The effect of reverberation time on sound masking method to improve speech privacy in open-plan offices

L L Valentina, D Arifianto*, F U Azmi, B Fajar and A Nadiroh

Engineering Physics Department, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

*dhani@ep.its.ac.id

Abstract. Lack of speech privacy is a significant problem in open-plan offices. Sound masking, which essentially covers the target speech with the competing speech simultaneously (masker), can increase speech privacy. However, a conversation takes place in a reverberant room at which will reduce speech intelligibility. This study observed the effectiveness of reverberation time on the sound masking to the target. In this early study, three conditions of stimuli were used, namely clean, 0.3 s and 0.6 s reverberation time added to both target and masker, respectively. The STI and subjective measure were used with twenty-five volunteers. As expected, the results suggest that the longer the reverberation time, the lower the effectiveness of the masker strength. The STI agrees with the subjective measure.

1. Introduction

According to Savills Indonesia in January 2020, Indonesia is having 9.8 million square meters of office space that consists of 80% open-plan offices. The open-plan office is also dominant over 70% in other countries like the United States [1]. The main characteristic of an open-plan office is the absence of a full-height partition to isolate workers from one another. Open-plan offices are widely used because they have advantages, including cheaper construction costs and fewer land requirements [2]. This room type [3] is capable of improving communication between colleagues and increase employees' productivity. However, various problems are often encountered in open-plan offices, such as interference caused by electronic equipment like printing machines, ringing the telephone, or talking to colleagues in the other room [4], and lack of speech privacy [5].

Speech privacy is defined as a conversation between two people whose contents cannot be heard or understood by third parties (eavesdropper) [6]. The conversation, whether the contents can be understood or not (as a masking sound) is potentially disturbing concentration can cause a decrease in employee work productivity [7]. Several efforts can be made to increase speech privacy, namely using sound absorption material in the workspace, use a higher barrier, and sound masking [8].

There are several types of sound masking that are commonly used, namely stationary noise (AC noise, pink noise, white noise) and natural sound (rain noise, river noise, and speech noise called babble speech) [9]. The type of conversation masking sound (babble speech), according to the previous study [10], has the potential to be a natural masking sound that suitable to be applied on open-plan offices.

However, room acoustics' performance in terms of intelligibility is affected by reverberation time. Increase reverberation times means to give a negative impact on intelligibility in a room [11]. Another study also stated that speech intelligibility in the classroom is directly proportional to the signal-to-noise ratio.
ratio (SNR) and inversely proportional to the value of reverberation time [12]. Therefore, this study's objective begins to observe how reverberation time affects speech intelligibility in order to increase speech privacy in open-plan offices.

2. Survey location
The survey aims to identify noise problems and calculate reverberation time variations based on the existing audial conditions. This survey was conducted at Institut Teknologi Sepuluh Nopember (ITS). Two-room were determined to be used as research objects, namely the Directorate of Research and Community Service (DRPM) office and the Faculty of Industrial Technology and System Engineering (FT-IRS) Dean Office. For more details, see Table 1.

Table 1. Comparison of DRPM and FT-IRS Dean office

| Parameter                  | Dean FT-IRS | DRPM ITS |
|----------------------------|-------------|----------|
| Room Volume (m³)           | ±250        | ±670     |
| Background Noise (dB)      | 43-45       | 55-56    |
| Number of Occupants (people) | 10         | 19       |
| Reverberation Time (second)| 0,301       | 0,661    |

3. Data collection of the existing condition
This step was divided into two main activities, namely sound recording during work hours and room acoustics parameter measurement. The recording was conducted to obtain information on background noise and types of noise at the research location. Recording of background noise was accomplished by placing the recorder randomly in the office. Meanwhile, the measurement of the open-plan office's acoustic parameters was carried out according to ISO 3382:3 [13]. The results can be seen in Table 2.

Table 2. Existing Room Acoustic Parameters.

| Parameter                  | DRPM ITS | FT-IRS Dean Office |
|----------------------------|----------|--------------------|
| Spatial decay rate of A-weighted sound pressure level of speech, \( D_{2.5} \) (dB\(_A\)) | Line 1: 2.91, Line 2: 2.83, Line 3: 5.79 | 2.82 |
| A-weighted sound pressure level of speech at a distance of 4 m, \( L_{p,4A,4m} \) (dB\(_A\)) | 54.9, 55.4, 56.3 | 47.7 |
| Background Noise (dB\(_A\)) | 56.6, 56.6, 56.6 | 42.6 |
| Distraction distance (m)    | 17.6, 15.4, 21.5 | 47.9 |
| Privacy Distance (m)        | 49.9, 45.7, 86.8 | 122.9 |

Based on the result in Table 2, it can be said that the two offices were categorized as not private offices. A not private office is a problem that is often found in open-plan offices so that workers become distracted and counterproductive [5].

4. Sound masking
The masking sound in this study used a sound database by Nadiroh [14], namely five-sound variations consisting of two, four, six, eight, and ten combined voices, which were referred to as babble speech. Meanwhile, the target sound in this study used a sound database by Cahyaningtyas [15]. The masking and target sound was added by reverberant effect using MATLAB software. Validation was carried out
using the sine sweep sound to find whether the reverberant effect is following the actual room conditions.

The parameter values by adding the reverberant effect were determined as written in Table 3. The masking and target sound with reverberant effect were combined using the SNR sum. SNR 5 dB means the target sound volume is 5 dB higher than the masking sound.

