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The Acoustical Design of Conventional Open Plan Offices

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Abstract

This paper uses a previously developed model of sound propagation in conventional open plan offices to explore the influence of each parameter of the office design on the expected speech privacy in the office. The ceiling absorption, the height of partial height panels and the workstation plan size are shown to be most important. However, it is not possible to achieve 'acceptable' speech privacy if all design parameters do not have near to optimum values. A successful open office should also include an optimum masking sound spectrum and an office etiquette that encourages talking at lower voice levels.

Résumé

Cet article s'appuie sur un modèle de propagation du son dans les bureaux à aires ouvertes mis au point antérieurement afin d'analyser l'influence de chaque paramètre de la conception du bureau sur l'insonorisation du local en question. L'absorption du plafond, la hauteur des cloisons et les dimensions du poste de travail apparaissent être les 3 paramètres les plus importants. Il est cependant impossible d'atteindre une insonorisation "acceptable" si tous les paramètres conceptuels ne sont pas proches de leurs valeurs optimales. Un bureau à aires ouvertes réussi doit aussi comprendre un spectre de son masquant optimal et une politique de bureau qui encourage à parler à voix basse.

1. Introduction

Open plan offices have existed for many years, and they have gradually become the predominant format of office space for a wide range of work activities. Older designs incorporating stand-alone screens and furniture have usually been replaced by modular workstations that are frequently referred to as cubicles. There are modern trends to experiment with so-called innovative designs such as 'team spaces' and other variations where the partial height panels between office workers are absent or much reduced in size. However the vast majority of open plan offices today consist of the rectangular cubicle format and this paper is concerned with the design of this type of open plan office.

Conventional open plan offices are said to be less costly to construct and less costly to rearrange to meet changing accommodation needs. Of course, there are counter arguments that lack of privacy and increased distraction will make office workers less efficient, and that at least point to the need for good acoustical design. Optimising the acoustical design of an open plan office can be a complex task because of the number of design parameters that must be considered. This problem has recently been made much easier to solve as a result of the development of a mathematical model of sound propagation between workstations in conventional open plan offices [1-4]. Using this model one can conveniently and quite accurately predict the speech privacy of a particular open plan office design. This model is used here to demonstrate the importance of each open office design parameter.

This paper will first describe measures of speech privacy that can be used to rate the acceptability of an open plan office design. Then design criteria for speech privacy and office noise levels are reviewed. The influence on speech privacy of ten office design parameters are then demonstrated and finally the overall approach to a successful design is discussed.

2. Speech Privacy and Noise Level Criteria

Because of the absence of full height partitions, the challenge for the acoustical design of open offices is to achieve an acceptable degree of acoustical or speech privacy between workstations. This must be done without creating unacceptably noisy conditions. Speech privacy is related to the speech-to-noise ratio and is more or less the opposite of speech intelligibility. If the level of speech is high relative to ambient noise levels, then the speech will be quite intelligible as would be desired in a meeting room. In an open office we would like the level of intruding speech to be low relative to the ambient noise so that speech is less intelligible or so that we will have some speech privacy. An appropriate level of noise can mask or cover up unwanted speech sounds. It is important to mask speech sounds because they are much more disturbing than relatively constant levels of more neutral sounds such as those of typical ventilation noise. Although higher noise levels may better mask the unwanted speech sounds, the higher noise levels can become a source of annoyance and cause people to talk louder and hence they will not optimally improve speech privacy.

The Articulation Index (AI) [5] has been used to assess speech privacy in open plan offices. AI is a weighted signal-to-noise ratio with a value between 0 and 1. It was originally developed to evaluate communication systems and has been widely used to assess conditions for speech in rooms. A value close to 1 should correspond to near perfect speech intelligibility. A value near 0 should indicate near perfect speech privacy. More recently the AI has been replaced by the Speech Intelligibility Index (SII) [6]. This is a little more complex to calculate than AI and includes the masking effect of lower frequency components on each frequency band. Like AI it has a value between 0 and 1, but for the same condition SII values are a little larger than AI values. Appendix I gives a detailed comparison of the two measures.

