Improvement of speech privacy in open-plan offices

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ABSTRACT

The present study evaluates subjective aspects of single number quantities stated in the ISO 3382-3 draft, and investigates how design parameters influence speech privacy in computer simulated open-plan offices. Auditory experiments were carried out to rate intelligibility in simulated sound fields with variations of $DL_{2,S}$, $L_{p,A,S,4m}$, and r_D. The results of the experiments indicate that the newly-proposed single number quantities are highly correlated with speech intelligibility scores, and the contribution of $DL_{2,S}$ to speech intelligibility score was greater than those of $L_{p,A,S,4m}$ and r_D. Computer models of the actual offices were then developed using the commercial room acoustic software, and parametric studies were conducted using computer simulated open-plan offices. The design parameters studied in the present study were screen height, room height, ceiling absorption, floor absorption, screen absorption, light fixture, and workstation size. From the computer simulation, the influence of each design parameter was investigated.

INTRODUCTION

Open-plan offices have become common in most office buildings to create an environment for both concentration and communication. However, the acoustic quality of open-plan offices has not been satisfactory because irrelevant information from neighboring work places can cause disturbance and distraction (Helenius et al. 2007). Therefore, one of the important goals of acoustical design in open-plan offices has been to provide adequate speech privacy to prevent occupants from being disturbed by sounds from neighboring workstations.

Recently, Virjonen et al. (2009) proposed new single number quantities to characterize the acoustical conditions of the whole office space considering the far field. These new single number quantities are the spatial decay rate of A-weighted SPL of speech, $DL_{2,S}$ [dB], the A-weighted SPL of speech at 4 m, $L_{p,A,S,4m}$ [dB], and distraction distance, r_D [m]. Based on the report by Virjonen et al. (2009), international standardization of the measurement procedure for these single number quantities has been discussed in ISO TC43 SC2 WG19, and the ISO 3382-3 (2010) draft has been published (ISO 3382-3 2010). However, subjective assessment using the newly proposed measures has not yet been performed. Therefore, subjective aspects of the newly proposed single number quantities stated in the ISO draft have to be validated prior to the standardization.

The present study aimed to investigate subjective aspects of the single number quantities discussed in WG19 and to investigate the effects of design parameters of open-plan offices on the single number quantities. A suitable single number quantity was investigated through auditory experiments, providing information regarding the degree of speech privacy. Auditory experiments were carried out in a laboratory with a group of adults in simulated sound fields. During the auditory experiments, the sentence intelligibility score was adopted as a subjective measure, and the relationships between intelligibility score and the newly proposed single number quantities were investigated. Furthermore, computer simulations were performed to find out the way for improvement of speech privacy considering design parameters.

AUDITORY EXPERIMENT

Experimental design

Auditory experiments were conducted using sound fields which represented open-plan offices in which a person was speaking. All sound fields were simulated using the impulse responses measured in open-plan offices in Korea with fixed room acoustical parameters such as reverberation time (RT) and early decay time (EDT). The background noise used in the experiments was 30 dBA ventilation noise recorded in the same open-plan offices.

To investigate the effects of single number quantities on the subjective evaluation of speech privacy, speech levels at 4 m from the sound source ($L_{p,A,S,4m}$) were controlled in the range of 43 dB to 57 dB in increments of 7 dB. Then the spatial decay rate of speech levels($DL_{2,S}$) was distributed from 4 s to 12 in intervals of 4 s, while $L_{p,A,S,4m}$ values were fixed at 43 dB, 50 dB, and 57 dB, respectively. Sound pressure levels of speech used in these auditory experiments are plotted in Figure 1 (a) along a source-receiver distance. Changes in speech levels at receiver positions with fixed background noise levels affected the speech-to-noise ratio (SNR). Therefore, STI values were also varied, and those at receiver positions are plotted in Figure 1 (b). At this point, the distraction distance (r_D) was distributed in the range of 4.2 m to 16.0 m.

