**Keywords:**

Room Acoustics, open-plan office, task performance, speech intelligibility, speech privacy, acoustical simulation

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# Acoustics and Speech Privacy in Open-Plan Offices: A Case Study on Computer-Based Task Performance[1]

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## Abstract

The aim of this study is to find out the effects of speech and speech intelligibility on computer-based task performance in open-plan offices. The research was conducted in a real open-plan office environment to include the open-office experience of subjects to the analysis. STM Bilkent Office was selected as the case, and 40 available open-office occupants were participated to the study. The experiment consists of two main phases. In the first phase, acoustical simulation of the site was done, to derive distribution graphs for speech related room acoustics parameters. In the second phase, occupants' computer-based task performances were tested under three different sound environments, which are continuous noise, speech and masked speech. According to statistical analysis of the performance test, and the acoustical properties of the case STM, suggestions for renovation were discussed. It was found that effects of intelligible speech on occupants' task performance are only psychological, because it is significant that there is no difference between results of performance test. However, all of the occupants respond to the questionnaires that speech sound environment was the most distracting one. Proposal for renovation was given to minimize the effects of intelligible speech on occupants for preventing the long-term effects on occupants' health.

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[1] This paper is based on the master's thesis 'Effects of Speech Intelligibility on Computer-based Task Performance in Open-Plan Offices'.

**Anahtar kelimeler:**

Oda akustiği, açık planlı ofis, görev performansı, konuşmanın anlaşılabilirliği, konuşma gizliliği, akustik simülasyon

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# Açık Planlı Ofislerde Akustik ve Konuşma Gizliliği: Bilgisayar Tabanlı Görev Performansı Üzerine Bir Vaka Analizi[2]

Kıvanç KİTAPÇI*

## Öz

Bu çalışmanın amacı, anlaşılabilir konuşmanın açık ofis çalışanlarının bilgisayar tabanlı iş verimi üzerindeki etkilerini incelemektir. Araştırma, çalışanların açık ofise alışkanlık etkisini de göz önüne almak amacı ile gerçek bir ofis ortamında gerçekleştirilmiştir. STM Bilkent ofisinde gerçekleştirilen çalışmaya, bu ofisi kullanan 40 kişilik bir grup katılmıştır. Araştırma iki ana aşamadan oluşmaktadır. İlk aşamada STM Bilkent binasından seçilen açık ofis alanının yerinde akustik ölçümleri, bölücü panoların ofis alanının akustik özellikleri üzerindeki etkisini anlamak ve akustik benzetimin güvenilirliğini sağlamak amacıyla gerçekleştirilmiştir. İkinci aşamada katılımcılara konuşma, maskelenmiş konuşma ve sabit gürültü olmak üzere üç farklı ses ortamı altında bilgisayar tabanlı çalışma verimi testi uygulanmıştır. Test sonuçlarının istatistiksel çözümlemesi ve akustik ölçümlerden alınan sonuçların ışığı altında, STM açık ofis alanı için çözüm önerileri sunulmuştur. Verim testinin sonuçlarına gore, konuşmanın açık ofis çalışanları üzerindeki etkisi sadece psikolojiktir. Fakat, test sonrasında verilen anketlere gore, katılımcılar en çok rahatsız oldukları ses ortamını konuşma olarak belirtmişlerdir. İç mekandaki değişiklik önerileri, stresin çalışanlar üzerinde yaratabileceği uzun vadeli etkileri düşünülerek sunulmuştur.

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[2] Bu makale 'Konuşma Anlaşılabilirliğinin Açık Ofislerde Bilgisayar Tabanlı İş Verimine Etkisi' adlı yüksek lisans tezinden üretilmiştir.

## Introduction

Today, open-plan offices are one of the most popular office types, mostly because of organizational and economic reasons. Open-plan offices generally consist of workstations, which can be separated by screens or divider panels. Eventually, the required area per occupant decrease, leading to economical savings, and changing the layout of the space is easy to carry out. Organizations usually cover the economic reasons by emphasizing the other features of open-plan offices, for instance spaciousness, refreshing and modern architectural design, improved communication and relationships, better flow of information, greater sense of work involvement, and shorter distances to common spaces (Hongisto, 2005).

There are three key elements that affect occupant satisfaction in office environments: thermal comfort, lighting and acoustics (Wang & Bradley, 2002b). According to Venetjoki, Kaarlela-Tuomaala, Keskinen and Hongisto (2006), work performance can decrease because of various office noises. Environmental effects on work performance caused by poor acoustical conditions, poor speech privacy, and difficulties in concentration caused by unwanted speech are not taken seriously because the expected economic and organizational benefits are so evident in open-plan offices (Desarnaulds, 2007).

Coexistence of activities with various noise emission, and need for quietness or privacy in the same area heavily distracts open-plan office occupants. Dividers in an open-plan office contribute to an improved acoustical comfort and high speech privacy. Additionally, by using an absorbent ceiling, the noise between two adjacent working places can considerably be reduced and shorter reverberation times (Desarnaulds, 2007) can be obtained. Various studies investigated the relationships between open-office design, work performance, and occupant satisfaction (Hongisto, Haapakangas, Varjo, Helenius, & Koskela, 2016)(Sarwono, Larasati, Novianto, Sihar, & Utami, 2015) (Passero & Zannin, 2012). The studies revealed that the acoustical condition of open-office spaces, and consequently, the occupant satisfaction can be increased by implementing appropriate design solutions, such as layout design, workstation design, and partition design.

Salter, Powell, Begault and Alvarado (2003) supported the idea of electro-acoustical solutions for sound masking, which is placing loudspeakers in the ceiling. The masking noise in office environments is called 'white noise', and it covers all frequencies in the sound spectrum, which overrides disturbing components of office noise. It should be noted that the white noise used for masking becomes an additional sound stimulus, which increases sound pressure level of the ambient noise (Loewen, 1992), leading to less intelligible conversations.

Wang and Bradley (2002a) (2002b) conducted extended researches, to predict speech intelligibility in open-plan offices. The first study investigated single screen dividers and the second study analyzed speech privacy between two adjacent rectangular workstations. They presented a mathematical model between two adjacent workstations by using image source technique. Problem was divided into two parts: a single screen model and a side-back panel model. These models were investigated in three varying workstation orientations; however, the effects of furnishing were not taken into account. The second study of Wang and Bradley (2002b) suggested a method for predicting the speech intelligibility index behind single screen in an open-plan office. A sound source and a receiver were used for calculating speech intelligibility index (SII). The effects of wall, ceiling and floor reflections on SII were discussed. Similar to the previous study, the mathematical model suggested was not tested in physical environments.

In a more recent study, work performance in open-plan offices was investigated in relation to speech transmission index (STI), which is another speech intelligibility measure (Ebissou, Parizet, & Chevret, 2015). 57 participants were tested under 4 different STI conditions, varying between 0.25 and 0.65. The study showed that under the effects of intelligible speech (STI>0.45), work performance of half of the participants were decreased. The other half of the participants were more resilient to intelligible speech. The results revealed that the effects of intelligible speech are mostly subjective.

Jones, Miles and Page(1990) found out that irrelevant speech restricts lower level of analysis performance such as detection of contextual errors in proofreading tasks were not affected by speech; however, detecting non-contextual errors are impaired. A longitudinal field study of Brennan, Chugh and Kline (2002) revealed that the major problems stated by employees were the lack of privacy and increased noise levels. Hongisto(2005) listed various tasks of work performance such as proofreading, short-term memory, and reading comprehension. In most of those cases, subjects were affected by intelligible speech. Banbury and Berry's (1998) experiment analyzed memory and arithmetic tasks, which were called 'office-related' tasks. The results showed that the irrelevant speech reduces memory for prose and mental arithmetic task performance impressively. In the second experiment, performance reduced about one-third of the quite environment. Another sequence of five experiments were presented by Salame(1982), which were dealing with phonological similarity effects of irrelevant speech on short-term memory of visually represented digits. However, there was no evidence of testing various task performances in real open-plan office environments that all of the participants are experienced and familiar with the environment.