It has been conventional to refer to two levels of criteria for speech privacy and to relate them to corresponding AI values. 'Confidential privacy' has been said to correspond to AI ≤ 0.05 [7,8]. This has been defined as corresponding to 'zero phrase intelligibility with some isolated words being intelligible'. Conditions corresponding to AI ≤ 0.15 have been described as 'acceptable' or 'normal privacy' for open plan offices [9]. Such conditions are said to be not too distracting. In practice they correspond to a level of speech privacy that can be achieved in a well designed open plan office. These two speech privacy criteria and their equivalent SII values are included in Table 1. Ongoing work is investigating the interpretation of these criteria.

Level of speech privacy	**AI**	**SII**
Confidential	0.05	0.10
Acceptable	0.15	0.20

Table 1. Speech privacy criteria in terms of AI and SII values.

Speech privacy and the calculation of AI and SII values depend on the speech and noise levels in open plan offices. The AI and SII standards [5,6] include standard speech spectra for 'normal' speech. The 'normal' voice level spectrum in the SII standard corresponds to 59.2 dBA. Although 'normal' speech levels have frequently been used to estimate speech privacy in open plan offices, Warnock and Chu [10] have recently published measurements of speech levels in open offices that indicate people talk more quietly than this 'normal' spectrum. Their data indicate average speech source levels of 50.2 dBA, which are essentially the same as Pearson's 'casual' speech levels [11]. This level represents the average of all talkers that they measured in a number of open plan offices. If this level were used in design calculations, it would underestimate the disturbance caused by the louder half of the talkers that talk more loudly than this average level. Therefore, an Intermediate Office Speech Level (IOSL) spectrum was created that had an A-weighted level approximately 1 standard deviation higher in level than the mean value and corresponds to a speech source level of 53.2 dBA. This is a more conservative speech source level to use in open office design and only about 16% of talkers are expected to talk louder than this. The actual speech spectra are included in Appendix II.

The level and spectrum shape of ambient noise in the office also significantly influences the degree of speech privacy as well as the related AI and SII values. Although increasing noise levels lead to reduced speech privacy, there is a limiting noise level above which the noise becomes more disturbing and less beneficial. Because it is difficult to carefully control the level and spectrum of actual ventilation noise, and because it will vary with the operation of the ventilation system, the desired speech privacy can be more precisely achieved using electronic masking sound. The spectrum of such masking sound should include energy at all frequencies with significant speech energy, and should sound like a neutral ventilation noise. Such spectrum shapes have been specified [12] and an optimum masking spectrum shape is included in Appendix II. There are also rules of thumb that the overall level of masking sound (or natural ambient noise) should not exceed 48 dBA [13]. Recent studies of worker satisfaction in an experimental open office found that an ambient noise level of 45 dBA was preferred [14]. Therefore we can say that an optimum masking noise should have a spectrum like that in Appendix II and have an overall level of 45 dBA. Masking sound levels should probably never exceed 48 dBA.

3. Effects of Office Design Parameters

The model described by Wang [1-4] was implemented in open office design software and was used here to demonstrate the effects of varying office design parameters. It assumes that the source talker is at the centre of one workstation and the receiver listener is at the centre of an adjacent workstation. The user can specify speech source and noise spectra, geometrical dimensions, as well as the sound absorbing properties of surfaces. The programme calculates speech privacy in terms of the SII value due to the speech propagating from the adjacent workstation and the specified office noise spectrum and level.

In the program, the effects of various reflecting surfaces are determined using an image sources technique. It also includes diffraction over the partial height panel separating the two workstations and includes further reflections of this diffracted sound energy. It was developed because available room acoustics ray tracing programs were not able to include diffraction and subsequent reflections of the diffracted energy. The program also includes empirical corrections for the difference between laboratory measurements of ceiling absorption and those values measured in a large series of tests of propagation in a mock up open office. There are similarly empirical corrections for the effects of ceiling mounted light fixtures. Comparisons with actual measurements have validated the accuracy of the program in the original evaluations [1-4] as well as in more recent tests in actual offices. The RMS differences between measured and predicted SII values have been between 0.02 and 0.03.

The following sections show the results of calculated SII values for variations of 10 different open office design parameters. One could perform calculations for many combinations of these 10 parameters. However, most of these results would lead to unacceptably low speech privacy. 'Acceptable' speech privacy can only be achieved when key office design parameters are close to optimum. Therefore the calculations that are presented are deviations from an 'acceptable' Base case design. These illustrate the range of conditions that should be of most interest to designers.