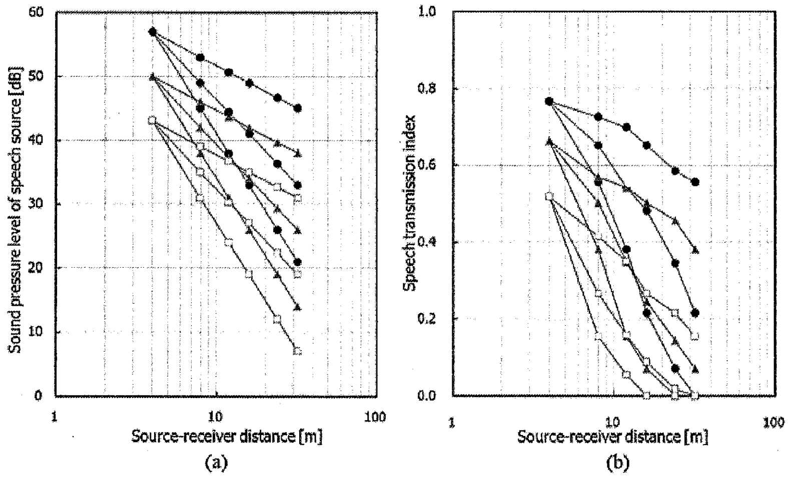

Figure 1: Speech levels (a) and STIs (b) along the source-receiver pathway

Procedure

Twenty subjects participated in the experiment: twelve male and eight female subjects between the ages of 24 and 32. All participants had thresholds ≤ 15 dB HL at octave band frequencies from 0.25 kHz to 8 kHz using an audiometer (Rion AA-77). The speech material used in the experiments was phonetically balanced Korean sentences. During the auditory experiments, five test sentences were presented to each subject in random order for 48 test situations. Thus, each participant listened to a total of 240 test sentences in random order.

All auditory experiments were conducted in a testing booth with approximately 25 dBA of background noise, and test sentences were presented to each subject via headphones (Sennheiser HD 600). Prior to the auditory experiments, each subject completed approximately 10 minutes of training to become familiar with the test signals and background conditions. Intelligibility scores were adopted as subjective measures for the evaluation of speech privacy. Each subject was asked to verbalize the sentences they thought they had heard, and the responses were scored by an experimenter positioned outside the test room. The score for each sentence was determined as the percentage of words that were correctly understood; all words were counted, and no partial scores were given.

RESULTS

Effects of $DL_{2,S}$ and $L_{p,A,S,4m}$ on mean speech intelligibility scores

Mean speech intelligibility scores obtained from auditory experiments are presented in Figure 2 in terms of $DL_{2,S}$ and $L_{p,A,S,4m}$. It was found that higher speech levels (that is, smaller $DL_{2,S}$ and larger $L_{p,A,S,4m}$) resulted in higher speech intelligibility scores while $L_{p,A,S,4m}$ and $DL_{2,S}$ were fixed. Figure 2 (a) shows that the changes in mean speech intelligibility score differed according to level of $L_{p,A,S,4m}$ when $DL_{2,S}$ changed from 4 to 8 dB. In this range of $DL_{2,S}$, a lower $L_{p,A,S,4m}$ caused a greater decrease in mean speech intelligibility. However, a similar tendency was observed when $DL_{2,S}$ changed from 8 to 12 dB, although the speech intelligibility scores decreased more rapidly than when $DL_{2,S}$ changed from 4 to 8 dB. This indicates that subjects were sensitive to changes in $DL_{2,S}$ in the range of 8-12 dB.

