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Evaluation of the acoustic environments of open-plan offices in Korean public buildings

국내 공공건축물 개방형 사무실 음환경 평가

Sang Hee Park,[1] Hye-Kyung Shin,[1] Seung-Min Lee,[1] and Kyoung Woo Kim[1†]
(박상희,[1] 신혜경,[1] 이승민,[1] 김경우[1†])

[1]Korea Institute of Civil Engineering and Building Technology

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ABSTRACT: Poor indoor acoustic environments negatively affect occupants. Previous research has shown that indoor acoustic environments affect not only task performance and job satisfaction of the occupants, but also their health and well-being. This study aimed for evaluating indoor acoustic environments of open-plan offices located in public buildings in Korea. It also aimed to review the matters that need to be considered in order to improve occupants' acoustic comfort. Indoor noise levels were measured in 13 sites; the measurements were conducted for five consecutive working days from Monday to Friday. The noise levels were evaluated based on the levels recommended by the ISO and the EU ALDREN project. The study found that most of the indoor noise levels measured in the sampled sites during the working hours met the ISO standard. In the case of the levels under unoccupied conditions at night, those at three sites did not meet the recommendation of the ALDREN. In addition, some characteristics of the sites had significant effects on the noise level. Since the exact acoustic performance of the building envelope could not be identified, future research is needed for investigating the relationship between accurate building performance and indoor acoustic environments.
Keywords: Indoor acoustic environment, Open-plan office, Acoustic comfort, Public building

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초 록: 열악한 실내 음환경은 재실자에게 부정적인 영향을 미친다. 선행 연구를 통해 실내 음환경이 재실자의 과업성취도나 직무만족도뿐 아니라 그들의 건강과 웰빙에도 영향을 주는 것으로 알려져왔다. 본 연구는 국내 공공건축물에 위치한 개방형 사무실의 실내 음환경을 평가하고, 재실자의 음환경 쾌적성 향상을 위하여 고려할 필요가 있는 사항을 검토하기 위한 목적으로 수행되었다. 국내 공공건축물에 위치한 13개의 개방형 사무실에서 실내 소음 레벨을 측정하였으며, 측정은 월요일부터 금요일까지 5일간 진행되었다. 측정된 실내 소음 레벨은 ISO 및 EU ALDREN 프로젝트가 개방형 사무실을 대상으로 권장하는 수준을 기반으로 평가하였다. 분석 결과, 근무 시간 동안 재실자가 있는 환경에서의 실내 소음 레벨은 대부분 ISO 기준을 충족하는 것으로 나타났다. 재실자가 없는 심야 시간대의 음환경을 평가한 결과, 3개 사무실의 측정 결과값이 ALDREN의 권장 수준을 충족하지 못하는 것으로 나타났다. 아울러 측정이 진행된 현장의 특성이 실내 소음도에 유의미한 영향을 주는 것으로 나타났다. 건물 외피의 정확한 음향 성능을 파악하는 것이 불가능하였으므로 향후 추가 연구를 통해 건물의 성능과 실내 음환경 간 관계를 규명할 필요가 있다.
핵심용어: 실내 음환경, 개방형 사무실, 음환경 쾌적성, 공공건축물

†**Corresponding author:** Kyoung Woo Kim (kwmj@kict.re.kr)
Korea Institute of Civil Engineering and Building Technology, 283, Goyang-daero, Ilsanseo-gu, Goyang-si, Gyeonggi-do 10223, Republic of Korea
(Tel: 82-31-910-0356, Fax: 82-31-910-0361)

I. Introduction

A number of studies have investigated Indoor Environment Quality (IEQ) and occupants' comfort in various kinds of buildings.[1,2] It has widely been known that a better IEQ substantially results in benefits for occupants' health and well-being. IEQ has four key attributes, namely thermal comfort, indoor air quality, lighting comfort, and acoustic comfort. Each of the four attributes has crucial impacts on occupants' performance and well-being.[3,4]

Recently, a growing number of studies have tried utilizing indoor environment monitoring sensors for measuring the IEQ.[5,6] Although using such sensors may be less accurate than standardized measurement methods, it is advantageous since it monitors each environmental quality level in the long term. Moreover, it is quick and easy to approach the monitored data if the data are stored online. Due to the fast development of smart building technologies, the demand for adopting such methods is gradually increasing.