The sound absorption and sound transmission loss data used were generic data representative of real screens and ceilings. They were obtained by averaging groups of test results for products with similar acoustical properties. The sound absorption ratings are referred to by their Sound Absorption Average (SAA) value. (SAA is the average of the 1/3 octave band absorption coefficients from 200 to 3.15k Hz and replaces NRC rating [15]). The Sound Transmission Class (STC) [16] is used to describe the transmission loss of panels.

The 'acceptable' Base case condition is described in Table 2. It had a calculated SII value of 0.19, which is just inside the desired range of SII ≤ 0.2 for 'acceptable' privacy.

Office Design Parameter	**Value**
Ceiling absorption	SAA=0.95
Screen/panel height	1.7 m (5.6 ft)
Screen/panel absorption	SAA= 0.90
Workstation plan size	3.0 m by 3.0 m (9.8 ft by 9.8 ft)
Floor absorption	SAA=0.19
Screen/panel transmission loss	STC=21
Ceiling height	2.7 m (8.9 ft)
Light fixtures	None
Speech source level	53.2 dBA (IOSL speech)
Noise level	45 dBA (optimum masking spectrum)

Table 2. Details of the 'acceptable' Base case used in calculations. (SAA, Sound Absorption Average [15], STC, Sound Transmission Class [16], IOSL, Intermediate Office Speech Level).

(a) Ceiling absorption

Figure 1 shows the effect of varying only the ceiling absorption of the Base case workstation design. Reducing the ceiling absorption much below SAA=0.95 significantly increases SII values to well above the range for 'acceptable' privacy. On the other hand a more absorptive ceiling could further enhance speech privacy or in other designs compensate for other less effective components than those in the Base case design. By re-plotting this data as a scatter plot, one can deduce that if the ceiling absorption is less than SAA=0.90, it is not possible to achieve acceptable privacy in an otherwise well designed workstation such as that of the Base case. Earlier work had recommended this same minimum ceiling absorption [17]. The ceiling is the most important reflecting surface in open plan offices and it is most important that it be as highly absorbing as possible.

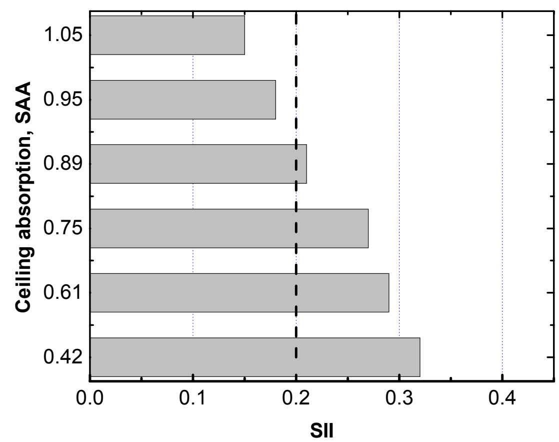

Fig. 1. Effect of varied ceiling absorption on Base case

(b) Screen/panel height

The partial height panels separating workstations must be high enough to block the direct path of speech sounds from one workstation to another and also must be high enough that the level of the sound diffracted over the panel is reduced enough to make possible 'acceptable' speech

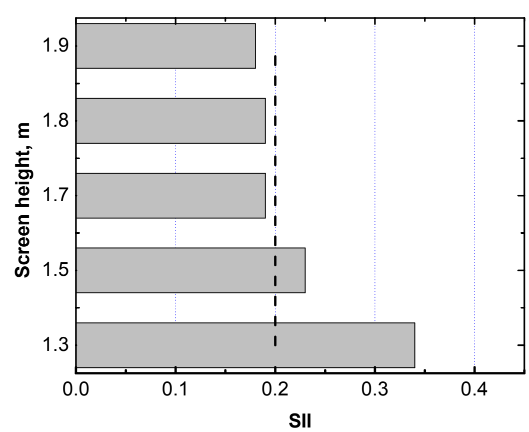

Fig. 2. Effect of varied screen height on Base case design.

privacy. Figure 2 shows calculated SII values for varied screen heights from 1.3 to 1.9 m high. Again these are variations to the Base case open office workstation design. When seated the mouth of a talker and the ear of the listener in adjacent workstations are approximately 1.2 m above floor level. The height of the separating panel must be substantially greater than this to make it possible to achieve 'acceptable' privacy. However above a height of 1.7 m, further increases in the height of the separating panel have quite small effects on calculated SII values.

