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SOUND MASKING SYSTEM DESIGN AND SPEECH PRIVACY

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1 INTRODUCTION

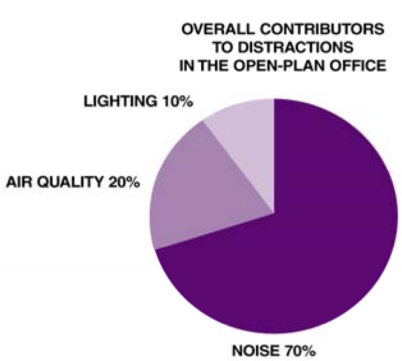
Speech intelligibility and speech privacy are two related acoustic issues that must be considered in the design of architectural spaces such as offices and healthcare facilities. Whereas it is generally obvious that individuals must be able to effectively communicate within an office space, it is equally important (although not as obvious) that those conversations be held either confidential from others, or at the very least that they not serve as a distraction (annoyance) to others. Proper acoustical design requires that both the architectural performance of the space (intruding Signal), and the background masking (Noise) in the space be controlled since speech intelligibility/privacy are based on the S/N ratio.

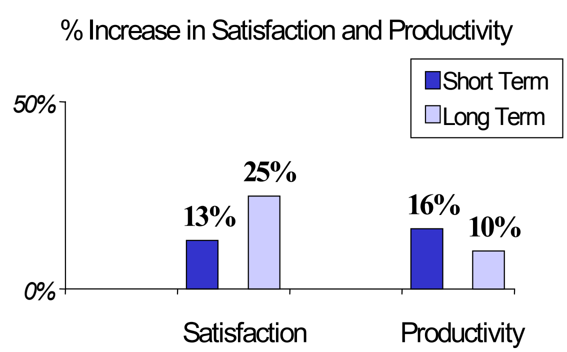
The purpose of this paper is to address the issues of 1) consequence of acoustic design for speech privacy on occupant productivity, 2) integrated design principles for speech privacy, 3) design principles for electronic masking sound systems, 4) field tests results for both traditional and ceiling plane masking systems, 5) masking design and tuning tools for electronic masking systems.

2 OCCUPANT PRODUCTIVITY

2.1 Field Evaluations of Knowledge Worker Performance

The Center for the Built Environment (CBE) at the University of California @ Berkeley has conducted numerous post occupancy evaluations of building interior environments for office buildings over the last 2-3 years. These surveys have consistently found that the acoustical environment is the quality attribute most lacking and thus the primary cause of dissatisfaction among factors including air temperature, air quality, lighting, furniture systems, etc. Another recent study (Armstrong W.I.) of 6 corporate open office spaces found the occupant dissatisfaction with the indoor environment to break down as shown below to the left:

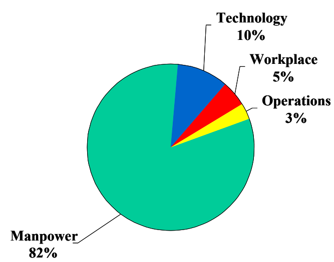




And exactly how much more productive will our "knowledge worker" be, if provided with a satisfactory and effective acoustic workspace? For the time being, we have to depend on the occupant "self-perception" of productivity. In the Armstrong study, both the satisfaction and productivity were found to increase both short term (after 2 weeks) and long term (more than 3 months) after remedial action was taken to improve the acoustic environment in each space as shown above to the right:

This change in "perceived" productivity is very important in light of the cost of doing business as found by Brill/Bosti et.al in 2001 wherein the cost associated with the workforce is over 80% of the cost of doing business as shown below:

Cost of doing business (10 yr average)



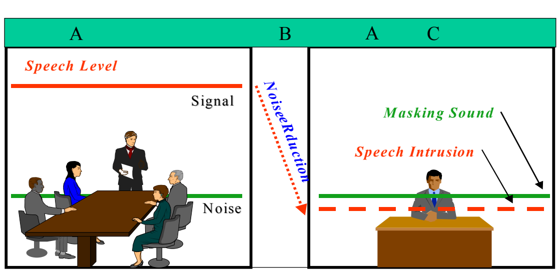
As an example of the leverage that exists between manpower cost savings, and building first cost, consider the following. If it were possible by good acoustical design to increase office worker productivity by just 5%, then this would translate into cost savings of [5% productivity increase X 83% manpower cost = .05 X 83% =] 4.15%.