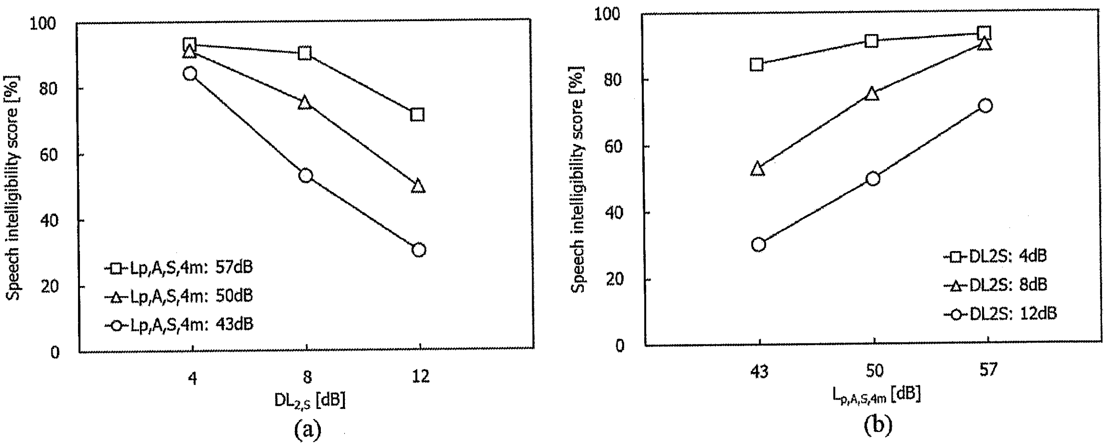

Figure 2: Relationships between mean speech intelligibility score and single number quantities ($DL_{2,S}$ and $L_{p,A,S,4m}$)

Figure 2(b) shows a different tendency according to the changes in $L_{p,A,S,4m}$. Mean speech intelligibility scores increased linearly with the increment of $L_{p,A,S,4m}$ when $DL_{2,S}$ values were fixed between 8 and 12 dB, whereas mean intelligibility scores did not change much when $DL_{2,S}$ was 12 dB.

The two-way analysis of variance (ANOVA) for mean speech intelligibility scores was conducted, and the results are listed in Table IV. It was found that $DL_{2,S}$ and $L_{p,A,S,4m}$ were statistically significant ($p<0.01$), although the effects of the interaction between them were not significant. Thus, $DL_{2,S}$ and $L_{p,A,S,4m}$ contributed to the speech intelligibility scores independently, so mean speech intelligibility scores (SIS_{mean}) can be expressed as

$$SIS_{mean} \approx f\,(DL_{2,S}) + f\,(L_{p,A,S,4m}) \approx a\,(DL_{2,S}) + b\,(L_{p,A,S,4m}). \quad (1)$$

The standardized partial regression coefficients of $DL_{2,S}$ and $L_{p,A,S,4m}$ in Eq. (1) were -0.55 and 0.41, respectively, and these coefficients were statistically significant (p<0.01 for *a* and *b*). Using these values, the obtained total coefficient of 0.68 was significant (p<0.01). Based on the results of ANVOA, the contributions of $DL_{2,S}$ and $L_{p,A,S,4m}$ to the mean speech intelligibility score were calculated. As presented in Table 1, the contribution of $DL_{2,S}$ to the mean speech intelligibility score was slightly greater than that of $L_{p,A,S,4m}$.

Table 1: Results of two-way ANOVA for mean speech intelligibility scores with factors of $DL_{2,S}$ and $L_{p,A,S,4m}$.

Factor	Degrees of freedom	Sum of square	Mean square	F-test	p value	Contribution (%)
$DL_{2,S}$	2	6931.705	3465.853	6.521	< 0.01	51.1
$L_{p,A,S,4m}$	2	5464.974	2732.487	5.141	< 0.02	40.3
Residual	4	1161.458	387.153			

Post hoc comparisons via Tukey's test indicated that the differences between $DL_{2,S}$ scores from 8 dB and 12 dB and those from 4 dB and 12 dB were significant (p<0.05). However, differences between $DL_{2,S}$ scores from 4 dB and 8 dB were not significant. Similarly, the differences between scores of $L_{p,A,S,4m}$ were statistically significant (p<0.05), except for the cases of 43 dB and 50 dB.

Effect of r_D on mean speech intelligibility score

Mean speech intelligibility scores obtained from auditory experiments can also be explained by another single number quantity, r_D. Figures 3(a) and 3(b) show how r_D is related to $DL_{2,S}$ and $L_{p,A,S,4m}$, respectively. As presented in Figure 3(a), only two r_D values were plotted in the case of 4 dB of $DL_{2,S}$ because STI did not decrease to 0.5 when $L_{p,A,S,4m}$ and $DL_{2,S}$ were 57 dB and 4 dB. Mean speech intelligibility scores increased as r_D increased, while the scores showed large variation according to $DL_{2,S}$