Hongisto (2005) developed a model using the results of the existing literature for predicting the effect of speech on work performance. The model predicted that, the complex task performance could be reduced by 7% when the STI was higher than 0.60, but direct speech did not affect work performance when STI is below 0.2. Three factors should be considered according to Hongisto's predicting model: high room absorption, high screens, and appropriate speech masking. Same rules are used for avoiding noisy activities and achieve speech privacy in open-plan offices. More recently, a model to predict speech decay in open-office environment was suggested (Keränen & Hongisto, 2013). The regression model uses ceiling absorption, furnishing absorption, screen height, masking sound level, speech effort and room dimensions, measured in 16 different open-plan offices, in order to predict speech decay curves. The model than converted into a free software, which can be used as an open-office design tool.

As Hongisto (2005) stated, both in open-plan offices and in conventional offices, designers should aim at lower speech intelligibility levels to improve work performance. Additionally, due to psychological reasons such as 'privacy', design of the open-office layouts gains great importance. Open-plan office occupants have a potential to initiate and maintain private conversations and chat between workstations. Salter, Powell, Begault and Alvarado (2003) stated that the streets in between open office cubicles become a natural conversation area. Additionally, a recent study investigated the effects of irrelevant speech on mental workloads in open-plan offices (Smith-Jackson & Klein, 2009). It was stated that the perceived privacy created by partitions dividing the cubicles, irrelevant speech still increases mental workloads, eventually decreasing overall work performance. Furthermore, Kim and Dear investigated the issues of privacy and proxemics in relation to communication needs. The results point out that occupants prefer private offices to open-office layout in various aspects of indoor environmental quality. Therefore, it can be stated that both spatial and acoustical requirements have to be considered in the design process, in order to protect the open-plan office occupants from impaired short-term task performance and long-term health problems. The spatial requirements also provide room acoustics parameters to match the ideal levels of acoustic comfort.

The aim of the study is to understand the effects of speech and speech intelligibility on computer based task performance in open-plan offices and to examine the work performance of open-office workers under variable room acoustic conditions (i.e. speech, masked speech, and continuous noise) It is expected that the results will reveal ideal acoustical conditions of an open-plan office in terms of speech and speech intelligibility. Additionally, current acoustical situation of the site STM Bilkent Headquarters is analyzed and possible solutions are discussed under the guidance of the computer simulations and the task performance test results.

## Methodology

In this section, the methodology used in the study is presented. The case study consists of two main phases; the computer simulation of the site, and the computer-based task performance test. In the first phase of the study, the room acoustics parameters of the selected open-plan office area (i.e. reverberation time ($T_{30}$), clarity ($C_{80}$), definition ($D_{50}$) and Speech Transmission Index (STI)) were analyzed. The aim of the computer simulations was plotting the distribution graphs of the room acoustics parameters mentioned above.

The computer-based task performance test evaluates the open-plan office occupants under three sound environments by using both subjective and objective methods, to understand the effects of speech and speech intelligibility on computer based task performance. Results of the three phases are used to propose a better acoustical design for the STM Bilkent Office, in order to improve the performance of the open-plan office occupants, and to improve the quality of the work environment.

**Test Site**

STM Bilkent University Cyberpark building consists of three floors; ground floor, first floor and second floor. The entrance and lobby areas, security, meeting room, human relations office, dining area and one large open-office area is located on the ground floor, which has a L-Shaped plan. The long arm of the L-Shape leads to technical offices and the dining area. In addition, an unsecured entrance is located on the ground floor, which is used for service purposes. First and second floors are identical, consisting of three small and one large open-plan office areas and administrative offices. The circulation areas are located around the atrium defined by the central staircase in a rectangular form, leading to office entrances. The first and second floors are different from the ground floor by their rectangular floor plan.

The building has a total of nine open-plan offices, which has varying occupant capacities of four to forty office personnel. The software development department uses the largest two offices, which are located on the ground floor and the first floor. The one on the ground floor level has a capacity of forty-five software developers. It also has a separate private office that is located near of the entrance of the open-office area for the administrative personnel. The dividers used in the open-plan office area are 167cm in height and allow visual and acoustical contact while standing at any point of the office. The other open-plan office is located on the first floor, and has thirty-two personnel capacity. The space dividers used in that open-plan office has a height of 190cm that does not allow any visual contact while standing in the open-office area.

For the present study, the open-plan office on the ground floor was selected. The first reason for selecting this office is the larger personnel capacity. Although the experiment was not applied to the residents of that office solely, the open-office capacity has a major effect on the background noise levels. The second reason is the type of dividers used. Openness is the key element of an open-plan office area, and the ground floor open-plan office has a better visual contact compared to the open-plan office on the first floor.

## Acoustical Simulation of the Site

The room acoustics simulations of the site were carried out by using Odeon 8.5 Room Acoustics Software. The software uses prediction algorithms (image-source method combined with ray tracing) to simulate the interior acoustics of buildings. Odeon is mainly used for analyzing room acoustics parameters and for evaluating and recommending solutions for large rooms such as concert halls, opera halls, auditoria, foyers, underground stations, airport terminals, and industrial workrooms (Brüel & Kjaer, 2007).

The initial step of the computer simulation was modeling the geometry of the space in AutoCAD 2007 Software by using face modeling technique. After modeling the space, the 3D model was imported to Odeon 8.5 Room Acoustics Software. The next step was defining source types and positions. A point source was defined by defining the directivity pattern, gain, equalization and delay, eventually allowing the software to simulate a natural sound source or a loudspeaker system. Additionally, the receiver type and position were defined as a surface receiver. The surface receiver was divided into grids of 0.50 m. to perceive detailed distribution graphs of variable room acoustics parameters for the site simulated.

Attention was given to select and assign the surface materials from Odeon's in-built material library that reflects the current finishing materials in the test site. The materials were assigned to surfaces that are already layered accordingly in the AutoCAD software.

Last step was the calculation of the results. Two methods are available in Odeon software. The Global Estimate based on ray tracing, which is taking room shape, source position, and the position of absorbing materials into account. It uses an infinite number of points to simulate reverberation decay in the model. The other method, Quick Estimate is based on statistical formulae. For evaluation of STM open-plan office, the results of quick estimation and global estimation were compared to obtain the results of different acoustical parameters and their distribution throughout the office.

## Computer-Based Task Performance Test

The aim of the computer-based task performance test was to analyze the basic information processing abilities of the open-office occupants under three sound environments; 'speech', 'masked speech' and 'continuous noise'. The difference between the results of three sound environments will reveal the relationship between the intelligible speech and the work performance of open-plan office occupants.

The experiment was composed of two questionnaires and a computer based task performance test. Each subject was required to answer two questionnaires, one before and one after the task performance test. The test was repeated three times (speech, masked speech and continuous noise sound environments) for each subject. Prior to the experiment, each subject attended an introductory session on the task performance test. The subjects are allowed to practice the test to familiarize with the experimental procedure.

The first questionnaire consisted of three questions to evaluate subjects' basic physical conditions (i.e. sleep deprivation; basic physical problems, and hunger). The subjects were asked to mark a number on a five-point scale. The second questionnaire investigates the participants' self-evaluation of their performance during the task performance test.