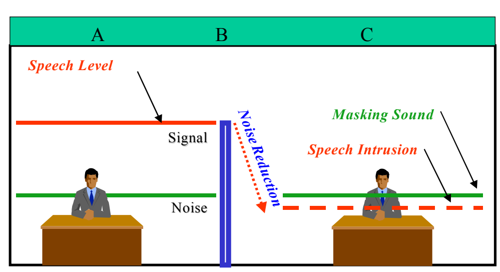
This saving is essentially equal to the first cost contribution to the overall cost of doing business, which is approximately 5% as shown above (building, owner occupied or rental). In other words, a good design makes for a good "office tool", which has a payback that should be applied to the first cost of the building as an investment in worker productivity.

3 INTEGRATED OFFICE DESIGN PRINCIPLES

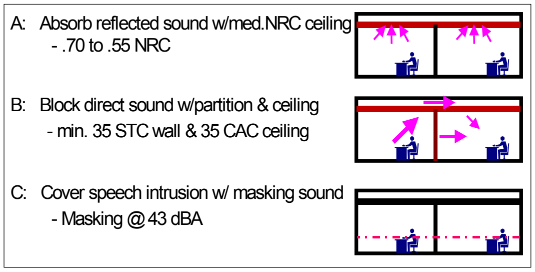
5.1 Design Practice for Closed and Open Plan Offices

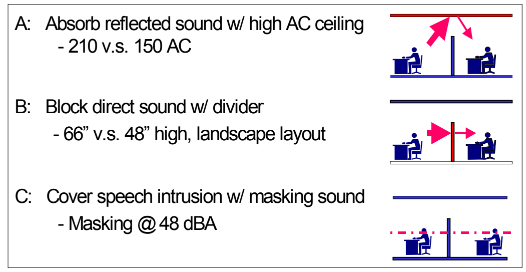
Solutions to voice related sound intrusion between adjacent offices are fairly straight forward as shown below, where we want a positive signal/noise ratio (speech louder than noise) within an office to support communication, but a negative ratio (noise louder than intruding speech) between offices to reduce distractions. And, there are two aspects to the speech privacy issue; 1) speech privacy from the point of view of the "talker" who wishes or needs to have confidentiality (i.e. Legal, HR and management), and 2) speech privacy from the point of view of the "listener" who wants to work free of distractions, both of which affect productivity.





The acoustical design of office spaces to accommodate good speech privacy is not all that difficult, as a matter of fact it is as simple as A-B-C as shown below:





<u>Talker Voice Level</u>

Speech privacy design for closed offices is generally based on "normal voice" levels of speech, but the use of speakerphones or raised voices should also be evaluated since that is often part of the reason that these occupants have a closed office. For open plan offices a normal voice level is always assumed.

<u>Listener Speech Privacy Level</u>

The intended level of speech privacy is generally considered to be confidential privacy for "knowledge workers", for HR and for management in the closed office. For knowledge workers in open plan offices, normal or non-intrusive privacy is always assumed.

<u>Architectural Path</u>

The design factors used to implement the A, B, C rule are listed below:

A - Closed Office Ceiling/Room Performance – NRC, room size

Two ceiling/room factors are important relative to the random sound reflections off the ceiling within both closed offices. First is the random incidence sound absorption of the ceiling tile, and the measure of ceiling tile performance to consider for closed plan offices is the Noise Reduction Coefficient (NRC) rating of the tile. The difference between a hard ceiling such as drywall and a medium performance acoustical ceiling such as mineral fiberboard is approximately .60 NRC points, or 5-6 dB of performance in each room. This means that a medium performance ceiling will reduce the reflected sound within the room significantly. Secondly, large rooms will have lower reflected sound levels than small rooms since the sound has to spread over a larger volume.