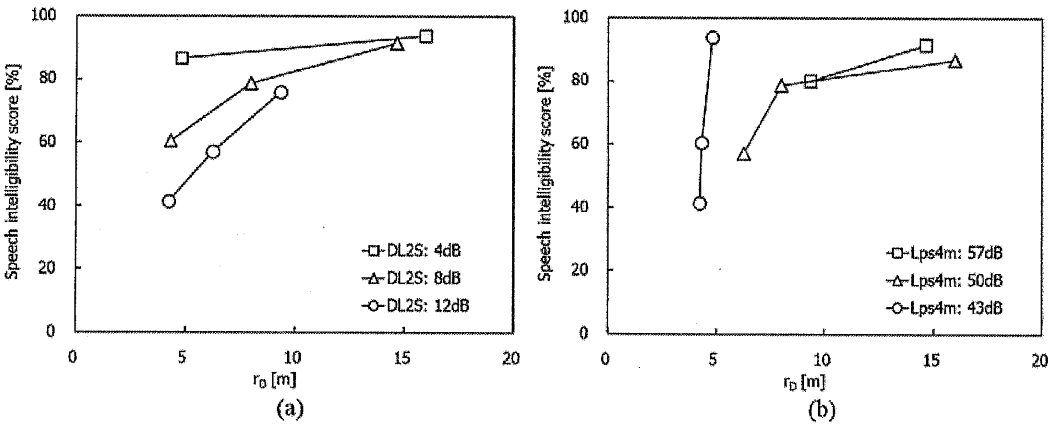

Figure 3: Relationships between mean speech intelligibility score and r_D

when r_D was less than 5 m. A significant tendency between $L_{p,A,S,4m}$ and r_D is not shown in Figure 3(b), but mean speech intelligibility scores also had large variation when r_D was less than 5 m.

Multiple regression analysis between the mean speech intelligibility score and single number quantities ($DL_{2,S}$ and r_D) was conducted to investigate the contribution of each single number quantity to the mean speech intelligibility score. In the regression analysis, $L_{p,A,S,4m}$ was not considered as an input variable because it was highly correlated with r_D (r=0.71, p<0.05). The relationship between mean speech intelligibility score and two single number quantities ($DL_{2,S}$ and r_D) was given by

$$\mathrm{SIS}_{\mathrm{mean}} \approx f\,(DL_{2,S}) + f\,(r_D) \approx a\,(DL_{2,S}) + b\,(r_D). \qquad (2)$$

The standardized partial regression coefficients of $DL_{2,S}$ and r_D in Eq. (1) were -0.62 and 0.38, respectively, and these coefficients were statistically significant (p<0.01 for a and p<0.05 for b). The regression equation was also significant (r=0.56, p<0.05). Contrary to the relationship between $DL_{2,S}$ and $L_{p,A,S,4m}$, the standard regression coefficient of $DL_{2,S}$ was much greater than that of r_D. Therefore, the contribution of $DL_{2,S}$ to the mean speech intelligibility score was the highest of the three single number quantities, followed by $L_{p,A,S,4m}$ and r_D.

COMPUTER SIMULATION

Field measurement

Field measurement was performed in one of the typical open-plan offices in Korea. The plan of the office considered in the present study is illustrated in Figure 4. The office was rectangular shape with similar length and width, and ceiling height was 2.4 m. And screens with heights of 1.2 m were installed between workstations.

