A Pilot Study on the Combined Multi-domain Impact of Indoor Air Quality and Noise on Office Productivity

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Abstract. As people spend 90% of their time indoors, it was necessary to improve indoor environmental quality to enhance human productivity. Indoor environmental quality consists of indoor air quality (IAQ), thermal, visual, and acoustic comfort. However, only a few studies have investigated the combined effects of IAQ and noise. During and after the COVID-19 pandemic, portable air cleaner is often used in buildings to reduce the concentration of particles in the air, but it also generates noise. The objective of this study is to determine the effects of a portable air cleaner on IAQ and noise level, and more importantly the resulting combined effects on office productivity. For this purpose, we conducted human subject tests in an office and each test lasted for 1.5h. For each case, the air temperature, relative humidity, and supply airflow rate were kept constant while the air cleaner was switched between on and off for various noise levels and IAQ. We recruited 7 participants and collected data on the concentration of CO2, particles, and TVOC every 5 minutes. We used wristbands to measure heart rate and skin electrodermal activity. And we used headbands to measure electroencephalogram (EEG) and facial activity. The questionnaire survey was used to learn the occupants’ responses to the indoor environment. To learn their productivity, occupants also did math addition tasks and typing tasks. We found that when using the portable air cleaner, the noise level raised from 55dB to around 70dB. The particle and TVOC concentrations were reduced by 90% and 20%, respectively. The questionnaire survey showed that the occupants felt unsatisfied due to noise. And the noise dissatisfaction exceeded the improved IAQ. By analyzing the EEG and the number of jaw clenches, the occupants felt more nervous and concentrated when the air cleaner was on. We confirmed the impact of noise and the combined impact of IAQ and noise on office productivity.

1 Introduction

As people spend 90% of their time indoors, it was necessary to improve indoor environmental quality to enhance human productivity. Indoor environmental quality consists of indoor air quality (IAQ), thermal, visual, and acoustic comfort. Among them, IAQ was a very important factor, especially after the COVID-19 pandemic [1]. Previous studies have found that indoor environmental quality impacted occupants’ productivity. For example, for thermal comfort, if the air temperature was higher or lower than the comfort level, the relative performance would drop by 10% to 15% [2]. As for IAQ, productivity would also drop by 10% if 70% of occupants were dissatisfied with the IAQ. Poor IAQ may also cause sick building syndrome (SBS), such as feeling sick, dry skin, and fatigue. These health effects really impacted the productivity in offices. But the relationship between different IAQ factors and SBS was very complex. A previous study [3] showed the SBS of IAQ in nine naturally ventilated schools in Greece. The perception of indoor environmental quality through questionnaires in conjunction with in-field measurements related to the IAQ, thermal comfort, and lighting environment was studied. Significant positive correlations were found between particulate matter and certain health symptoms. Student performance appeared to be affected by ventilation rates and CO2 concentrations, while some health effects were positively correlated with particle and CO2 levels. One recent study by Satish et al. [4] showed the impact of volatile organic compounds (VOCs) on decision-making and productivity. They found that productivity was a function of decision-making at various VOC levels. Significant decrements related to productivity in paint exposure. Xu et al. [5] summarized the specific VOCs with great impact in offices, such as acrolein, acetone, and methyl isobutyl ketone. Acetone, ethanol, toluene, naphthalene, and acrolein were the most abundant VOCs. Wallenius et al. [6] found that high mold counts and high TVOC led to adverse health perceptions. They also found that a higher number of female participants experienced SBS compared to males. The particle concentration and CO2 concentration had relationship with SBS, such as allergy, headache, throat irritation, and cough. Fisk [7] estimated the money-saving and productivity gain from improving the indoor environment. Thus, it is very important to design building heating, ventilation, and air conditioning (HVAC) systems with good environmental quality to improve the occupants’ productivity.