The present study is involved in a project aiming to assess the IEQ of public buildings in Korea. Particularly, the study focused on indoor acoustic environments. Noise has adverse effects on human health and well-being,[7] and poor acoustic environments in office spaces have been acknowledged to reduce employees' performance and satisfaction.[8,9]

The study sampled public buildings in Korea and measured indoor noise levels. There are a few standards providing recommendations on indoor noise levels. As shown in Table 1, the International Organization for Standardization (ISO) classifies six space types depending on the characteristics of activities and suggests recommended noise levels.[10] The European standard suggests ambient noise levels for the different purposes of space usage, and those for landscaped offices were between 35 dBA and 45 dBA.[11] The British standard proposes ranges of indoor ambient noise levels when the spaces are unoccupied and privacy is important - it has been recommended that the design range of indoor ambient noise levels in open-plan offices is between 45 dBA and 50 dBA.[12] and Also, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has developed Noise Criteria (NC) curves for specifying acceptable indoor noise levels.[13] Recommended NC curves for open-plan offices are NC-35 and NC-40, which are equivalent to 45 dBA ~ 50 dBA. Furthermore, there are tools for assessing acoustic comfort of indoor environments such as the TAIL indices developed by the European Union's ALliance for Deep RENovation in Buildings (ALDREN) project.[14] Its recommendations for indoor noise level are shown in Table 2. Based on the existing recommendations, this study examined the acoustic environments in the sampled public buildings.

Table 1. The ISO recommendations for indoor noise levels in open-plan offices (ISO 22955:2021).

Space type	Expected activity in the space	Target level ($L_{Aeq,T}$)
1	Activity not known yet: vacant floor plate	Unspecified
2	Activity mainly focusing on outside-of-the-room communication (by telephone/audio/video)	55 dB
3	Activity mainly based on collaboration between people at the nearest workstations	52 dB
4	Activity-based on a small amount of collaborative work	48 dB
5	Activity that can involve receiving public	55 dB
6	Combining activities within the same space	Varied

Table 2. The EU ALDREN recommendations for indoor noise levels in open-plan offices.

Category	Expected level of the category	Target level ($L_{Aeq,T}$)
1	High level of expectation and recommended for spaces occupied by sensitive and fragile people with special requirements	≤ 35 dB
2	Normal level of expectation	≤ 40 dB
3	Moderate level of expectation	≤ 45 dB
4	Low level of expectation - poor quality and unacceptable regarding health	Unspecified

Table 3. Sample sites where the indoor noise measurements were carried out.

No.	City	Purpose of the building	Area type[a]	Floor[b]	Distance from the major road (m)	Number of lanes of the major road	Age of the building (years)
1	Seoul	General public sector	I	11/15	80	6	47
2			R	2/5	198	6	55
3			R	3/3	210	10	27
4			R	1/4	145	10	36
5	Goyang		I	9/10	52	8	26
6			I	3/3	21	4	32
7	Gunsan		I	2/8	45	4	9
8	Seoul	Community center	I	1/3	30	4	52
9			R	2/2	110	4	34
10			I	1/4	85	4	31
11	Daejeon		R	3/3	115	7	30
12	Goyang	Research institute	I	2/2	170	10	11
13	Daejeon		I	2/2	90	7	43

[a] Type of the surrounding area: Industrial or Residential
[b] Floor where each site was located / Top floor of the building

II. Methods

2.1 Sites

As presented in Table 3, a total of 13 sites with open-plan offices were sampled for the measurements. Seven of them were in Seoul, three in Goyang, two in Daejeon, and one in Gunsan. Buildings with seven sites were used for general public purposes, four were office spaces in community centers, and two were located in research institutes. Five of them were located in the areas which were mainly residential areas while the other eight were in industrial areas. Three measurements were conducted on the 1st floor of the building and two were done on relatively high floors, on the 11th and 9th floors (Sites 1 and 5), respectively. Six sites were located on the top floor of the buildings. The study also considered the distance from major roads which had more than four lanes. Distance from the major road ranged from 21 m to 210 m (Sites 6 and 3), respectively. The number of the lanes ranged from four to ten. The ages of the buildings were computed with the year of completion of each building. The ages of the buildings varied, ranging from 9 to 55 years (Sites 7 and 2), respectively. It was unknown whether each building, particularly the exterior of each building, has been undergone any refurbishment.

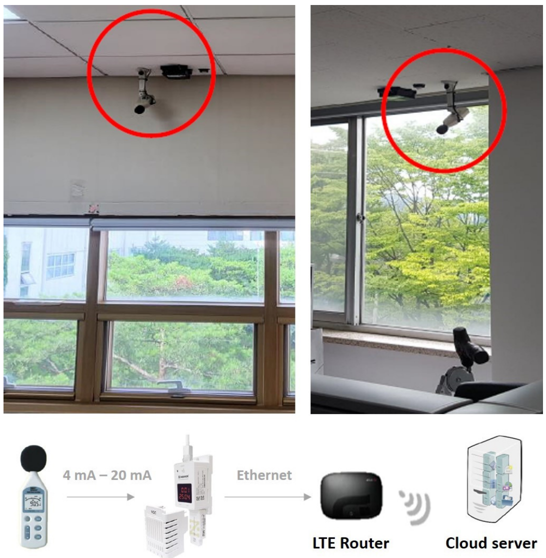

Fig. 1. (Color available online) Sound level meters installed at the sites and the procedure how the measurements were carried out.