**Sound Environments**

Three sound environments were used for the experiment. Every subject was exposed to three sound environments in the sequence of 'continuous noise' environment, 'masked speech' environment and 'speech' environment. To achieve more realistic results, both realistic office noises and white noise was mixed with the speech sample. Equivalent sound pressure level of the final sound signal was 60 dB(A).

Audacity 1.2.6 free software was used for mixing audio samples. Samples used for 'continues noise' composition were derived from both live recordings via Shure Beta 58A microphone connected to Apple iMac G5 personal computer via M-Audio Audiophile soundcard, and office-related sound samples found on the internet. Final compositions were ten minutes long, which was enough for very long test sessions. An average person completes the test between forty seconds, and one and a half minute. Normalization was not applied to final recording, because of the risk of distracting the high and low frequencies. The context of the speech sample used for the 'speech' environment was health issues. The male sound was calm and stable; therefore, there were no distracting variations in the speech sample. Subjects listened to the final sound environment mixes through the headphones in the real open-plan office environment, to benefit from other environmental parameters such as thermal conditions and lighting as it is in STM Bilkent Headquarters open-plan office area.

The first sound environment was the 'continuous noise' environment. This sample was composed by mixing recorded office sounds (i.e. computer typing sounds, chair sounds, footsteps, and white noise). Speech cannot be heard at this sound environment because the speech to noise ratio was -23dB, which lead to STI=0.00 (Venetjoki, Kaarlela-Tuomaala, Keskinen, & Hongisto, 2006).

The second sound environment was the 'masked speech' environment. It was composed by digitally mixing the 'continuous noise' sound sample and a ten-minute speech sample derived from a Turkish TV news program. The equivalent sound pressure level of the speech sample was

40 dB(A), and it was mixed with the 'continuous noise' sound sample. The sound level difference between the samples was -8 dB(A), which lead to STI=0.30, simulating adjacent workstations in an open-plan office. Although the speech could be heard, the context of the speech could not be understood clearly.

The third and last sound environment was the 'speech' sound environment. The same 'continuous noise' sample was mixed with the same 'speech' sample; however, this time the sound pressure level difference between the two sound samples were +13 dB(A) (STI=0.80), which corresponds to open-plan offices with no acoustic design.

**Software**

Computer-based task performance test was an arithmetic test, which determines both accuracy and reaction time of the subjects. An arithmetic problem and a target number were presented to the subjects on a computer screen. The arithmetic problems were always comprised of two single-digit numbers bound by an arithmetic symbol (+ or –). Subjects were asked to;

- Press the right arrow key on their keyboard as quickly as possible, if the answer to the arithmetic problem is greater than the target,
- Press the left arrow key on their keyboard as quickly as possible, if the answer to the arithmetic problem is less than the target,
- Press the left and right arrow keys on their keyboard simultaneously as quickly as possible, if the answer to the arithmetic problem equals the target,
- Press the left arrow key if the answer is greater than the target and press the left arrow key if the answer is less than the target, when the word 'Reversal' appears.

Two parameters were recorded after each test. The first parameter was 'accuracy', and the second parameter was 'reaction time'. After the session was completed, every subject's gender and age information were recorded.

**Participants**

The sample group consisted of a total of 40 full-time engineers of STM Bilkent Cyberpark. The building accommodates administrative, technical and software departments. However, total number of personnel working in that building is 110, circulation between STM headquarters, SSM (Civil Defense Undersecretaries) and STM Bilkent University Cyberpark decrease the number of available software developer personnel. For the experiment, 40 available software developers participated to the computer-based task performance test. All of the participants work in open-plan offices, so they are all familiar to the work environment selected for the experiment.

## Results

In this section, results of the computer simulation of the site, and the computer-based task performance test results are presented.

### Computer Simulation

Acoustical simulation of the site was analyzed by investigating distribution graphs of reverberation time ($T_{30}$), clarity ($C_{80}$), definition ($D_{50}$) and speech transmission index (STI). Frequencies in the range of speech spectrum, which are 500 Hz, 1000 Hz, and 2000 Hz were evaluated. The basic information on each room acoustics parameter is given under the relevant section.

### Reverberation Time ($T_{30}$)

General scientific description of reverberation time is the time is required for sound energy to decay 60 dB after the sound source stopped. Today, reverberation time is the major acoustical parameter that defines acoustical characteristics of a room, and it is usually constant throughout the space (Barron, 1993).

Reverberation time ($T_{30}$) requirement for offices is generally known as below 0.5 seconds, but in open-plan offices, there need to be a sufficient level of reverberation time to decrease intelligibility of speech. This ideal $T_{30}$ is based on the level of background noise and masking system in the open-plan office area. Offices with natural or electro-acoustical background noise require shorter reverberation times to achieve speech privacy; however, offices with lower background noise levels require longer reverberation times.

The quick estimate and global estimate results were analyzed to find out the $T_{30}$ values at the open-plan office volume. The differences between the quick and global estimate results showed the effects of geometry and volume of the office area. Eyring results are 0.61 s at 500 Hz, 0.63 s at 1000 Hz and 0.70 s at 2000 Hz. The global estimate calculations with grid responses were 0.67 s at 500 Hz, 0.83 s at 1000 Hz and 1.03 s at 2000 Hz. When compared to the quick estimate results, global estimate $T_{30}$ values were slightly higher at 500 Hz and 1000 Hz, and showed a greater difference at 2000 Hz. In order to achieve good acoustical conditions, both the global $T_{30}$ values and its distribution is important, which needs to be balanced throughout the environment. In the current study, the distribution graphs plotted from Odeon (Figure 1, 2, 3) revealed that especially at the corner points of the open-plan office, there were multiple focal points of higher reverberation times up to 2.40 s.