A – Open Office Ceiling Performance – AC, ceiling height

Two ceiling factors are important relative to the specular sound reflection off the ceiling between the adjacent open office cubicles. First is the sound absorption of the ceiling tile, and the measure of ceiling tile performance to consider for open plan cubicles is the Articulation Class (AC) rating of the tile. The difference between a hard ceiling such as drywall and a high performance acoustical ceiling such as foil-backed fiberglass is approximately 100 AC points, or 10 dB of performance. This means that a high performance ceiling will reduce the ceiling reflection to about ½ as loud. Secondly, high ceiling heights are preferred since the ceiling reflection is reduced in level as a function of height, particularly for lower performance ceilings.

B - Closed Office Dividing Partition/Ceiling – STC, CAC

There are 3 factors of importance relative to the blocking of reverberant sound between the adjacent closed offices. First is the size of the partition, the larger the adjoining wall, the greater the sound that transmits into the listener room. Secondly, the partition is only effective if the sound does not go through the body of the partition itself, such that the Sound Transmission Class (STC) rating of minimum STC 35 is necessary to block sound. Thirdly, the sound can alternately transmit through the ceiling in the talker room, across the ceiling plenum (assumes wall is only ceiling height), and through the ceiling in the listener office. This measure of ceiling tile performance is the Ceiling Attenuation Class rating, and a minimum CAC 35 is necessary to adequately block sound transmission.

The concept of "balance design" tells us that the ceiling CAC and the wall STC should be of the same order of magnitude to result in the best value between cost and performance. In any case one should not exceed the performance of the other by more than 10 dB, at which point there is diminishing returns in performance for the increased investment.

B – Open Office Cubicle Sound Divider – Height, STC, office size & layout

There are 3 factors of importance relative to the blocking of direct sound between the adjacent open office cubicles. First is the divider height, and the higher the divider the better, except for dividers less than 48" which all perform the same acoustically (as though they are not there at all). This is because an average seated person has a voice and ear height of 48", such that the sound will have a direct path to the ear if the divider is 48" or less in height. Secondly, the divider height is only effective if the sound does not go through the body of the divider itself, such that tall dividers should have a Sound Transmission Class (STC) rating of approximately STC 24 to block sound. Thirdly, the larger the office, the greater the distance between occupants and the more the intruding sound level will be reduced due to distance. Again the furniture layout needs to preclude any line-of-sight arrangements, meaning that the dividers must be strategically located.

C: Electronic Masking Sound

The masking sound system can be implemented to cover the residual speech intrusion between spaces and the lower the required masking sound level the better. Three factors are important relative to the use of electronic masking sound in offices. First, the masking sound level should be relatively uniform throughout the space and between spaces. Second, the frequency content of the masking sound should be tailored to provide maximum speech masking at a minimum sound level while being perceived to be acoustically bland in nature. Third, the level of the masking sound never exceed 46 dBA, preferable 44 – 42 dBA in the closed office plan, and 50 dBA, preferable 48 – 46 dBA in the open plan, otherwise it runs the risk of being perceive as a nuisance in of itself.

It is far better to select a “robust design” by the choices of ceiling and office dividers than to depend on the masking sound to provide the desired degree of speech privacy. Masking sound is the tool of last resort, and should be used in support of the architectural design, not in place of good architectural design.