It is very challenging to evaluate the productivity of occupants because it was very difficult to determine the
baseline and the difference between various subjective evaluation methods [8]. We need to learn that deeply in a physiological way. Previously, researchers have tried to collect physiological signals for occupants’ feedback. For example, for thermal comfort, people found that the skin temperature, heart rate, and electroencephalogram (EEG) pattern were different when feeling comfortable and warm or cold [9, 10]. Similarly for acoustic comfort, people also found a similar result that the different number of electrodermal activity (EDA) indicated the occupants felt nervous or relaxed [11]. And the physiological responses were not affected by the type of noise source and the sound pressure level. As for heart rate, it typically indicated the metabolism. However, most previous studies only focused on one factor. We need to find the relationship between physiological signals and productivity for multi-domain indoor environmental quality factors [12], especially the combined effects of IAQ, visual comfort, and acoustic comfort. Then we can design the indoor environment and HVAC system for better environmental quality. Previously, only a few researchers have studied the interaction of IAQ and the thermal environment. For example, both air temperature and RH could impact the perception of IAQ factors [13]. And people also found that the air temperature and RH may impact the particle and virus viability [14]. Another previous study by Clausen et al. [15] did chamber tests on the relative importance of sensory air pollution, thermal load, and noise, and how the IAQ factors, air temperature, and noise affected the comfort. They found that 1°C change in operative temperature was found to have the same effect on human comfort as a deterioration in the perceived air quality of 2.4 decibol or an increase in noise level of 3.9dB. Pan et al. [16] did chamber experiments to investigate the interaction between perceptions of noise and odor in humans. They did tests on nine healthy subjects and concluded that additions of noise reduced the perception of discomfort from odor. However, additions of odor had no or little effect on the perception of noise. Therefore, when IAQ factors interacted with lighting and noise, it was much more complex with no clear conclusion [16]. A recent review by Torresin et al. [17] showed that the related studies of IAQ interactive with other environmental factors were very few. For example, there were 29% of previous studies focused on the interaction of temperature and lighting, 24% focused on temperature and noise, and 9% on temperature, noise, and lighting, but only 18% focused on temperature and IAQ. Only less than 10% of the previous research focused on the interaction between IAQ with noise and lighting. To summarize the past research findings, the multi-domain indoor environmental quality and the combined effect of IAQ and other factors was not well studied. What is more, some IAQ parameters may affect physiological parameters, such as EEG and EDA, but the relationship and sensitivity were not clear. The correlation between physiological parameters and office productivity in various IAQ and noise levels was not well studied. Therefore, to study the IAQ and productivity and provide better indoor environments, we need to focus on both environment and occupants, and monitor both the environmental factors and physiological parameters. During and after the COVID-19 pandemic, portable air cleaner is often used in buildings to reduce the concentration of particles in the air [18], but it also generates noise. The research questions were that how the portable air cleaner affects indoor air quality and noise level, and what are their combined effects on office productivity and physiological signals.

The objective of this study is to answer the above-mentioned research questions. For this purpose, we conducted human subject tests in an office to collect the data and analyzed the multi-domain impact of IAQ and noise on office productivity. We monitored the IAQ factors such as CO₂, particle, and TVOC concentration. We also used wristbands and headbands to record the various physiological signals in different IAQ and noise levels. The questionnaire survey was used to learn the occupants’ responses to the indoor environment. To learn their productivity, occupants also did math addition tasks and typing tasks. By analyzing the collected data, we could verify the hypothesis of the combined impact of IAQ and noise level on office productivity.

2 Methods

2.1 Set up of human subject tests

We conducted human subject tests at the Syracuse Center of Excellence to collect data on IAQ, noise level, and physiological signals. Fig. 1 (a) shows the private office for data collection. We controlled the air temperature to around 23°C and relative humidity (RH) to around 25-35% during the tests. There were multiple ventilation systems in the office, and we used displacement ventilation in this study. The ventilation system in the room provided 66 CFM (cubic feet per minute) of outdoor air, which was based on ASHRAE Standard 62.1 with room area and the number of occupants. Occupants wore normal office cloth (clo=1.0) during the tests. There were 7 volunteers (5 males and 2 females) participating in the human subject tests in this paper. They were all university students and the range of age was from 25 to 30. The range of Body mass index (BMI) of the participants was from 16.7 to 31.5.
2.2 Procedure of human subject tests

In addition, in order to evaluate the occupants’ productivity in the office, we used two kinds of tasks in the human subject tests. They were math addition tasks and typing tasks, as Fig 3 shows. The math addition task (https://www.factmonster.com/math/flashcard?op[0]=addition&level=5) was two-digit addition. The subjects needed to answer as many as possible within the allotted time. As for the typing task, the online program (https://www.ratatype.com/typing-test/) randomly selects a passage that the subject needed to type. The program could record the speed and accuracy of addition and typing. After the two tests, we summarized the speed and accuracy of all the occupants in various tests and used these results to evaluate the impact on productivity.