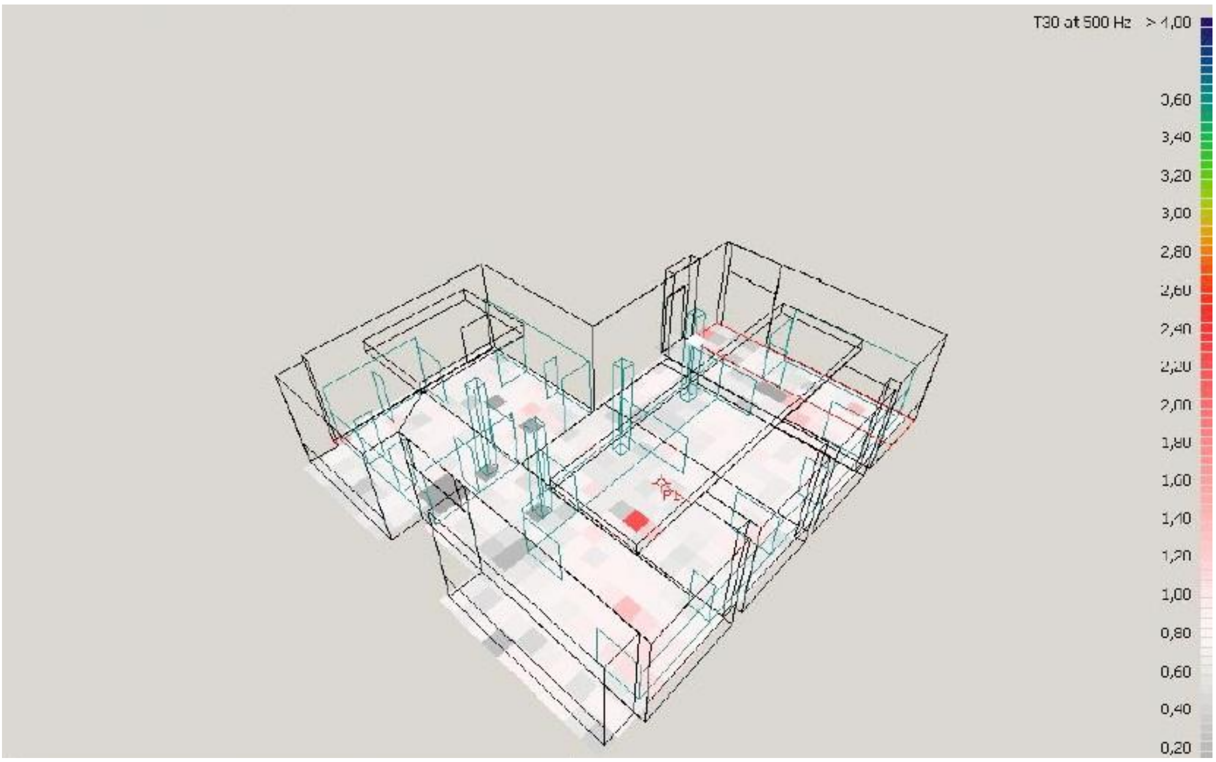


**Figure 1** T30 distribution graph at 500 Hz.

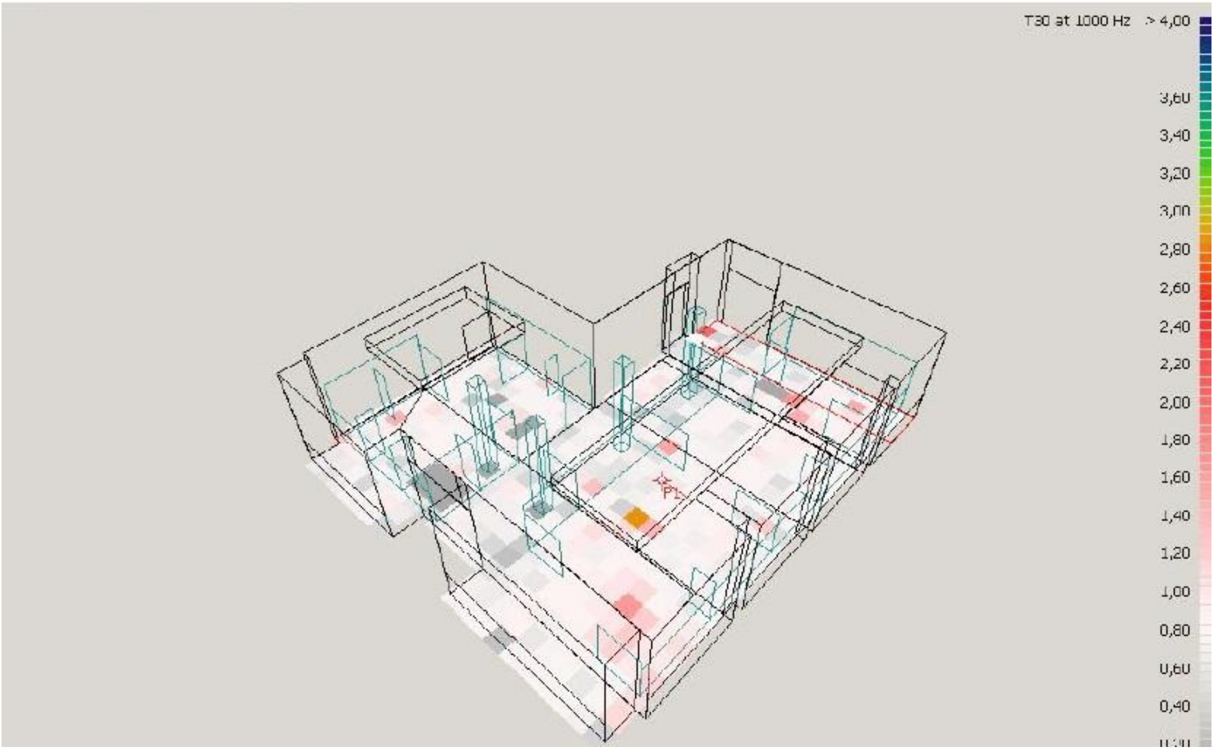


**Figure 2** T30 distribution graph at 1000 Hz.

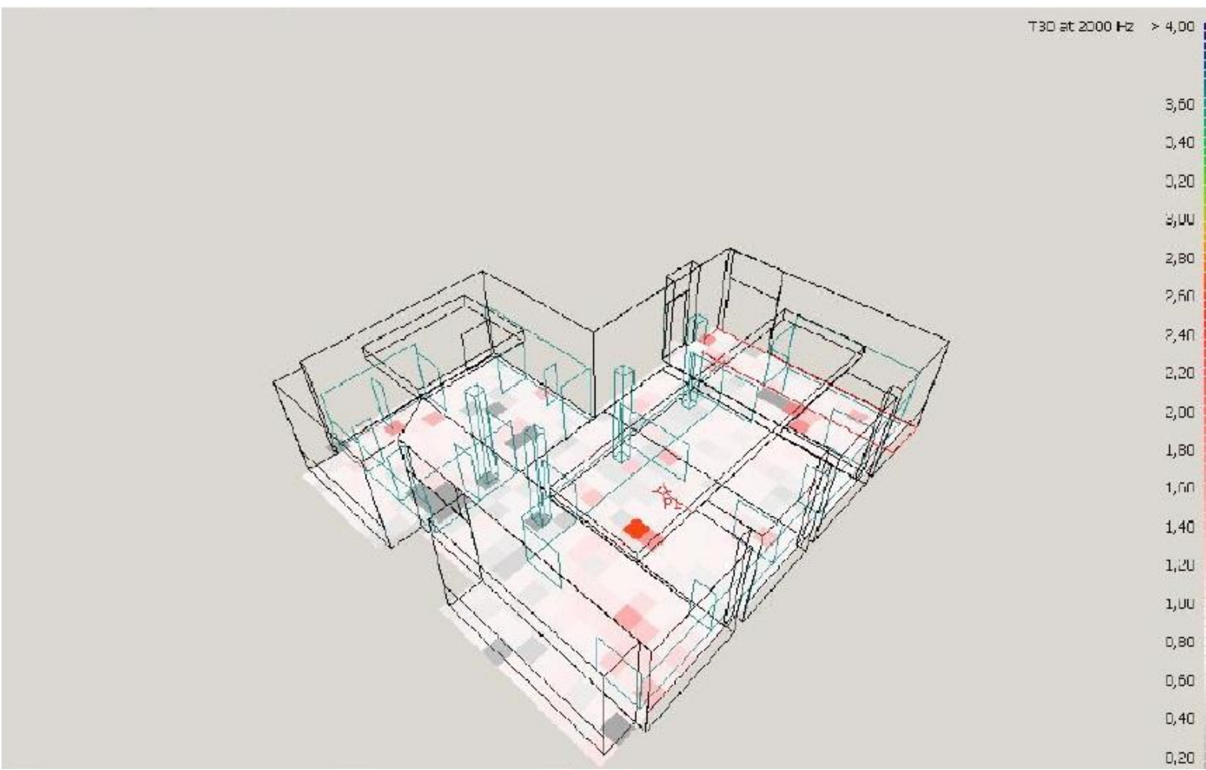


**Figure 3** T30 distribution graph at 2000 Hz.

**Clarity ($C_{80}$)**

The second room acoustics parameter that is related with speech privacy is the clarity of the sound in a field. Clarity is defined as the ratio of early sound energy to late or reverberant sound energy. Early-arriving reflected sound energy is the main parameter that defines clarity of sound in an enclosure. Early sound is usually defined as the direct and reflected sound arriving within the first 80 ms (Egan, 1988). The early arriving sound energy contributes to the clarity and definition, while the late reverberant part provides an acoustic context against which the early sound is heard. To evaluate the clarity of music, the relevant time interval is 80 ms, and 50 ms for speech. To achieve a more blurred speech and to decrease the intelligibility of speech, $C_{80}$ needs to be as low as possible.