2.2 Measurement procedure

One sound level meter (AR824, Smart Sensor®) and a transmitter (RN171, Radionode) were set for measuring indoor noise levels at each site. Each sound level meter used a 1/2-inch condenser microphone. The measurement interval was 2 minutes. The measured data were transmitted via the transmitter and stored on the server. For safety reasons, the sound level meter, the transmitter, and the router were installed where occupants were not likely to reach (Fig. 1).

2.3 Data analysis

This study analyzed sound pressure levels (dBA) measured for five consecutive working days from October 17th Monday to 21st Friday, 2022. Although occupants in different buildings might have had varied working hours, the study chose the time period between 9 am and 6 pm as working hours and looked into this time frame in more detail. $L_{Aeq,working\text{-}hours}$ have been computed with the data measured for the working hours for each day. In addition, $L_{Aeq,night\text{-}time}$ has been derived with the data measured between 11 pm and 12 am on the same days in order to assess the acoustic environment in an unoccupied condition. The statistical tests were performed using jamovi (v. 2.3).[15-17]

2.4 Evaluation of acoustic environment

Target noise levels suggested by the ISO 22955:2021[10] were used for assessing the $L_{Aeq,working\text{-}hours}$ (Table 1). Although the present study used sound monitoring sensors and it was not in line with the methods that the ISO has stated, its recommended levels were adopted to evaluate the acoustic environments of the sites. This standard was chosen since it is for evaluating indoor noise levels of open-plan offices in an occupied condition. It recommends upper limit values of noise level for different types of space. To evaluate the acoustic environments measured at each site, the present study adopted a recommended value of 52 dB for Space type 3. In this type of space, activities are expected to be mainly based on collaboration between people at the nearest workstation. This target value is for securing good intelligibility at workstations when occupants speak normally without raising their voices.[10]

Moreover, the ALDREN recommendation[14] was adopted for evaluating the $L_{Aeq,night\text{-}time}$ measured in an unoccupied condition (Table 2). It classifies four categories depending on the expected level of indoor environments. The present study adopted the upper limit level of 45 dBA which is proposed as a moderate level of expectation (Category 3).

III. Results

As presented in Table 4, $L_{Aeq,working\text{-}hours}$ ranged from 42.5 dBA to 59.0 dBA. The lowest was from Site 13 on Friday while the highest level was found from Site 1 on Wednesday. There were six sites which showed indoor noise levels not meeting the ISO recommendation at least for one day. Particularly, $L_{Aeq,working\text{-}hours}$ measured at Site 6 exceeded the recommendation for four days. In addition, $L_{Aeq,night\text{-}time}$ ranged from 34.0 dBA to 51.2 dBA (Table 5). The lowest level was measured at Site 13 on Wednesday and Thursday. The highest level was from Site 6 on Friday. Three sites (Sites 5, 6, and 11) consistently presented higher noise levels than the recommendation. Since the high background noise levels at these sites may be due to

Table 4. Noise levels measured from each site when occupied during working hours; those exceeding the recommendations are presented in bold and in red cells.

No.	$L_{Aeq,working\text{-}hours}$ (dB)				
	Mon.	Tue.	Wed.	Thur.	Fri.
1	48.9	47.3	**59.0**	**53.9**	47.4
2	46.2	50.8	44.8	46.2	43.6
3	46.7	45.4	45.6	51.3	**57.3**
4	51.5	48.7	**52.7**	48.0	49.3
5	48.6	48.0	49.4	49.8	47.0
6	**52.1**	**54.1**	51.6	**52.3**	**52.5**
7	50.0	47.4	47.1	46.3	47.8
8	48.0	**53.5**	**55.9**	45.4	48.4
9	47.2	43.4	46.2	50.6	46.1
10	48.2	50.2	50.2	50.7	48.3
11	50.9	**52.5**	50.6	**54.8**	51.7
12	44.0	45.2	43.9	44.5	44.4
13	42.6	44.2	42.6	44.1	42.5

Table 5. Noise levels measured from each site when unoccupied at night-time; those exceeding the recommendations are presented in bold and in red cells.