**Table 3. Reverberation Effect Parameter**

| Parameter                  | Reverberation time |
|----------------------------|--------------------|
|                            | 0.6091             | 0.3297             |
| Pre-Delay                  | 0.000025           | 0.000025           |
| Wet Dry Mix                | 1                  | 0.95               |
| Diffusion                  | 0.75               | 0.63               |
| Decay Factor               | 0.92               | 0.95               |
| High-Frequency Cutt Off    | 20000              | 20000              |
| High Frequency Damping     | 0.21               | 0.19               |
| Sample Rate                | 44100              | 44100              |

5. Testing

Sound masking effectiveness test was carried out in 4 scenarios, henceforth called Female Target with Female Masking Sound (WW), Female Target with Male Masking Sound (WP), Male Target with Female Masking Sound (PW), Male Target with Male Masking Sound (PP), and Target without masking sound (T). The objective test was conducted by calculating the Speech Transmission Index (STI) to the stimuli. It was used to determine the impact of reverberation time on speech intelligibility.

The listening test was conducted to determine the participant’s perceptions of the addition of sound masking with reverberant effect. The sound masking effectiveness was obtained by calculating the % correct word method. Twenty-five normal-hearing listeners were tested in this study and asked to listen to target sound in all scenarios using a pair of headphones. Eight hundred sixty-six words were used as target sentences, and each sentence was only used for one experimental scenario. The sound masking consists of 20 different sentences with ten male and ten female voices. The stimuli were delivered to the participants in the following setting, both target-masker pair without reverberation, 0.3 s, and 0.6 s reverberation time, respectively.

6. Results and discussions

6.1. Objective test

Figure 1 and 2 shows the relationship between the STI and the reverberation time. From the graph, it can be seen the x-axis provides information on the reverberation time variations, and the y-axis provides information on STI. The more excellent the STI value, the greater the speech intelligibility. It means if the level of speech intelligibility is good, speech privacy can be obtained. Figure 1 shows the relationship between STI and the reverberation time with two simultaneous talkers as a masker.

Figure 1 shows the target STI values are in the range of excellent, good, and fair for all experimental scenarios. Due to the addition of a masking sound, the STI value has been decreased. Based on the result, it can be seen that the decrease in the STI value is inversely proportional to the extension of the reverberation time. The more prolonged the reverberation time, the smaller the gap line between the target and test STI values, which means that the reverberation time had a negative impact on the effectiveness of the sound masking. Due to the addition of a masking sound, the STI value has been decreased. Based on the result, it can be seen that the STI decrease in the PP and WP experiments is
also inversely proportional to the extension of the reverberation time. Whereas for the experiment with a female masking sound, the most effective masking was obtained when the reverberation time value was 0.3 seconds. From all the results, it can be seen that male sound masking was more effective because the gap line between STI masking and targets was more significant than female sound masking.

The STI decrease due to RT happens since reverberation time can reduce the transmitted sound modulation's amplitude [12]. Even the reverberation time did not significantly impact STI value changes, but it affects reducing the effectiveness of sound masking. Based on the result, clean speech is more effective in obscuring the target sound. However, in actual condition, it is difficult to get office condition without reverberation time. Overall, the graph's trend line indicates that adding the reverberant effect can reduce sound masking effectiveness, which was also stated in a study by Hioka et al. [16].

![Graphs showing the relationship between STI and RT with a two-talker scenario and 5 dB SNR for different experiments.](image)

**Figure 1.** The relationship between STI and RT with a two-talker scenario and 5 dB SNR for a) PP, b) PW, c) WP, and d) WW experiments.

6.2. Subjective test

A subjective test was conducted to determine how the participant's perception of sound masking variations conditions. The participants were asked to write sentences that they heard. The number of correct sentences was calculated to describe the level of speech intelligibility that the participant can hear. 50% of the correct word does not necessarily indicate that the participant can understand 50% of the sentence's contents. This value was used to show that participants can understand all the sentences being tested. Thus, the correct word value has to be greater than 50% to indicate that the participants can understand the sentence/conversation [17]. Sound masking can be effective if the % correct word value is lower than 50%. It was indicated that a masking sound succeeds in covering the target sound, and the participants challenging to understand the content of the tested sentence.

Figure 2 shows the relationship between % correct word and reverberation time. The x-axis shows the value of the reverberation time variations. It is shown that sound masking can work effectively at a
reverberation time of 0.6 seconds for PP and WP experiments. While for the female masking (PW and WW), the results show that masking slightly effective because the % correct word value greater than 50%. Whereas for the experiment with ten talkers masking, male masking sound was more effective than female. The 0.3 s reverberation time also effective for reducing the% correct word value, which means the amount of talker in the masker also affects the effectiveness of the sound masking. However, from these data, it can be seen that the data obtained has quite a significant deviation, this is due to differences in the use of headphones, and there was no hearing test to the participants before carrying out the test. Therefore, the on-going measurement is to collect additional data in the actual office by involving the staff.

![Figure 2](image_url)

**Figure 2.** The relationship between % correct word and reverberation time, with a two-talker scenario and 5 dB SNR for a) PP, b) PW, c) WP, and d) WW experiments
7. Conclusion

The relationship between reverberation time and speech intelligibility has been observed in this study. The objective tests show that the longer the reverberation time, the lower the sound masking effectiveness can get. However, the subjective test shows the opposite conditions, which means that the longer reverberation time, the higher sound masking effectiveness can get. For further research, the staff perception also needed to be observed when masker applied at the offices. Thus, the results can be compared with the experimental results in order to achieve satisfying speech privacy in offices.

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