We also used hand-written questionnaire surveys to learn the occupants’ responses to the indoor environment quality and their productivity. The occupants would answer the survey to indicate their feeling, preference, and vote on indoor air quality and noise. They also indicated environmental satisfaction. As for productivity, they also provided self-assessed productivity and how different environmental factors affected productivity. Fig 4 shows the timeline of the human subject test. All the human subject tests were in the morning starting between 9 am and 10 am. This was to exclude the interference of time and diet factors. The participants were asked to not stay up late the night before the tests, and not smoke, or drink coffee or alcohol before the tests. This was to avoid the impact of these factors on

![Fig. 4. Timeline of math addition test, typing test, and measurements for 30 minutes in each case of human subject tests.](image-url)
productivity. Before the tests, the office was preconditioned for half an hour to obtain a steady state environment. And the participants were trained by the researchers to get familiar with the testing program and the data collection devices. During the 25-minute measurement in each case, the participants first did addition tests for 5 minutes and then typing tests for 5 minutes. This was mostly used to mimic typical office work. Between the two tests, the occupants rest for 3 minutes. Then we measured ECG and EDA with the Fitbit wristband. And the participants answered the questionnaire survey. After each case, the participants rested for 5 minutes. The heart rate and EEG were monitored during the test all the time.

To study the combined impact of IAQ and noise level on productivity, we used a portable air cleaner (IQAir-HealthPro Plus) inside the office to generate noise and improve the IAQ as Fig 5 shows. The flow rate of the portable air cleaner was 300CFM (500m³/h). It could achieve pelleted chemisorption, granular activated carbon adsorption, micro-particle filtration, and Hyper HEPA filtration. When turning on, the concentration of TVOC and particles could drop quickly. We also measured the noise level in the office with the air cleaner on. We found that the noise level was 68 dB, 58 dB, and 55 dB when the distance was 0m, 2m, and 4m from the air cleaner, respectively. And the background noise level in the office was 47 dB. The high-performance filter of the air cleaner could be removed. Without the filter, it could only generate noise but did not impact the IAQ in the office. Since the purpose of the human subject tests was to investigate the integrated impact of IAQ and noise level on productivity, we tested three cases as Table 1 lists. Case 1 was when the air cleaner was off with poor IAQ and no generated noise. This was the baseline and reference case in the office. Case 2 was when the air cleaner was on without the filter so that the IAQ was poor but the noise was high. Case 3 was when the air cleaner was on with the filter. In this case, the IAQ was good but the noise level was still high. Comparing Case 2 with Case 1, we could find the separate impact of the noise level. Comparing Case 3 with Case 1, we could find the combined impact of IAQ and noise level on office productivity.

![Portable air cleaner in the office and the flow setting.](Fig. 5)

<table>
<thead>
<tr>
<th>Case</th>
<th>Air cleaner</th>
<th>Filter</th>
<th>IAQ</th>
<th>Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Off</td>
<td>-</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>On</td>
<td>Not used</td>
<td>Poor</td>
<td>High</td>
</tr>
<tr>
<td>3</td>
<td>On</td>
<td>Used</td>
<td>Good</td>
<td>High</td>
</tr>
</tbody>
</table>

2.3 Data analysis of EEG signals

After the human subject tests, we analyzed the collected data to find the relationship between the physiological signals and office productivity. Previously, researchers have identified some correlations between different physiological signals and comfort. For example, the more number of jaw blench indicated the nervousness. The number of EDA could be a measure of emotional and sympathetic responses. As for the brain wave, by using the frequency filter on EEG, we could get the data for different frequency bands from low to high, such as Delta (0.5-4Hz), Theta (4-8Hz), Alpha (8-12Hz), Beta (12-27Hz), and Gamma (27Hz and up). Different frequency bands mean the brain states were different, such as concentrated, active, or relaxed. For example, Delta represented the brain state was sleeping. Theta meant a deeply relaxed condition. Alpha represented a very relaxed state. Beta represented alert and focus. And Gamma represented the brain was in concentration and high performance. Therefore, in this study, we also used a frequency filter to obtain the signal on different frequency bands. Then we could use the data to calculate the absolute power and relative power of different frequency bands of EEG. The high power represented that the frequency band dominated the brain activity. The absolute power could be calculated with the following equation

\[ E_i = \sum |D_i|^2 \]

where i and j run all the time and locations on the human head. The relative power of each frequency band could be calculated based on the absolute power over their summation by

\[ E_r = \frac{E_i}{\sum E_i} \]

3 Results

The above methods in Section 2 conducted human subject tests to collect the related data on environmental factors, questionnaire surveys, and physiological signals. Then in this section, we would analyze the data to determine the relationship on productivity.