(c) Screen/panel absorption

Figure 3 shows the calculated effects of varying the sound absorption of the workstation panels. Decreasing the SAA from 0.9 to 0.6 increased the calculated SII from 0.19 to 0.22. However, using non-absorbing workstation panels (SAA=0.10) is seen to increase the SII much more to a value of 0.29. It is important to have sound absorbing panels but the change in privacy between typical medium and higher absorption workstation panels is small.

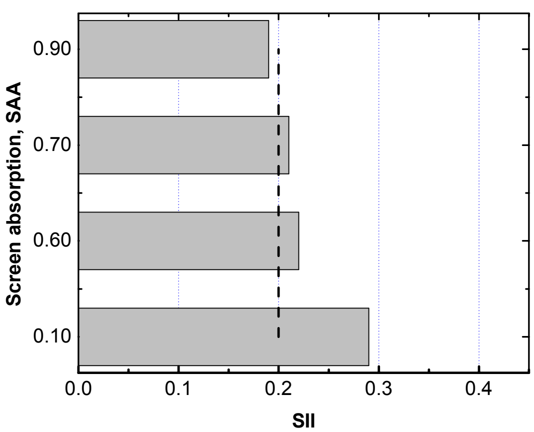

Fig. 3. Effect of varied screen absorption on Base case design.

(d) Workstation plan size

Workstation plan size was varied from a minimum of 2 m by 2 m to a maximum of 4 m by 4 m. SII values systematically decrease as the workstation size is increased. This is due to the increasing distance between the source and receiver at the centre of each workstation. Clearly there is an advantage to having larger workstations when attempting to achieve good speech privacy. Decreasing the workstation size below the base case (3 m by 3 m) decreased speech privacy. Even the 2.5 m by 2.5 m (8.2 ft by 8.2 ft) workstation would not quite meet the 'acceptable' speech privacy criteria.

(e) Floor absorption

Figure 5 shows the results of calculations when the floor absorption of the Base case workstation design was varied. These results correspond to thin carpet (SAA=0.19), thick carpet (SAA=0.25) and a hard non-absorbing floor

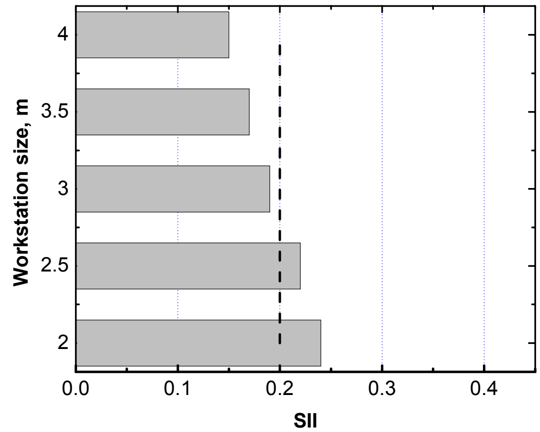

Fig. 4. Effect of workstation plan size on Base case design.

(SAA=0.05). There are only very tiny differences between the two calculations for varied carpet thickness. However, having a non-absorbing floor does decrease the speech privacy above the acceptable SII value. There are other reasons to recommend the use of carpet too. It will reduce some sources of noise such as footsteps and the moving of chairs. It will also help to minimize sound propagation through gaps at the bottom of screens. Although there is no reason to select thicker carpets, it is important to include a carpeted floor in open plan offices.

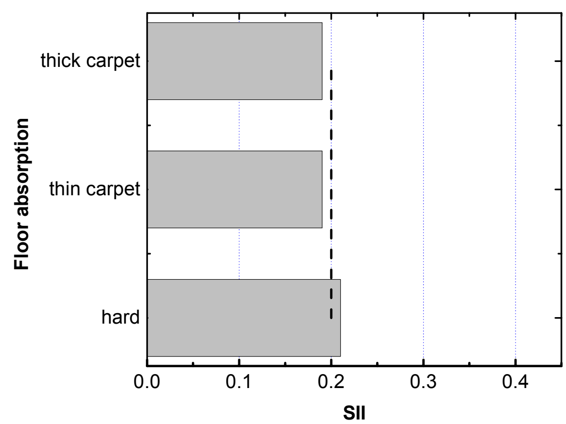

Fig. 5. Effect of floor absorption on Base case design.