4 ELECTRONIC MASKING SOUND SYSTEMS

5.1 Design Practice for Masking Sound Systems

There are five factors that need to be addressed in the design of a masking sound system as listed below:

1 Noise Source
- Analog or Digital (random, pseudo-random)
- Crest factor, bandwidth, spectral shape
- Temporal uniformity (over bandwidth)

2 Signal Distribution
- Centralized electronic center w/distributed speakers (70v, 100v)
- Distributed electronic/speaker systems (1-10 speakers)

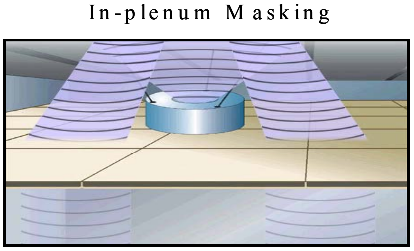
3 Loudspeaker Radiation/Sound Distribution
- Speaker radiation – hemispherical polars
- Spatial Uniformity – speaker installation (plenum, ceiling plane), speaker spacing, dBA uniformity

4 Masking Sound
- Frequency spectrum to cover voice intelligibility (200-5000 Hz)
- NC40 modified
- - 4 dB/OB
- specification defined

5 Masking System Operation/Control
- “whole space” sound masking (no user control)
- “task masking” (user controlled)

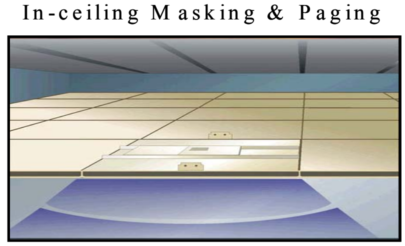
The traditional method for implementation of a masking sound system is by installation of in-plenum masking sound speakers. A new method is with the use of DML technology speakers installed as direct sound radiators located in the ceiling plane. These are depicted below:

In-plenum Masking



Standard NC40

In-ceiling Masking & Paging



New – 4 dB slope

Performance of the traditional system is highly dependent on the consistency of the ceiling plane, including type of tile, presence of air return diffusers and lights, and any obstructions within the plenum itself such as air ducts, and I-beams. The performance of the new system is dependent only on the uniformity of the speaker polars over the speech frequency range, and the speaker spacing.

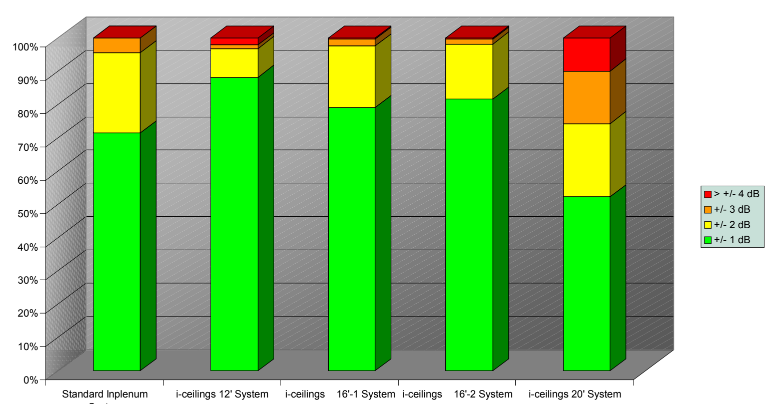
5 MASKING SOUND SYSTEM FIELD TESTS

5.1 Comparison of Traditional vs. New System Design – Spatial Uniformity

Successive tests were performed in the same building space 1st with a traditional in-plenum system installed with speakers located on a 14 ft spacing in a diamond pattern, and 2nd with the DML speakers installed in the ceiling plane at 12 ft, 16 ft, and 20 ft spacing in a square pattern. The office space is furnished as an open plan layout with 8 ft x 10 ft cubicles using 71 inch height sound dividers, and the space was approximately 30 ft x 100 ft x 9-1/2 ft height.