3.1 Comparison of IAQ, noise level, and productivity results in three cases

![Comparison of IAQ, noise level, and productivity results in three cases](a) (b)
Fig. 6 shows the comparison of CO₂, TVOC, and particle concentration with different noise levels in the three cases. When using the portable air cleaner with a filter, the TVOC and particle concentration dropped quickly. The average particle concentration dropped from 5 μg/m³ in Case 1 & 2 to 0.8 μg/m³ in Case 3 as Fig 6 (c) shows. Fig 6 (b) indicated that the average TVOC concentration dropped from 480 μg/m³ to 380 μg/m³. The particle and TVOC concentrations were reduced by 90% and 20% with the air cleaner, respectively. However, the portable air cleaner could not reduce the CO₂ concentration. During the tests, the CO₂ concentration was between 500 and 1000 ppm over the time during the tests, with an average of around 900 ppm, as Fig 6 (a) displays. The CO₂ concentration did not exceed 1000 ppm most of the time. A previous study [19] has found that 1000-2000 ppm of CO₂ may cause fatigue and drowsiness, and 3000 ppm may cause difficulty in thinking and long response time. So the concentration of CO₂ in this study may not have a significant effect on productivity in different cases. We also found that when using the portable air cleaner, the noise level raised from 55 dB to around 70 dB. Thus, compared between the three cases, we could reveal the impact of noise level and IAQ on occupant productivity and physiological signals.

Fig. 7 displays the results of the addition test and typing test in the three cases. For the addition test, we found that the accuracy was reduced from 98-100% to 94-97% with the air cleaner on and the noise level increased in Cases 2 and 3. Although the speed raised a little from 36 to 42. Fig 7 (b) indicated that the average TVOC concentration dropped from 97% to 96% with the noise level increased in Cases 2 and 3. The typing speed also reduced from 48 wpm (word per minute) to 44 wpm. The speed was reduced by about 8%. Since productivity was related to both speed and accuracy, in the tests, higher speed may lead to lower accuracy due to psychological trade-offs. To evaluate office productivity with the relationship between both speed and accuracy, then we used the following equation to evaluate the inverse efficiency score (IES) in offices, the most frequently used measurement that integrated response time (RT) and proportion of error (PE) [20]:

\[ IES = \frac{RT}{1 - PE} \]

We found that in Case 1, the average IES of the addition test and typing test were 0.036 and 0.032, respectively. In Case 2 with noise generated by the air cleaner, the average IES of the two tests was 0.034 and 0.03. In Case 3, they were 0.030 and 0.028. Therefore, the noise of the air cleaner really impacted the occupant productivity in offices. Only the noise may reduce productivity by 16% and 13% in addition and typing tests. However, the improved IAQ did not show a significant positive impact on productivity.

3.2 Results of the questionnaire survey

Fig. 8. Comparison of subjective questionnaire survey results in the three cases: (a) environmental satisfaction and (b) effect on productivity.

After analyzing the testing results in three cases, we also checked the questionnaire survey, in which the
participants also voted on their satisfaction and how different factors affect their productivity. Fig 8 illustrates the questionnaire survey results of IAQ and noise perception in the three cases. We found that the noise dissatisfaction of occupants exceeded the IAQ improvement by the air cleaner. And the noise level really had a negative effect over IAQ on productivity. Fig 8 illustrates the questionnaire survey results of IAQ and noise perception in the three cases. We found that the noise dissatisfaction of occupants exceeded the IAQ improvement by the air cleaner. And the noise level really had a negative effect over IAQ on productivity. Fig 9 shows the self-assessed productivity by the occupants. For the estimated productivity in the specific environment compared to normal office, the alternative answers include: below 80% - much lower than normal, 80~90% - lower than normal, 90~100% - slightly lower than normal, 100% - around normal, 100~110% - slightly higher than normal, 110~120% - higher than normal, and above 120% - much higher than normal. In Case 1, the baseline with no noise and poor IAQ, the self-assessed productivity was around 100%, the normal productivity. However, the noise of the air cleaner reduced productivity by 10% and 5% in Cases 2 and 3, respectively.

3.3 Results of physiological signals

Fig. 10. Comparison of physiological signals in the three cases: (a) heart rate, (b) EDA, (c) eye blink, and (d) jaw clench.