(f) Screen transmission loss

Some recommendations specify that the transmission loss of the separating partial height panel should have an STC of at least 20 [17]. This is intended to ensure that the propagation of speech sound energy through the separating panel does not limit speech privacy. Figure 6 shows calculated SII values for varied STC of the separating panel. Decreasing the panel STC from 21 to 15 increased speech privacy to a little above the 'acceptable' criterion. However, increasing the transmission loss of the panel from STC 21 to STC 25 produced only a negligible improvement in SII. A minimum STC of 20 for the separating panel is seen to be adequate to avoid degrading speech privacy.

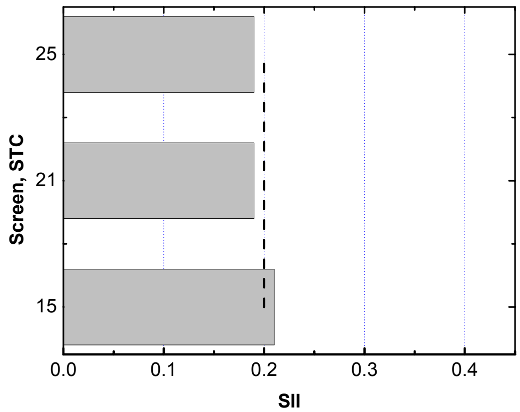

Fig.6. Effect of panel STC on Base case design.

(g) Ceiling height

The height of the ceiling in most open plan offices is usually quite similar to that of the base case (2.7 m). The calculated results in Figure 7 show that increasing the height to 3.5 m had a negligible effect on the calculated SII. However, decreasing the height from 2.7 m to 2.4 m did decrease speech privacy to a little above the 'acceptable' privacy criterion. One should therefore avoid particularly low ceiling heights in open plan offices.

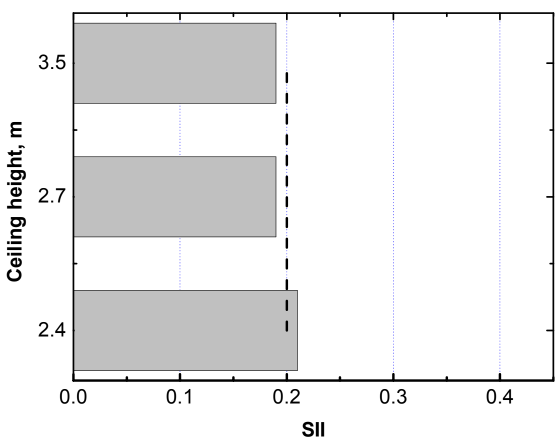

Fig.7. Effect of ceiling height on Base case design.

(h) Light fixtures

Calculations were made for three different ceiling lighting conditions and are shown in Figure 8. The Base case had no ceiling mounted lights. The empirical corrections in the software were then used to estimate the effect of a flat lens light positioned over the separating partial height panel. This would represent the worst possible effect of ceiling light fixtures. This condition led to a substantial increase in the SII values and hence would correspond to significantly decreasing speech privacy. Clearly this lighting configuration should be avoided. Using open grill lighting either positioned over the separating screen or over the centre of the workstations would have a smaller effect but again decreases the speech privacy of the base case so that it is no longer 'acceptable'. Locating flat lens fixtures over the centre of the workstations is more acceptable than over the separating panel. However, lights are usually installed before workstations and it is usually difficult to control their position relative to the location of each workstation. This is especially true after the workstation layout has been modified from the original plan. It is obviously better to use open grill light fixtures if ceiling mounted lighting is required.