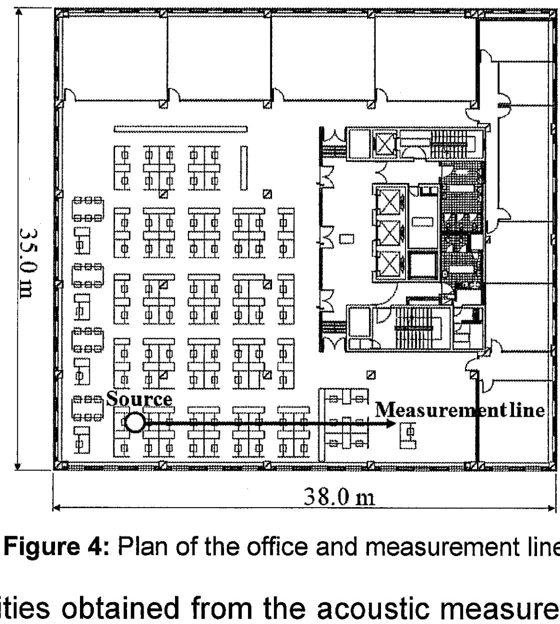

Figure 4: Plan of the office and measurement line

Single number quantities obtained from the acoustic measurement are summarized in Table 2. It was observed that T20 and EDT were less than 0.3 s, and the background noise level ($L_{p,A,B}$) was around 34 dBA. In addition, $DL_{2,S}$, $L_{p,A,S,4m}$, and r_D were 5.5 dB, 54.4 dBA, and 10.8 m, respectively. The acoustic class of furnished open-plan offices was proposed in the previous study in terms of $DL_{2,S}$, $L_{p,A,S,4m}$, and r_D. The acoustic classes of this office were different according to the single number quantities. This office were classified into the lowest class (D) in terms of $DL_{2,S}$ and $L_{p,A,S,4m}$. But it was also class C in terms of r_D.

Table 2: Measurement results of single number quantities in open-plan office

$DL_{2,S}$ [dB]	$L_{p,A,S,4m}$ [dB]	r_D [m]	$L_{p,A,B}$ [dB]	T20 [s]	EDT [s]
5.5	54.4	10.8	33.8	0.29	0.27

Computer modeling

A computer model of the office was created based on acoustic parameters analyzed from the field measurement using the ODEON room acoustic software. Simulations were performed by setting transition order (TO) = 2, by using 33301 rays and truncation time of 600 ms. Moreover, background noise level were set as measured in the office, and absorption and scattering coefficients of interior surfaces were determined considering the real office. For the validation of the computer model, measured and predicted results were compared. Source and receivers for computer simulation were located at same positions of field measurement. It was shown that the results from the simulation showed a good agreement with those from the field measurement within 5 % error.

Conditions

Previous studies (Bradley 2003; Virjonen et al. 2007) have investigated the effects of various design factors on speech privacy in open-plan offices; ceiling and floor absorption, screen height, workstation plan size, screen transmission loss, light fixtures, and ceiling height. Among those factors, ceiling and floor absorptions, ceiling height, and screen height were considered in the present study as an initial approach. Others will be dealt with in the future study. Ceiling heights were changed from 2.1 to 3.3 m, and absorptions of floor and ceiling were also varied from 0.1 to 0.9 in intervals of 0.2. In addition, screen heights were varied from 0.9 m to 2.4 m.

Result

Figure 5(a) shows the effect of varying only the ceiling height on acoustical parameters. In general, increasing the ceiling height was not positive to obtain the speech privacy in this office in terms of $DL_{2,S}$, $L_{p,A,S,4m}$, and r_D. As ceiling height increased, $DL_{2,S}$ decreased whereas $L_{p,A,S,4m}$ and r_D increased. This is because distances that reflected sounds from the ceiling reached increased as the ceiling height increased.

Figure 5(b) shows the results of predictions when the floor and ceiling absorptions were varied. It was observed that $DL_{2,S}$ increased whereas $L_{p,A,S,4m}$, and r_D decreased when absorptions increased from 0.1 to 0.9. Increasing the ceiling absorption was more effective to enhance the speech privacy than increasing the floor absorption. This result is in accordance with the previous finding (Virjonen et al. 2009) that the ceiling is the most important reflecting surface in open-plan offices, and it is most important that it should be as absorptive as possible.

Figure 5(c) shows predicted values for varied screen heights from 0.9 to 2.4 m high. It was observed that increasing the height of the separating panel significantly affected the speech privacy in open-plan offices. As the height of the screen increased $DL_{2,S}$ increased up to around 10 dB. And the effect of screen height was dominant in the variation of r_D.