Evaluating the clarity distribution maps for low, mid and high frequencies (Fig. 4, Fig. 5, and Figure 6), it was revealed that the divider panels decrease the clarity of the sound significantly. The average clarity values are 0.7 dB at 500 Hz, 0.5 dB at 1000 Hz and 0.2 Hz at 2000 Hz, as a consequence of higher ceiling and wall reflections at such frequencies. The clarity distribution graphs show the effects of the divider panels, as well (Fig. 4, Fig. 5, and Figure 6). The areas close to the sound source had higher clarity values of 8.5 dB - 12.5 dB; however, the backside of the divider panels' clarity values decrease to the ranged between -1.5 dB and 2.5 dB. There were three focal points shown on clarity distribution graphs at mid frequencies, resulting at 16.5 dB.

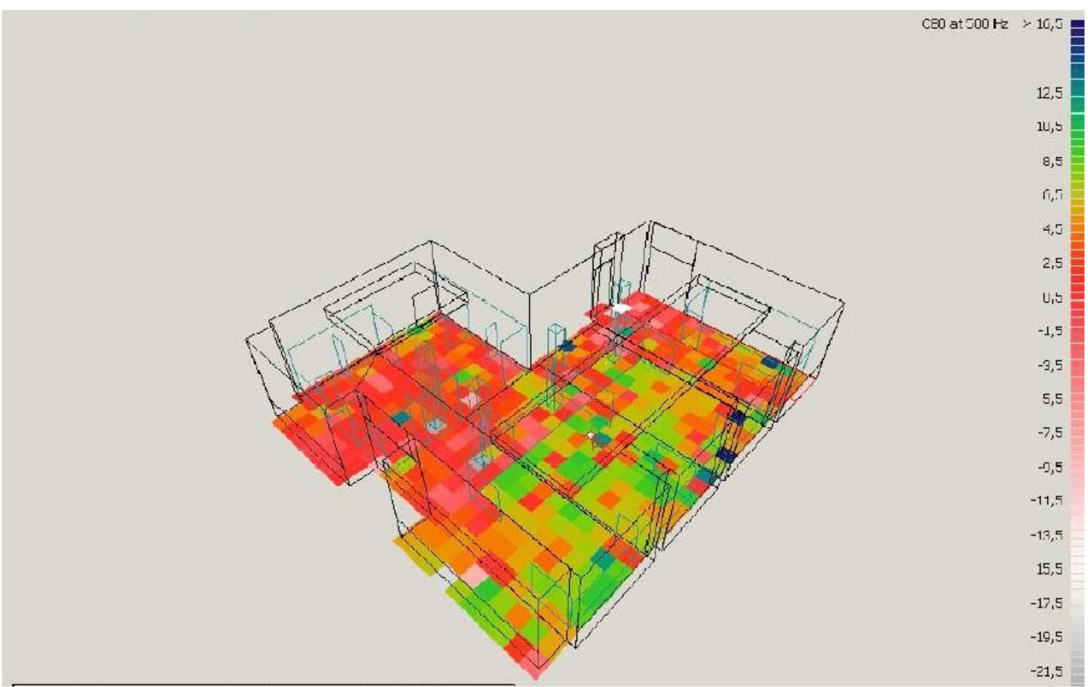


**Figure 4** C80 distribution graph at 500 Hz.

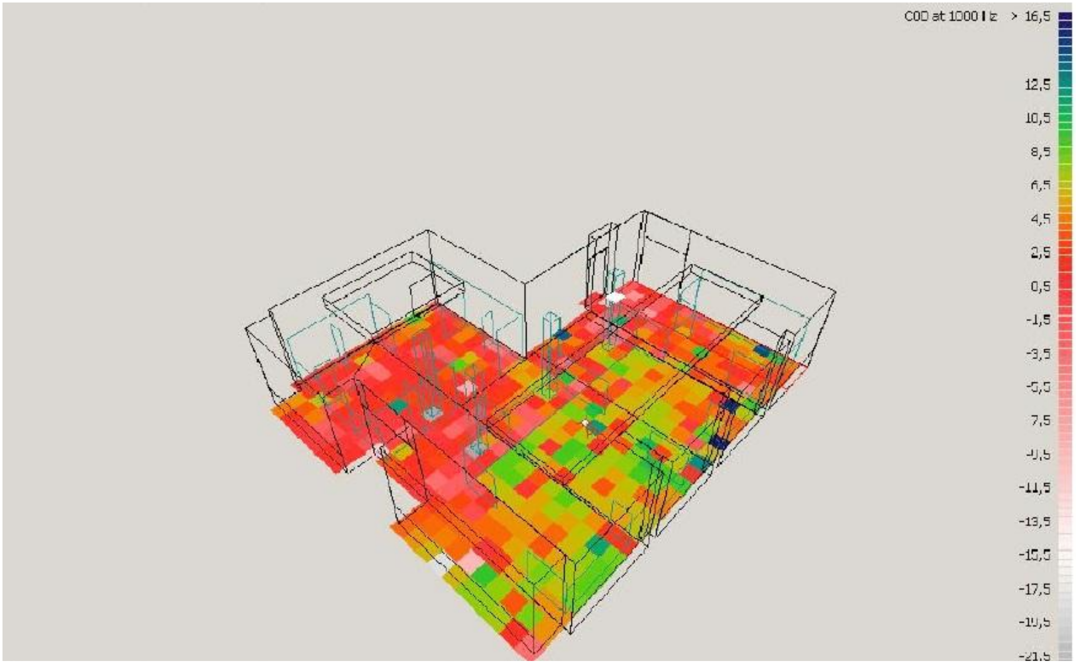


**Figure 5** C80 distribution graph at 1000 Hz.

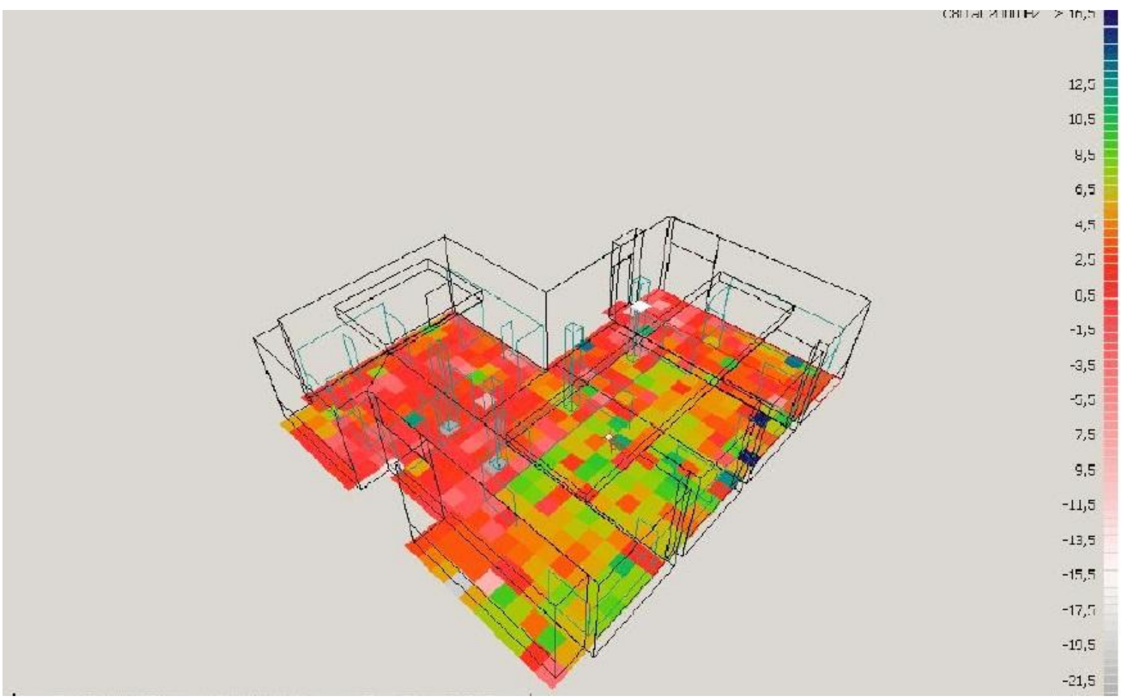


**Figure 6** C80 distribution graph at 2000 Hz.

**Definition ($D_{50}$)**

Definition is the ratio of the effective energy to the total energy in an impulse response. The effective energy contains both the direct sound energy and the reflected sound energy with respect to the direct sound by up to 50 ms (Egan, 1988).

Early arriving sound energy should be high enough to achieve good acoustical conditions for speech[21]. The ideal value of definition at halls for speech is higher than 0.15; however, in open-plan offices, the aim should be achieving unintelligible speech. Therefore, a lower value of definition is required to create better speech privacy in open-plan office environments.

The definition distribution graphs (Fig. 7, Fig. 8, and Fig. 9) showed that average $D_{50}$ values were 0.43 at 500 Hz, 0.40 at 1000 Hz and 0.38 at 2000 Hz. Distribution of the parameter was not homogeneous in the area because of varying sound energy levels across the volume. The areas closer to the sound source had higher $D_{50}$ levels ranged from 0.75 to 0.80. The back of the divider panels that were away from the sound source had a larger spectrum of $D_{50}$ ranging from 0.01 to 0.70. Lower $D_{50}$ levels cause poor speech intelligibility; therefore, the distribution graphs showed that the divider panels were working effectively at low frequencies. At high frequencies (i.e. 2000 Hz and 4000 Hz), $D_{50}$ values decreases at closer points to the sound source, as well. As it was seen in the definition distribution graphs, far corners of the open-plan office area were lack of total sound energy, and showed very low sound definition properties.