No.	$L_{Aeq,night\text{-}time}$ (dB)				
	Mon.	Tue.	Wed.	Thur.	Fri.
1	41.1	41.4	42.6	41.6	41.7
2	39.7	40.0	40.0	40.1	40.4
3	36.2	36.3	36.5	36.5	36.3
4	42.2	41.6	41.8	41.8	42.3
5	**45.9**	**45.2**	**46.3**	**45.6**	**47.0**
6	**50.3**	**50.0**	**50.8**	**50.9**	**51.2**
7	42.2	41.8	41.5	43.1	43.4
8	42.9	40.5	40.5	39.8	40.7
9	35.7	35.7	35.5	35.8	35.9
10	36.7	38.4	35.1	36.1	36.9
11	**45.7**	**46.2**	**45.7**	**45.8**	**45.6**
12	43.2	44.0	43.3	43.6	43.2
13	35.7	34.0	34.0	34.6	34.1

various reasons, the study excluded these data from the following statistical analyses.

Shapiro-Wilk tests showed that the indoor noise levels did not meet the normal distribution. Thus, non-parametric tests were conducted for further analyses. First, the paired Wilcoxon signed rank test was performed and there was no significant difference between the days (e.g., Monday vs. Tuesday). Second, the one-way analysis of variance (ANOVA) on ranks (Kruskal-Wallis H tests) was performed and found that the floor of the site did not change $L_{Aeq,working\text{-}hours}$ [$H(4) = 7.47$, $p = 0.113$] while it significantly changed $L_{Aeq,night\text{-}time}$ [$H(4) = 17.24$, $p = 0.002$]. Besides, significant differences were found in $L_{Aeq,working\text{-}hours}$ [$H(9) = 29.0$, $p < 0.001$] and $L_{Aeq,night\text{-}time}$ [$H(9) = 49.0$, $p < 0.001$] affected by the age of the building and the distance from major roads. The number of lanes in the road also had significant effects on $L_{Aeq,working\text{-}hours}$ [$H(3) = 12.2$, $p = 0.007$] and $L_{Aeq,night\text{-}time}$ [$H(3) = 12.8$, $p = 0.005$]. Third, Mann-Whitney U tests indicated that $L_{Aeq,working\text{-}hours}$ was greater for the buildings used for the general public sector (Mdn = 47.8 dB) than the buildings for other purposes (Mdn = 46.8 dB), $U = 201$, $p = 0.031$. In addition, $L_{Aeq,night\text{-}time}$ was higher for sites in the industrial area (Mdn = 40.3 dB) than those in the residential area (Mdn = 38.0 dB), $U = 175$, $p = 0.013$.

IV. Discussion

High indoor noise level is expected to have negative impacts on occupants. Particularly, in the case of office spaces, a poor indoor acoustic environment is likely to disturb occupants not just with their speech intelligibility but also with their work performance and job satisfaction.[8,9] The present study measured indoor noise levels at 13 open-plan offices in different public buildings in Korea. The indoor noise levels during the working hours met the ISO recommendation at most of the sites. It implies that occupants might have been in satisfactory acoustic environments in general. The study used the ISO target level of 52 dBA which was for Space type 3 where activities mainly based on collaboration between people at the nearest workstation are expected. This level secures good speech intelligibility at workstations when occupants speak normally without raising their voices.[10] However, there is still a need for an improvement in intelligibility at the workstations. Aiming for securing the target level of 48 dBA of Space type 4 where activities are expected to be mainly based on collaboration between people at the nearest workstations,[10] would be beneficial for occupants using and working in the space.

Furthermore, acoustic environments in an unoccupied condition were evaluated by the ALDREN recommendation. Three sites showed noise levels exceeding the recommendation. It might be either due to unidentified noise sources located indoors nearby the sound level meters or due to poor sound insulation of the building envelope. In the former case, it is believed that future studies would set the methods of data collection more carefully. The sound level meters should be located where noise from any devices would have no impact on the measurements. In the latter case, improvement in acoustic performance should be considered when planning the building renovation. Assuming that the age of the building may account for the acoustic performance of the building envelope, the study examined the effects of the age of the buildings on the indoor noise levels. The results showed significant differences in the noise levels affected by the age factor, implying potential effects of the acoustic performance of each building. However, it is unknown whether the buildings had undergone any refurbishment in the past and thus, further studies are needed on the relationship between the actual performance of the building envelope and the indoor noise levels. Besides, the present study adopted the recommended level of 45 dBA for Category 3 of ALDREN. It is recommended that a higher level of expectation (e.g., 40 dBA for Category 2) can be aimed when planning for building renovation for providing occupants with better acoustic comforts.

