subjects on average rated the speech privacy as just less than 'Acceptable'. A mean rating of 'Acceptable' speech privacy corresponded to SII=0.15 or AI=0.10. Their mean rating of the degree of distraction was just below 'Moderately distracting'.

Listeners with small to moderate hearing loss had lower speech intelligibility scores than subjects with more sensitive hearing. Increased hearing loss therefore correlates with increased speech privacy for the listener. However, the same person may create as much, or possibly more, distraction to other listeners.

The Speech Intelligibility Index (SII) and Articulation Index (AI) are almost equivalently accurate indicators of privacy. In these data, results tended to correlate slightly better with the newer SII measure than with the AI measure.

A-weighted speech and noise level differences (S/N(A)) were distinctly less satisfactory predictors of intelligibility scores and subjective ratings of the simulated open office conditions. Previous work by Young [26] had proposed the use of A-weighted signal-to-noise ratios as a substitute for AI values. Similarly a simple scheme for estimating speech privacy initially proposed by Warnock [27] was also based on A-weighted speech-to-noise ratios. It is clear from the present results that A-weighted signal-to-noise-ratio measures are much less satisfactory than the SII and AI measures.

Finally, these results and other recent work [5] suggest that the criteria of SII=0.20 or AI=0.15 are a reasonable basis for the acoustical design of an open-plan office. Design studies suggest that it is not easy to achieve much better privacy than indicated by these values in a practical open office design. Plots in this report show that these values represent corners in the curves of intelligibility or privacy versus SII. For lower SII values than 0.20, the intelligibility scores decrease rapidly and hence would correspond to much improved speech privacy. SII values much higher than this point offer no more privacy than doing nothing to improve acoustical conditions.

These results support the recommendation that conventional open-plan offices be designed to achieve an SII rating of no more than 0.20 (or equivalently an AI rating of no more than 0.15). A design that further reduces these values by 0.05 (i.e. SII=0.15 or AI = 0.10) would represent greatly improved privacy relative to these criterion values.

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Acknowledgements

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