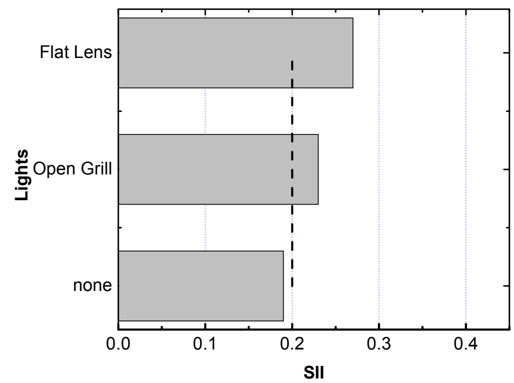

Fig. 8. Effect of Ceiling lighting fixtures on Base case design.

(i) Speech level

Figure 9 shows the calculated SII values when the source speech levels were varied for the Base case office design. Results were calculated for the 'normal' voice level from the SII standard [6], for the Intermediate Office Speech Level (IOSL), and for a 'casual' speech source level. Voice level can have a very large effect on the resulting SII values. Clearly it is important to use a representative speech source level. As explained earlier, it is thought best to use the IOSL speech spectrum. However, there are further large benefits to be obtained by encouraging office workers to talk with lower voice levels. It is important to promote an office etiquette that encourages the use of lower voice levels and relocating to closed meeting rooms when more extensive discussions are needed. It may be difficult to accommodate work that includes telephone conversations of a more confidential nature in open plan environments.

(j) Ambient noise

The effect of varied ambient noise is illustrated in Figure 10. The Base case office included the optimum-masking spectrum described previously and included in Appendix II. Increasing this masking noise from 45 dBA to 48 dBA (corresponding to the maximum masking noise spectrum) is seen to substantially decrease SII values. Although speech privacy would be significantly improved, experience has shown that this will begin to lead to decreased occupant satisfaction. A further calculation was performed with an ambient noise with an RC35 shaped spectrum (corresponding to 42 dBA). This would be

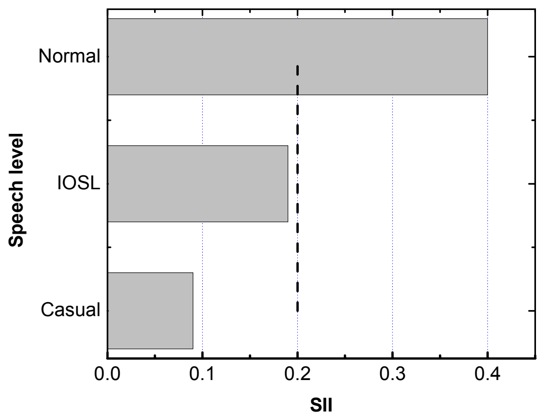

Fig. 9. Effect of speech source level on Base case design.

representative of a little quieter ventilation noise type spectrum and leads to a substantial decrease in speech privacy. It is clearly important to optimise the level and spectrum of ambient noise by using a masking sound system to create exactly the desired masking sound that will lead to a desirable level of speech privacy without leading to further disturbance of office workers.

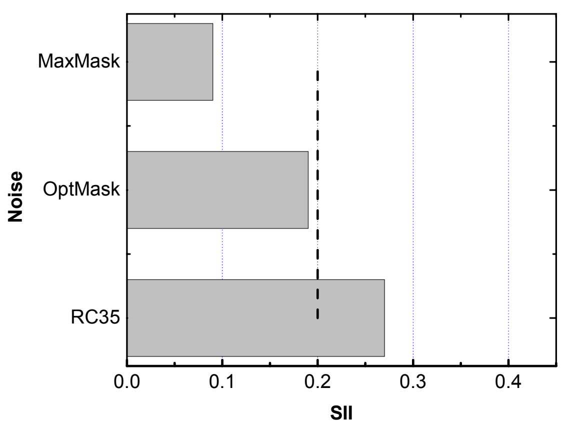

Fig. 10. Effect of ambient noise on Base case design.

4. The Overall Design Approach and Design Trade-offs

The various calculations give clear indications of the importance of each of the office design parameters. The most important factors for achieving 'acceptable' speech privacy are: (a) the sound absorption of the ceiling, (b) the height of panels between workstations, and (c) the workstation plan size. Although less important, one cannot ignore the other open office design parameters: (a) panel absorption, (b) panel transmission loss, (c) floor absorption, (d) ceiling height and (e) the details of ceiling mounted lighting.