After checking the questionnaire survey, we also analyzed the physiological signals in various cases with different noise levels and IAQ. Fig 10 shows the comparison of the physiological signals, such as heart rate, EDA, eye blink, and jaw clench. We found that the heart rate showed no significant change among various cases. The average was 72, 71, and 66 beats per minute (bpm). This physiological factor also showed large personal differences. The varied range could be 30 bpm. Since the heart rate primarily represented the participants' basal metabolic rate, the room air temperature remained in the comfortable range of 23°C. The small reduction in heart rate only indicated that the participants were gradually calming down during the 1.5-hour test. As for the EDA, it showed a little variation. The average number was 20, 20, and 18 in the three cases with 10% variation. Even though previous studies have found that noise could increase EDA, we did not observe this phenomenon in this study, as EDA only varied 15% from Case 1 to 3. Finally, we found that in Cases 2 and 3 when the noise level was high, although the number of eye blinks did not increase very much, the number of jaw clench raised a lot. The average number raised from 1.5 bpm in Case 1 to 3 bpm in Case 2 and 7 bpm in Case 3. This 300-500% of huge boost showed the nervousness and anxiety of the participants with noise.

Finally, we analyzed the EEG signals collected by headbands. Fig 11 shows the results of EEG absolute and relative power for various frequency bands in the three cases. The absolute power showed that Delta, Theta, and Alpha decreased only in Case 3. The pattern of relative power was different in the three cases. We found that with noise levels in Cases 2 and 3, the increase of relative power for the Gamma band meant the brain status was from active to more concentrated. And the reduction of the relative power of the Delta band meant the brain status from sleep to active. The Theta and Alpha band did not show much variation. Therefore, brain activity became more concentrated and active as the noise was generated by the air cleaner. The improved IAQ did not show a clear impact on brain activity.
4 Discussion

Since the multi-domain indoor environmental factors and the interaction and combined effect of IAQ and other factors was not well studied, in this study, we focused on the combined impact of IAQ and the noise of portable air cleaner on office productivity. We conducted human subject tests to collect the related data. Addition tests and typing tests were used to evaluate office productivity. The environmental factors were well controlled. The highlight of the present study was that we also monitored the physiological signals, such as EDA, ECG, EEG, eye blink, and jaw clench. Since the combined effect of IAQ and noise was complex, by analyzing these physiological signals, we could get a better understanding of this effect. This was a great supplement to the subjective results of the questionnaire survey. The interesting findings were that the number of jaw clenches and the relative power of brain waves of participants in different cases clearly represented the effect of IAQ and noise on productivity.

As for the limitation of the current study, the number of participants was not large enough. More participants could obtain better de-biased results. And the age range of the participants was not wide enough. Participants were often young students, and they were not necessarily representative of the population. We could only draw conclusions on the effect of IAQ and noise on productivity for young office workers. Future works include expanding the size and age range of the human subject tests to reach broader conclusions. What is more, the IAQ did not show a significant impact over noise on productivity. The possible reason was that the impact of short-term variation of IAQ was not clear. The long-term impact was not well studied. Most previous studies were also short-term, as conducting research in actual buildings for long-term study was very hard. Therefore, the long-term study of the impact of IAQ and noise level on productivity is also a future research direction.

5 Conclusion

In this study, we recruited 7 participants and conducted human subject tests to collect data on IAQ, noise, questionnaire survey, and physiological signals. We try to answer the research question that how the portable air cleaner affects IAQ and noise level, and their combined effects on office productivity and physiological signals.

The main conclusions are listed below:
1. Through addition tests and typing tests, only the noise may reduce the productivity by 16% and 13%. However, the improved IAQ did not show a significant positive impact on productivity. The questionnaire survey showed similar results. The noise dissatisfaction of occupants exceeded the IAQ improvement by the air cleaner.
2. The heart rate, EDA, and eye blink did not vary very much with 10-15% variation when the noise level was raised and IAQ improved. However, the 300-500% of huge boost in the number of jaw clenches showed the nervousness and anxiety of the participants with noise.
3. By analyzing the EEG signals, the relative power variation of the Gamma band and the Delta band meant the brain status was more concentrated and active when the noise was generated by the air cleaner. Therefore, the more concentrated and active brain activity resulted in the impact of noise generated by the air cleaner on productivity. The improved IAQ did not show a clear impact on brain activity.

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