The study found that the floor level of the sites had a significant effect on the indoor noise levels at night-time. This may be due to increased outdoor wind noise exposed to higher floors. It implies that occupants on higher floors are more likely to be exposed to higher outdoor noise levels. Some previous studies have also reported such a tendency of increased outdoor noise levels on the higher floor[18,19] but there are still research needs for in-depth investigation to generalize the finding. Moreover, the study regarded the increased indoor noise levels during the working hours were due to the activities of the occupants because it showed similar tendencies over the five days for all sites. However, it is believed that there is a need for the identification of the noise sources for more accurate investigation. Future research may adopt research methods of noise source localization in order to identify what the noise sources are and where they are coming from.[20,21]

Additionally, the distance from the major road also showed significant effects on the indoor noise levels. In other words, the closer the sites were to the roads, the higher the noise levels were. The study also found that noise levels changed when the sites were grouped by the purpose of the building and the type of surrounding area. These results lead to future investigations on additional variables considering diverse factors related to the building and the surrounding area. Consideration of the indoor space itself is also needed. A suggestion can be made to look into the occupant density of the space. In order to compute the density, information about the average number of occupants in the space and the floor area (m^2) of the space would be needed. Furthermore, a follow-up study can be conducted to examine the data obtained in different seasons, so that the effects of the noise events that the Heating, ventilating and Air Conditioning (HVAC) systems induce can be included.

The study used monitoring sensors. The data were useful to look into the acoustic environments at each site in the long term and to understand the methods for improving occupants' comfort at each site. Nonetheless, there are still limitations in the methods. First, the present study did not obtain frequency characteristics. Given that it only measured sound pressure levels, there was a lack of in-depth data analyses. Second, the study performed one measurement for each site. It cannot be believed that the indoor noise levels measured by one device can represent the acoustic environment of the whole space. Depending on the size of the space, multiple microphones are recommended to be used for more accurate data collection. In addition, the devices were installed close to ceilings, walls, or windows where flanking noises can affect the measures. Given that the measurements were not performed in accordance with the standards, future research should carefully design the measurement procedure. Third, although the IEQ contains three other key attributes (i.e. thermal and lighting environments, and indoor air quality), the present study only focused on the acoustic environment. In order to improve occupants' comfort in indoor environments, it is believed that a comprehensive study of all the IEQ attributes is needed. Lastly, this study did not collect any data on occupants. Future research may expand its scope to the effects of indoor environments on occupants. This would also involve measuring occupants' various psychological and physiological responses.[22] Given that the ultimate goal of a better acoustic environment is for occupants who use the space, it is needed to probe how the level of individuals' demands on the IEQ varies depending on the purpose of the space, job characteristics, and various other individual traits.

V. Conclusions

This study analyzed the measurements of indoor noise levels at 13 open-plan offices in Korean public buildings. The study analyzed the indoor noise measurements performed for five consecutive working days. The measurements were conducted in October 2022. $L_{Aeq,T}$ values were calculated for working hours from 9 am to 6 pm and at night-time from 11 pm to 12 am. The study evaluated the acoustic environments of each site based on the target noise levels that the ISO and the EU ALDREN project have suggested. The results showed that most of the office spaces met the ISO standard during working hours. In addition, three sites did not meet the recommended level of the ALDREN when it was in unoccupied conditions at night-time. The results showed that the indoor noise levels were significantly affected by some features of the sites such as floor or distance from major roads. The manuscript concludes by making discussions on the findings, limitations of the study, and future research directions.

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Profile

▸ Sang Hee Park (박상희)

She completed her Ph.D. at the Acoustic Research Unit, University of Liverpool in 2019. She is currently a senior researcher at the KICT (Korea Institute of Civil Engineering and Building Technology). Her research involves exploring measures to promote human well-being in built environments.

▸ Hye-Kyung Shin (신혜경)

She is currently a research specialist at the KICT (Korea Institute of Civil Engineering and Building Technology). She received her M.S. degree in Dept. of architectural engineering from University of Seoul in 2015. Her research interests are architectural acoustics and environmental noise.

▸ Seung-Min Lee (이승민)

She received her Ph.D. in architectural engineering at Hanyang University in 2002. She has been working at the KICT (Korea Institute of Civil Engineering and Building Technology) as a senior researcher. Her research interest includes zero energy building policy and indoor environmental quality evaluation.

▸ Kyoung Woo Kim (김경우)

He received his Ph.D. in architectural engineering from Hanyang University in 2009. He is working at the KICT (Korea Institute of Civil Engineering and Building Technology) as a Research Fellow. His research interests are floor impact sound, vibration, insulation and absorption in architectural environment.