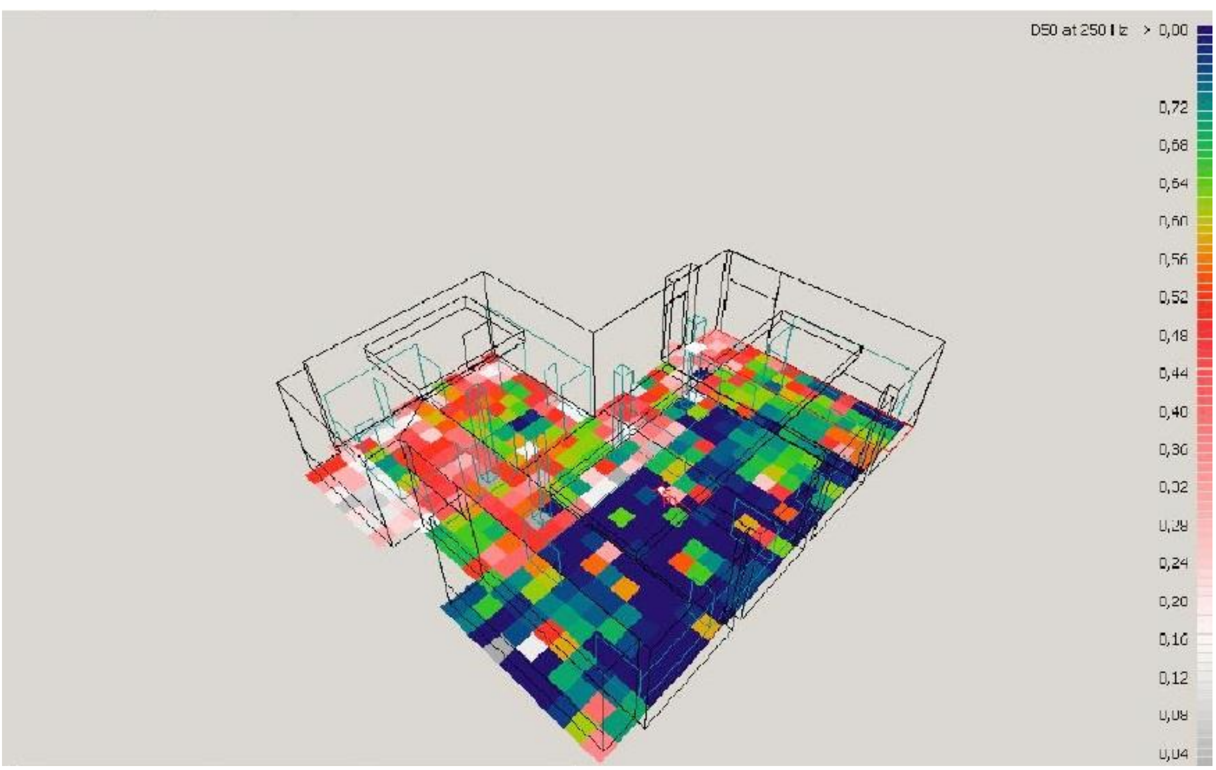


**Figure 7** D50 distribution graph at 500 Hz.

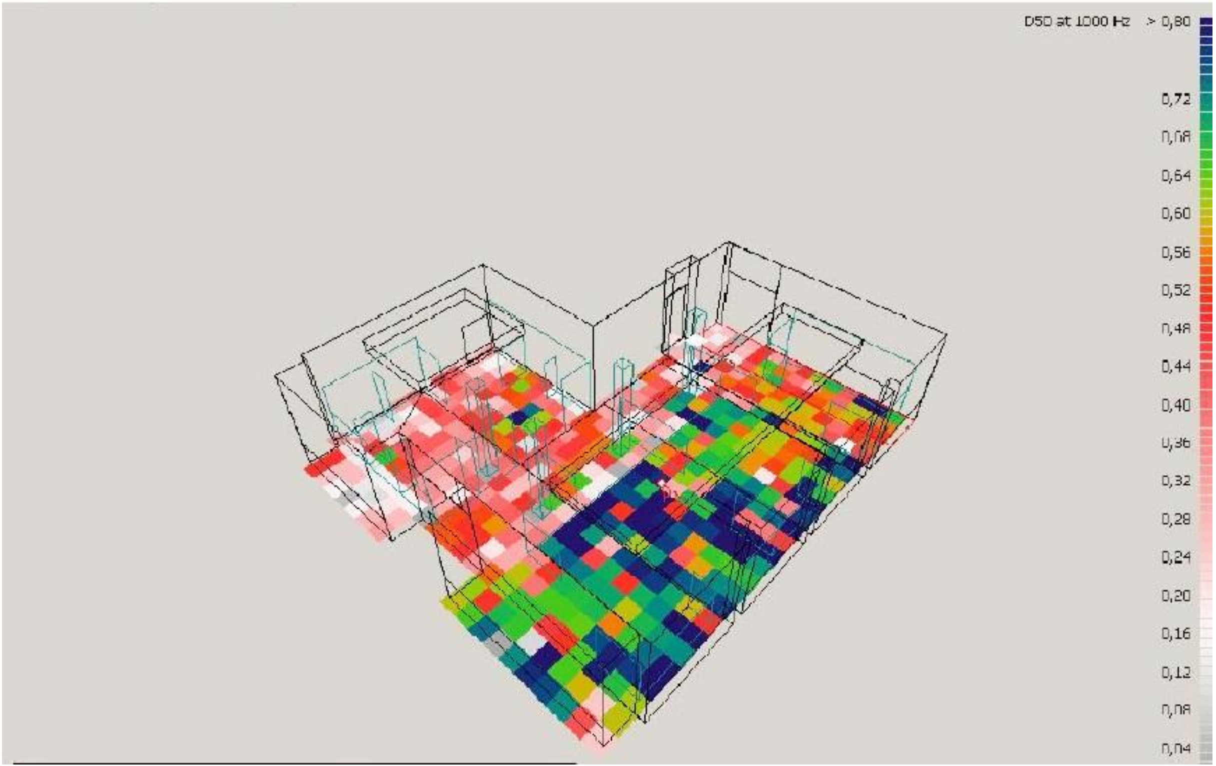


**Figure 8** D50 distribution graph at 1000 Hz.

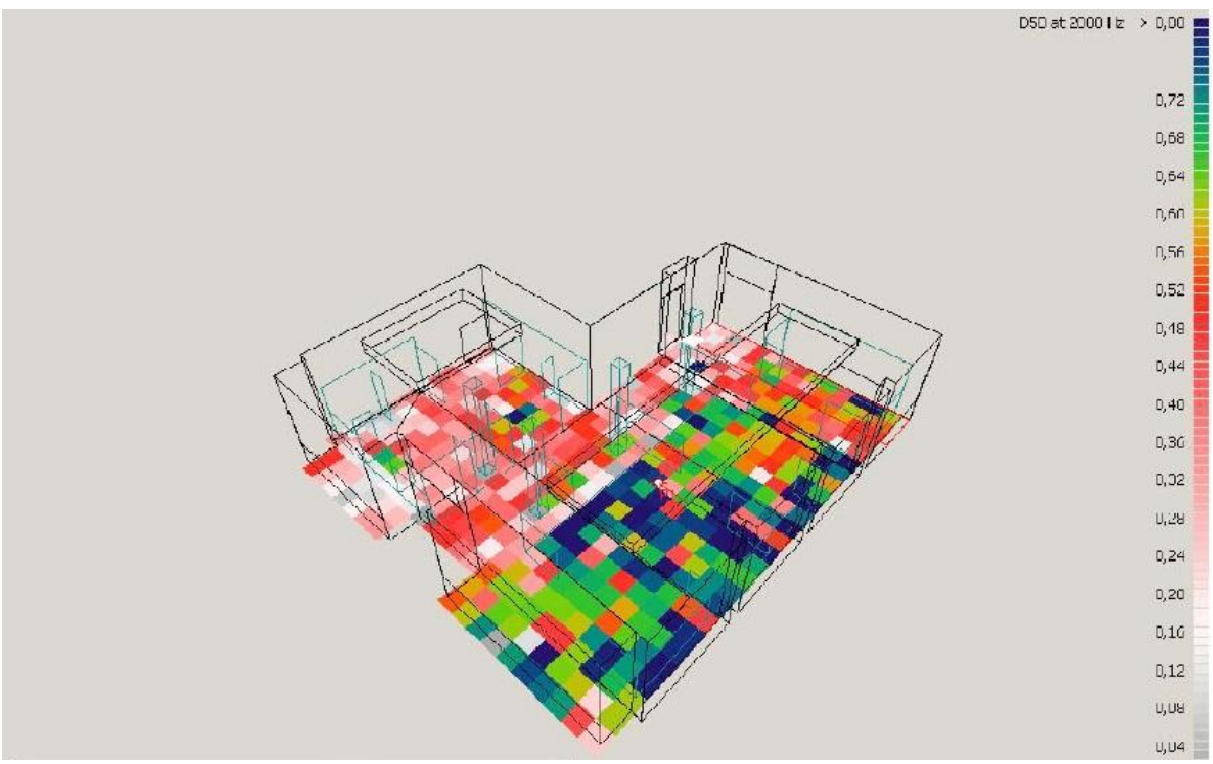


**Figure 9** D50 distribution graph at 2000 Hz.

**Speech Transmission Index (STI)**

Developed in the early 1970's, the Speech Transmission Index (STI) is a machine measure of intelligibility whose value varies from 0 (completely unintelligible) to 1 (perfect intelligibility). The speech transmission index (STI) has been developed for the evaluation of speech intelligibility in both direct communication situations and electro-acoustical situations.

The calculation of STI combines various distortions, for instance echoes, peak clipping, and other nonlinear distortion and interfering noise. The STI parameter has been improved and it takes into account other effects like non-contiguous frequency transfer and severe band pass limitation. While calculating STI male and female speakers are treated separately and a diffuse sound field is assumed. The reverberation time and the background noise have a direct effect on speech transmission index and speech intelligibility. STI also can be calculated by impulse responses of enclosed spaces (Egan, 1988). The explanation of STI values can be conducted as: excellent (0.8 – 1.0), good (0.6 – 0.8), fair (0.4 – 0.6), and bad (0.0 – 0.4).

Overall STI values in an open-office should not reach to excellent values; however, too low STI is caused by either very high value of reverberation time or background noise levels. Therefore, long-term effects of high background noise on occupant health have to be considered to achieve a better open-plan office environment. Attention should be given to balance the ratio between reverberation time and background noise, especially if the background noise source is natural and uncontrolled.

Average speech transmission index for the open-plan office area simulated was 0.60 (Fig. 10), which means 'good' in terms of speech intelligibility. Areas closer to the sound source had higher STI values ranging between 0.75 and 0.80, meaning 'excellent' speech intelligibility. Even at close distances from the sound source, there were some dead spots in terms of speech intelligibility. Those dead points were mostly at the back of the divider panels used in the open-plan office area. The lack of energy transmission from one side of the divider panel to the other caused the STI to decrease to the levels ranging between 0.55 – 0.60. At the far corners of the office area, there were spots of high speech transmission index that were caused by the excessive surface reflections.