The Base case design, described in Table 2, represents a combination of values that just meet the criterion for 'acceptable' privacy. Small degradations of one design parameter can be compensated for by augmenting the values of other parameters to still achieve 'acceptable' speech privacy. For example, decreasing the workstation plan size to 2.5 m by 2.5 m, reducing the separating panel height to 1.6 m and reducing the panel absorption to SAA=0.70 would still result in an SII of 0.19 if the ceiling absorption were increased to an SAA of 1.03. Alternatively the same increased ceiling absorption could be used to compensate for reduced plan size and the addition of open grill lighting. The details of these examples are compared with those of the Base case in Table 3. A difference in SII of less than 0.03 is probably not detectable.

These examples illustrate that there is not much room to compromise in trading off increases in one parameter to compensate for decreases in another. Most significant deviations from the Base case will result in open offices with less than 'acceptable' speech privacy. In particular the reduction of workstation plan size must be accompanied by an improved ceiling absorption to maintain conditions of 'acceptable' speech privacy. The expected saving for a higher density office with smaller workstations may be reduced by the increased cost of a more absorptive ceiling.

The speech and noise levels in the open plan office are at least as important as the office design for achieving 'acceptable' speech privacy. Therefore, in addition to a near-perfect office design, one is forced to the conclusion that an electronic masking sound system is an essential part of a successful open office design. The masking sound system should produce ambient noise levels similar to the optimum masking spectrum in Appendix II. These levels should be evenly distributed throughout the office. When adding such systems to existing offices, it is desirable to increase the level gradually over several weeks to allow office workers a chance to adapt to the new conditions.

The design of the open office can reduce the propagation of speech sounds from one workstation to another. It is also very important to reduce speech levels at the source by encouraging an office etiquette of talking more quietly. More extensive discussions, and especially those involving more than 2 people, should be relocated to a closed meeting room. Of course telephone conversations can be a source of disturbance. Where reduced voice levels are not possible or where the information is confidential, this activity is not compatible with a typical open office environment.

Although the new model allows precise examination of the effects of various parameters, in many cases such detailed design may not be necessary. Success requires that almost all design parameters are near to optimum and one could readily specify minimum requirements for most of them. This would avoid the need for future detailed design calculations. The examples in Table 3 could form a basis for such minimum design values. Using these values will

Office Design Parameter	Base case	Example #1	Example #2
Ceiling absorption	SAA=0.95	SAA=1.03	SAA=1.03
Screen/panel height	1.7 m	1.6 m	1.7 m
Screen/panel absorption	SAA= 0.90	SAA=0.70	SAA=0.90
Workstation size	3.0 m by 3.0 m	2.5 m by 2.5 m	2.5 m by 2.5 m
Floor absorption	SAA=0.19	SAA=0.19	SAA=0.19
Panel transmission loss	STC=21	STC=21	STC=21
Ceiling height	2.7 m	2.7 m	2.7 m
Light fixtures	None	None	Open grill
Speech source level	53.2 dBA (IOSL)	53.2 dBA (IOSL)	53.2 dBA (IOSL)
Noise level	45 dBA (Opt Mask)	45 dBA (Opt Mask)	45 dBA (Opt Mask)
SII	0.19	0.19	0.21

Table 3. Details of open office designs with approximately 'acceptable' speech privacy.

result in conditions that approximately correspond to the minimum criterion for 'acceptable' speech privacy. Of course this approach should include an optimum masking noise spectrum and an office etiquette that encourages using lower voice levels.

5. Conclusions

The results in this paper demonstrate the effects of each open office design parameter. They indicate that the values of each parameter must be near to optimum to ensure 'acceptable' speech privacy in conventional (cubicle type) open plan offices. Examples of combinations of values of 10 parameters are given that would lead to 'acceptable' speech privacy. Although one can, to some extent, trade off increases in one parameter to compensate for decreases in another, the range of such compromises is very limited.

The present results describe the average characteristics of cubicle type open plan offices because the source and receiver were positioned at the centre of adjacent workstations. The actual speech privacy experienced will also depend on each individual's location within their workstation as well as the direction in which talkers are facing.