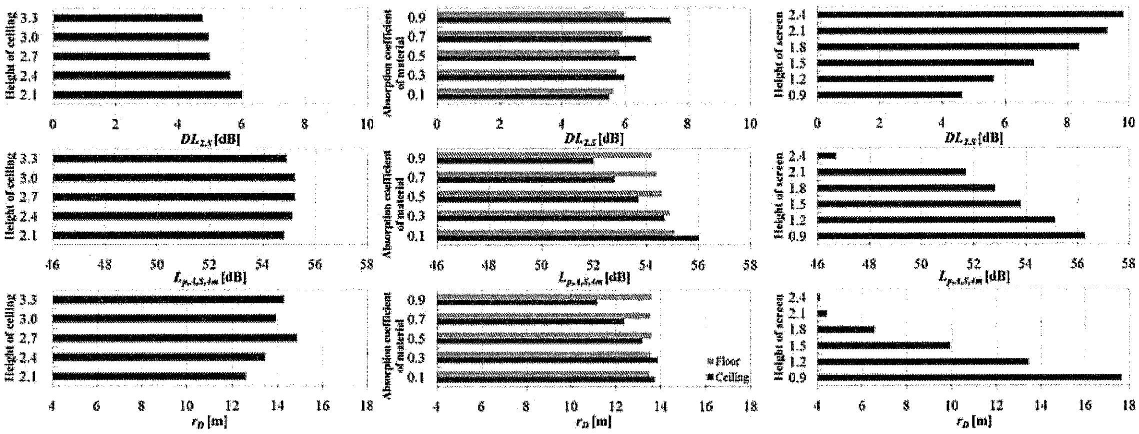

Figure 5: Effects of varied ceiling height (a), floor and ceiling absorptions (b), and screen height on speech privacy (c)

CONCLUSIONS

In the present study, auditory experiments simulated in a open-plan offices were performed to determine the single number quantities of speech intelligibility suitable for speech privacy. $DL_{2,S}$ and $L_{p,A,S,4m}$ were found to be good measures of speech intelligibility for characterization of the acoustic properties of large spaces. It was also found that the contribution of $DL_{2,S}$ to speech intelligibility was slightly greater than those of $L_{p,A,S,4m}$ and r_D. It was demonstrated through computer simulation that speech privacy can be improved with increases in ceiling absorption and screen height.

ACKNOWLEDGMENTS

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Comparison of different vehicle backup-alarm types with regards to worker safety

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INTRODUCTION

Audible backup alarms installed on mobile equipment are used to warn or alert nearby workers. Still, accidents and fatalities involving vehicles in reverse are reported every year (Murray et al. 2007; NIOSH 2004; Blouin 2005). Two important factors may affect the effectiveness of backup alarms on workers safety (Laroche 1995). Firstly, the uniformity of the sound field behind the vehicle is not guaranteed, in particular for tonal alarms. Secondly, spatial localization of the alarm can be a problem, particularly for workers wearing hearing protectors. Additionally, the noise generated by such devices will propagate and, quite often, be a source of nuisance for residents living in close proximity. In recent years, a new type of vehicle backup-alarm has been drawing increasingly more interest from many industrial sectors. The new alarm, based on the use of broadband noise instead of the typical tonal ("beep") signal, is deemed to reduce environmental noise annoyance close to industrial settings and construction sites and to be more efficient for spatial localization and uniform noise propagation behind vehicles. While conceptually appealing, few published and peer-reviewed scientific studies have demonstrated the advantages and disadvantages of such an alarm to ensure worker safety, particularly in comparison to existing technologies (Burgess & McCarty 2009; Homer 2008; Withington 2004). This two-part study was intended to compare three types of backup alarms: the standard tonal signal, a multi-tone signal and the broadband noise technology. The first part, performed in the field, focused on objective measurements of the sound propagation behind vehicles for various vehicles and terrain configurations. The second part, performed in a laboratory environment, was centered on the measurement of various psychoacoustic metrics (hearing threshold, loudness, and perceived urgency), as well as the study of spatial localization tasks. The paper presents the methods used for the "field" and "laboratory" parts. Results illustrating some of the findings, both from the field and from the psychoacoustic standpoint, are finally presented.

METHODS

Sound field behind vehicles

Three backup alarms were tested in this study: i) a standard tonal alarm from Grote (Grote Industries Inc. 2011); ii) a broadband alarm from Brigade (Brigade Electronics 2011) and; iii) a custom-made multi-tone alarm. The multi-tone was proposed by Laroche (1995) as an improvement over the conventional tonal alarm. It was included in this study for comparison with the two other types of signal. The frequency content of the three alarms is illustrated in Figure 1. The sound pressure levels (SPL), measured at approximately 1 m in front of the alarms, are shown as a function of frequency. The multi-tone alarm consists of three major tones located between 1,000 and 1,300 Hz, contrarily to the standard tonal alarm where the acoustic energy is concen-