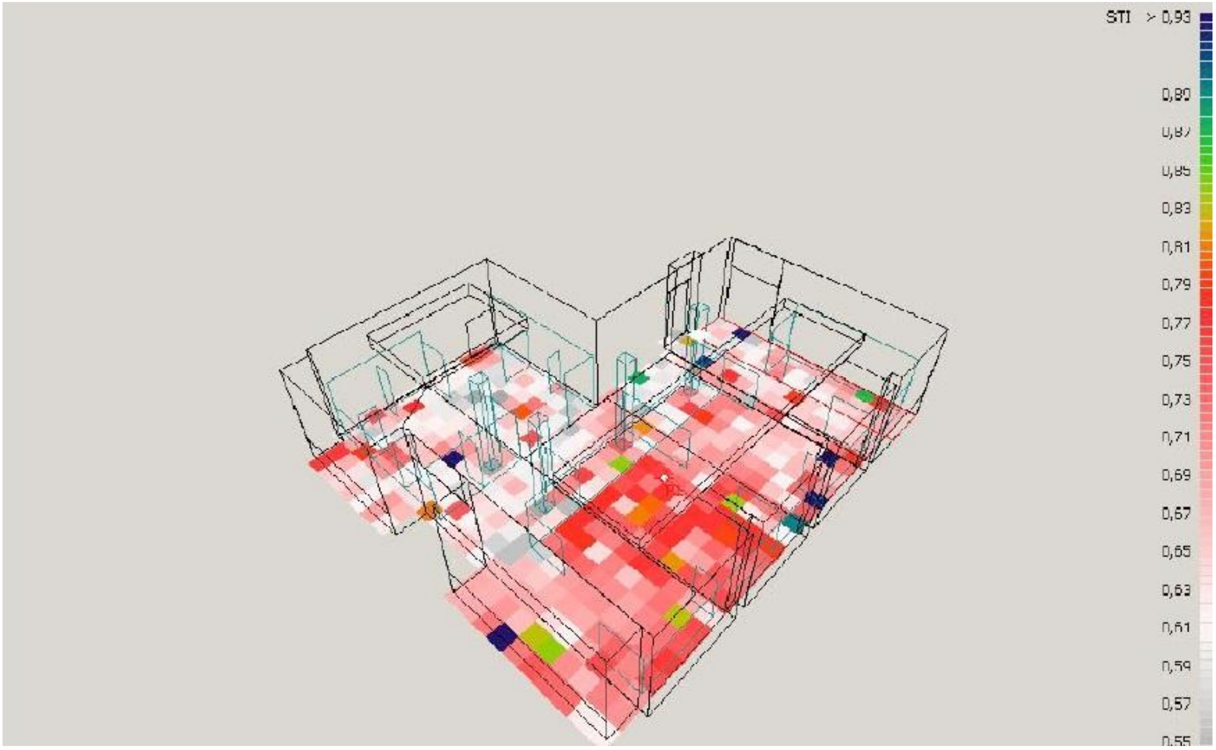


**Figure 10** Average STI distribution graph.

### Computer-Based Task Performance Test

For statistical analysis of findings from computer-based task performance test and subjective evaluation questionnaire, Statistical Package for the Social Sciences 15.0 (SPSS Inc., Chicago, IL, USA) was used. The one-way ANOVA test was used in the analysis of the data.

Two different parameters were recorded after the test; the reaction time, and the accuracy. Although it was expected that the reaction time results would increase and the accuracy results would decrease at masked speech (MS) and speech (S) environments, contradictory results were obtained between the three sound environments. It was significant that subjects' accuracy increased (F=9.875, Sig.=0.000) and reaction time decreased (F=16.369, Sig.=0.000) throughout the three sound environments. This increase of overall performance can be explained by familiarity to the test; however, all of the subjects had time to practice, and the test was simple enough for senior software developers to show the negative effects of intelligible speech between the three sound environments.

The data from the second questionnaire revealed that, the subjects felt distracted and under stress under the masked speech (MS) and speech (S) sound environments. The mean values of the results from the five-point scale questionnaire for the continuous noise (CN), the masked speech and the speech sound environments were 1.8, 2.37 and 3.27 sequentially. The difference between the three sound environments was statistically significant across all subjects (F=24.006, Sig.=0.000). The internal validity of the questionnaire was tested by SPSS reliability module. Cronbach's Alpha result of the analysis was 0,989, where over 0,75 is considered reliable.

**Discussion**

According to literature survey, there was a significant effect of speech and speech intelligibility on various task performances. For instance, Hongisto listed various tasks of work performance (i.e. proofreading, short-term memory, reading comprehension). In most of the cases, subjects were affected by intelligible speech (2005). Banbury and Berry's (1998) experiment analyzed memory and arithmetic tasks, which were called 'office-related' tasks. Results showed that irrelevant speech reduced memory for prose and mental arithmetic task performance impressively. However, those studies were carried out under laboratory conditions. This study, analyze the effects of speech and speech intelligibility in a real open-plan office environment, which all of the subjects participated to the test is familiar to the working environment, and the task.

The computer simulation results of the site were analyzed to evaluate the speech privacy requirements of an open-plan office; therefore, the same four parameters related to speech privacy ($T_{30}$, $C_{80}$, $D_{50}$, STI) were analyzed. The results showed that, reverberation time was slightly higher than open-plan office acoustic requirements mentioned above; however, in open-plan offices, to achieve a less intelligible speech, reverberation time can be higher in case of lower background noise situations. By looking at clarity and definition distribution graphs, it was seen that the divider panels were effective at blocking the direct sound energy; however, the range of the effective areas behind screens were not enough to prevent the office open-plan office occupants from intelligible speech. The STI distribution graph showed the uneven distribution of reflections, and the effects of the divider panels on the intelligible speech.

The results of the computer-based task performance test showed that the effects of intelligible speech on work performance were only subjective. Objective test results did not show any negative effect on workers' task performance in the arithmetic test, neither in accuracy nor in reaction time parameter; however, according to the subjective questionnaire results, it was significant that the participants felt under stress under speech sound environment. It is suggested that the effects of intelligible speech in open-plan office environments have negative effects on occupants in a long term due to stress caused by room acoustic conditions. Intelligible speech needs to be controlled in open-plan office environments, to avoid the long-term negative effects caused by stress. The short-term effects of intelligible speech should be investigated by using other tasks that are not relevant with the subjects' professional background and working habits.

Ultimately, the results suggest that if the worker is experienced with the task and familiar to the open-plan office environment, effect of intelligible speech is only psychological. Stress factor may cause various health or psychological problems in a long-term, rather than instant performance drops. According to those results, the site should be renovated to achieve an open-plan office environment with less intelligible speech.

It is claimed that the effects of unwanted speech is independent from sound pressure level of the sound; it is more related with the meaning of speech (Banburi & Berry, 1998). Speech becomes disturbing only when it is clear. Increasing the speech-noise ratio and decreasing the reverberation time provides more intelligible speech in rooms. As Hongisto stated, the designers should aim at high speech privacy in both conventional and open-plan offices. By evaluating real-size measurements and computer simulation of the site, three main renovations were suggested to improve work performance by decreasing speech intelligibility in STM case. First suggestion is the renovation of ceiling and floor materials on the circulation axis to absorb direct sound energy of sound instantly, by using heavy weighted carpet on the floor and acoustical gypsum board with glass wool on the ceiling. This renovation also prevents footstep noises that may distract the open-office personnel. Second suggestion is raising divider panels in between work surfaces to 160 cm, to enlarge the effective area of blocking the sound energy and early reflections. The final suggestion is isolating major noise sources like photocopy and fax machines, because of relatively high level of reverberation time.

## Conclusions

Open-plan office environments are very popular today, because of the organizational benefits and better flow of communication. However, it is hard to achieve an ideal condition for a better work environment in open-plan settings. Intelligible speech and speech privacy are the most distracting effects on both work performance and occupants' health.

In the present study, interior design solutions were suggested according to the results of the acoustical simulation of the site and the occupants' computer-based task performances test results. The results revealed that, similar to the previous study of Ebissou et al. (2015), the effects of intelligible speech on task performance were only subjective and psychological. Stress factor may cause various health or psychological problems in a long-term, rather than instant performance drops. However, it should be stated that the office occupants who participated the task performance tests were all software engineers and it is possible that the short-term memory test was not challenging enough for them. Further studies can implement different task performance tests that are challenging for subjects from various professions. By increasing the sample size and the variety of professions participating to the tests, it is possible to observe the differences between various tasks, and how they are affected by intelligible speech. Additionally, the tests should be conducted in a real open-plan office acoustic environment, rather than a digitally simulated acoustic environment, in order to evaluate the room affects.

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**Biography of the Author**

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