The spatial uniformity was measured in dBA by placing a microphone at ear height (seated, 4 ft) on a 2 ft x 2 ft grid wherever there was no furniture interference, throughout the entire office space. The measured values were compared to the spatial mean value of the masking sound level. With the in-plenum system there seemed to be some deficiencies due to either improper speaker set-up or to some architectural details. Since this was not rectified during this test evaluation, those measurement points only, were neglected in the following analysis for the traditional system. The DML speaker did not show this problem as the system seemed to perform relatively uniformly over the entire space, thus all data points were used. However, there is some caution about this with the 20 ft space as the same deficiencies may be starting to emerge .
The cumulative distribution of the spatial uniformity are presented in the following chart where the dBA level variations from the spatial average are given by the following breakdown:

Red	= More than 4 dB
Orange	= between 2 & 3 dB
Yellow	= between 1& 2 dB
Green	= within 1 dB of ave



These results indicate that the standard in-plenum system [14 ft spacing, diagonal pattern, 2 channel] has approximately 68% of dBA values within +/- 1 dB, and 93% within +/- 2 dB. This was verified by the occupants to be a “good” masking sound application. These results also indicate that the new DML direct radiator system performed better than the traditional system for both 12 ft and 16 ft spacing, square pattern, 1 or 2 channel.

DML 12 ft spacing, 2 channel: 84% within +/- 1 dB, 96% within +/- 2 dB
DML 16 ft spacing, 1 channel: 75% within +/- 1 dB, 96% within +/- 2 dB
DML 16 ft spacing, 2 channel: 79% within +/- 1 dB, 97% within +/- 2 dB

The occupants verified that the new DML system performed very well in spatial uniformity.

6 Comparison of Traditional vs. New System Design – Privacy Index

The Privacy Index PI is defined according to the following:

- Confidential Privacy - PI range 100% - 95%
  - speech can be detected but not understood … only muffled sounds
  - expected privacy level for management, HR, legal, etc.
  - usually requires closed offices

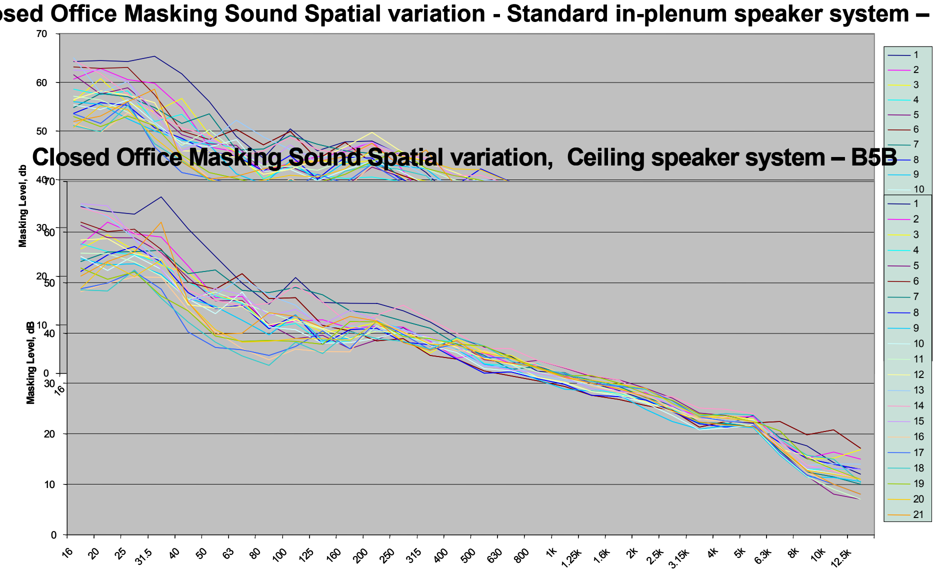
- Normal (non intrusive) Privacy - PI range 95% - 80%
  - effort required to understand speech, and generally not distracting
  - expected privacy level for professionals, most knowledge workers
  - usually attainable in open plan layouts

- Marginal/Poor - PI range 80% - 60%
  - speech is mostly understood and distracting
  - expected privacy level for clerical workers

The Privacy Index was calculated from measurements made in 21 closed plan offices and 28 open plan offices similar to the office space previously measured in section 5.1 above. The PI is calculated from the Articulation Index (AI, ANSI standard S3.5 (1969)), by the expression PI = (1-AI)*100%. The AI is calculated from measurements made of the Noise Reduction between 2 adjacent office areas, and the background (masking) sound level measured in the listener office space.