The main argument in favour of open plan offices is the expected reduced cost relative to closed offices with full height partitions. The cost savings may be a little reduced with the extra expense of meeting 'acceptable' speech privacy requirements. However, these additional costs are usually assumed to be small relative to the costs of decreased performance by distracted office workers. It is difficult to accurately assess the costs of poor office design and future research should consider this issue. It would also be useful to investigate which types of office work activity are most suitable to be performed in open plan office environments.

Acknowledgments

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Appendix I. Relation Between SII and AI Values

Measured attenuations in a series of mock up workstation tests were used to calculate both AI and SII values. By repeating these calculations for a range of speech and noise levels a very wide range of values of each measure was obtained. The resulting SI values are plotted versus AI values in Figure A1. The regression line shown on this plot is a fourth order polynomial that very accurately fits the data between AI values of 0 and 0.5. Its equation is as follows,

$$SII = 0.0194+1.942\ AI - 5.263\ AI^2 + 11.731\ AI^3 - 9.247\ AI^4$$

Alternatively one can approximate the relationship by two simple straight lines.

For $0 \le AI \le 0.05$, $SII = 1.9755\ AI + 0.0163$,

and for $0.05 \le AI \le 0.5$, $SII = 0.9915\ AI + 0.0721$.

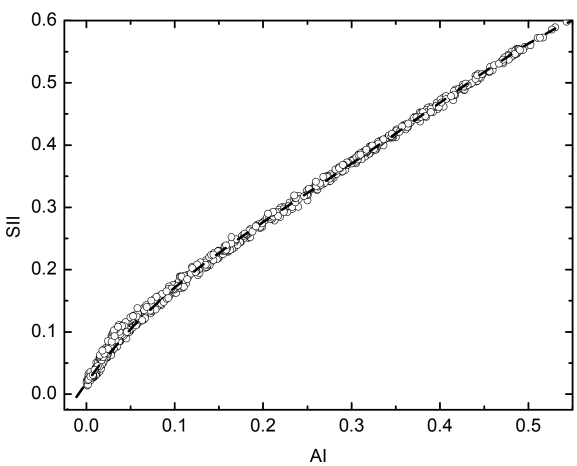

Fig. A1. Relationship between SII and AI values.

Appendix II. Data Used in the Calculations

This appendix includes the speech and noise spectra used in the calculations of this report. Figure A2 plots the speech source level spectra used. ‘Normal’ corresponds to the ‘normal’ speech source spectrum in the SII standard [6]. IOSL is the intermediate office speech level spectrum created in this work as approximately 1 standard deviation greater than the average speech levels found in open plan offices. ‘Casual’ is the mean of the average speech levels found in open plan offices [10] and Pearson’s very similar ‘casual’ speech source spectrum [11].

Figure A3 plots the Optimum masking spectrum and the Maximum masking spectrum that were used in the calculations of the current work.

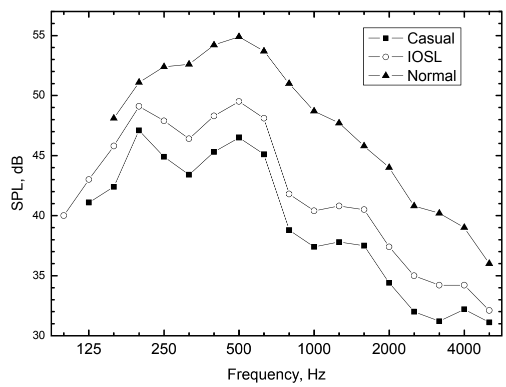

Fig. A2. Speech source spectra used in calculations

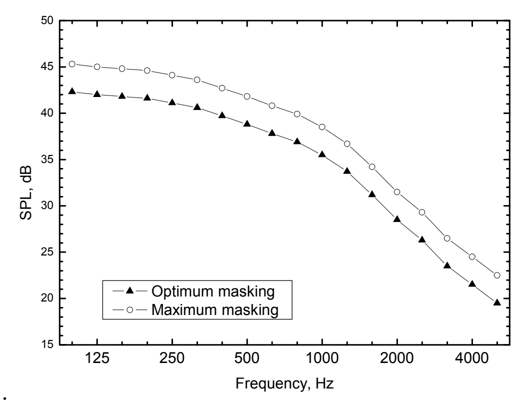

Fig. A3. Masking noise spectra used in calculations.