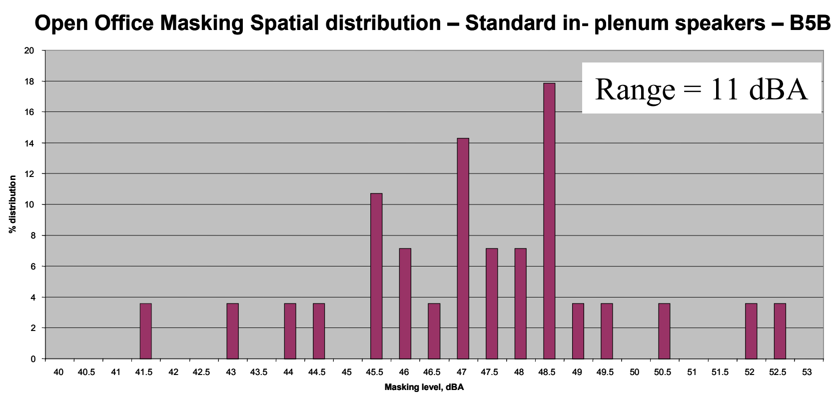
The measured masking sound spectra in each of the closed offices, for both Traditional and New masking systems are presented below:

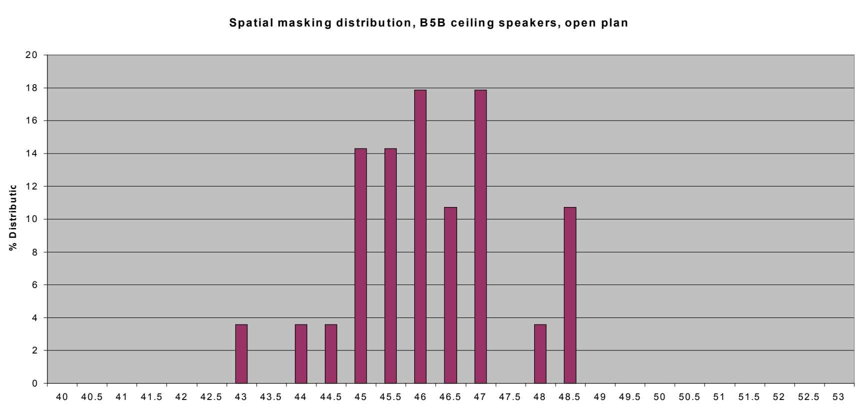
Closed Office Masking Sound Spatial variation - Standard in-plenum speaker system – B5B



Obviously, the spatial variation of the masking spectra is much greater for the traditional in-plenum masking system than for the new ceiling speaker masking system. These spectra represent a dBA variation of 40 –48 dBA for the traditional closed office masking sound, which means that some offices are twice as loud as others, hence some have better speech privacy than others and/or are more annoying due to the louder masking. These spectra also represent a dBA variation of 41-45 dBA for the new closed office masking sound, which means most offices sound about the same, and also have essentially the same level of speech privacy (a good thing).

The masking spectra were likewise measured in the 28 open plan offices for both the traditional in-plenum speaker, and the new ceiling speaker masking systems. The range of dBA values are presented in the following charts. The range of dBA sound masking in the open plan with the traditional masking system is 11 dB, which means that some offices have less than acceptable speech privacy, and there is a great deal of variability in performance between spaces. In other words, there is unacceptable control of the masking sound between the various open office spaces. With the new masking system, there is significantly better control of the spatial uniformity of the masking sound, the dBA range being only ½ of that for the traditional system. This is shown in the 2 charts below:





The resulting Privacy Index for each of the open plan offices are presented in the following chart. For normal (non-intrusive) speech privacy the target PI range is 95-80%.

Obviously the PI varies much more with the traditional in-plenum masking system, and is actually unacceptable in some offices. The new direct radiator masking system has much more uniform performance in all office spaces, such that speech privacy is more-or-less the same for all.