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Impact of Urban Air Pollution on Occupants' Visual Comfort, Alertness, Mood in an Office with Various Glazing Systems

An Investigation in Beijing

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ABSTRACT: Urban air pollution is currently one of the top 10 worst pollution problems in China. It can not only worsen indoor air quality but also substantially reduce daylight availabilities in buildings, both of which are directly linked to occupants' health and well-being. This article presents results of a winter experiment focusing on testing human performances in a daylit office room with three various glazing systems in Beijing. The impact of external air pollution on occupants' visual comfort, alertness and mood is the research focus. Some important findings can be achieved as follows: 1) Urban air pollution can significantly reduce the indoor daylighting availability; 2) Urban air pollution would significantly affect occupants' performances. 3) The impact varies in window glazing type and colour. Most importantly, it seems that a properly selected glazing system could mitigate the negative impact of urban air pollution on human performances.

KEYWORDS: Air pollution, Visual comfort, Alertness and mood, Glazing systems, Office

1. INTRODUCTION

Several surveys have exposed that there is a substantial link between daylighting and visual performance, alertness, and mood in offices [1-4]. Based on subjective assessments, two studies showed that the glazing systems may have a significant effect on visual and non-visual performances of office workers [5-6]. Figueiro & Rea [2] pointed out that more investigations would be required in order to further clarify how daylight regulates sleep and mood, especially in working places. Currently, urban air pollution is the world's top 10 worst pollution problems, especially in China [7]. It can not only worsen indoor air quality, but also significantly reduce daylight availabilities in buildings, both of which can affect occupants' health & well-being.

This study presents results of a winter experiment focusing on testing human performances (visual and non-visual aspects) in a daylit office room with various glazing systems in Beijing. The effect of external air pollution on occupants' visual comfort, alertness and mood is the research focus.

2. METHODS AND MATERIALS

Three parts were included in this section, such as room description and glazing types, subjective assessment, as well as lighting measurement and the approach used for displaying external air quality in urban areas.

2.1 Office room and glazing types

From 17th November 2016 to 11th January 2017, the experiment was conducted in an office of the School of Architecture at Tsinghua University in Beijing. On average, this city has the annual sunshine hours of 2707. Figure 1 shows room plan and dimensions, window, and sitting positions. This room has a dimension of 6.3 × 3.2 × 3.6 m and its surface reflectances are: 0.3 (floor), 0.88 (wall), and 0.88 (ceiling). Two spaces are separated as one testing room (length 4.6m) and the preparation room (length 1.7m). This office has only one side window facing south, and several sitting positions including A1 & A2 (working places for participants), B (for the person who conducted measurements and controlled the experiment). Three types of glazing were individually applied at the window, including clear, bronze and blue. Their visual transmittance (VT) values are 0.92, 0.37 and 0.55 respectively.

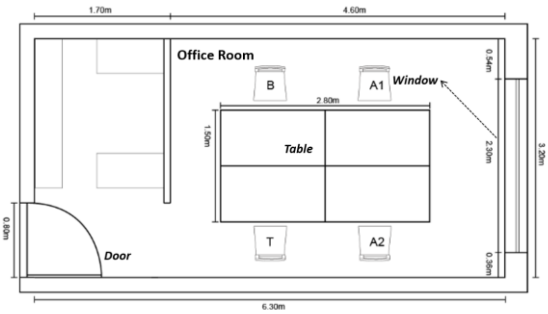

Figure 1: Room plan and dimension, window, and sitting positions.

2.2 Participants and subjective assessments

Seventeen participants were recruited from the university students and staffs (mean age: 22.68 ±1.8 years). No participants should have medical and psychiatric diseases and sleep disorders. All participants were required to attend the experiment during a normal work schedule (8:30 – 16:00). The daily experiment was divided into two time-slots: 08:30-11:30 and 13:00-16:00, with a 1.5 hours lunch break in between. In order to control prior light exposure, each participant was asked to start his/her sleep earlier than 23:00 at the night before the testing day. During the experiment, the participants were just allowed to carry out regular office work in the office room, such as reading, writing, typing, etc. No food and drinks with caffeine or similar content can be taken on the testing day.

Two VAS (visual analogue scale [8], 0-100mm) questionnaires were adopted to assess visual and non-visual performances. The questions for visual performance are: VQ1, Room lighting is comfortable? (0mm, extremely uncomfortable; 100mm, extremely comfortable); VQ2, Room is bright? (0mm, very bright; 100mm, OK); VQ3, Room is dark? (0mm, very dark; 100mm, OK); VQ4, Glare? (0mm, intolerable; 100mm, Imperceptible); VQ5, Light colour is comfortable? (0mm, extremely uncomfortable; 100mm, extremely comfortable); VQ6, Colour appearance is proper? (0mm, absolutely not; 100mm, perfect). These questions were suggested and/or applied in two field surveys of lighting and human performances [4, 9]. In addition, four questions were used for assessing non-visual aspects: NVQ1, Alertness (0mm, extremely sleepy; 100mm, extremely alert); NVQ2, Mood (0mm, very bad; 100mm, very good); NVQ3, Physical well-being (0mm, very uncomfortable; 100mm, very comfortable); NVQ4, Relaxation (0mm, very tense; 100mm, very relaxed). Their applications were also reported in the study [4]. The use of such questions to investigate self-reported satisfaction of psychological and physiological well-being was supported by another study [10]. Each participant was asked to complete the two questionnaires every 45 minutes.

2.3 Lighting measurements and air quality index

The daylighting conditions were measured by a portable Illuminance Colour Spectral meter (SPIC-200). Each meter reading was recorded every 10 minutes. Three key values were available in this investigation: illuminances at the table and near the participant's eyes (lux), and correlated colour temperature (CCT) near the eyes (K). No artificial lighting can be used in the experiment, even if the daylighting level was insufficient to meet the lighting standard at the working plane (e.g. late afternoon).

At the same time, a six-level air quality index (AQI) was used to justify the external air pollution level [11], such as excellent, good, lightly polluted, moderately polluted, heavily polluted, and severely polluted.

In addition, the indoor temperature and humidity were measured as a reference of thermal conditions.

3. RESULTS AND DISCUSSIONS

IBM_SPSS (v23) was the data analysis package (measurement and questionnaire feedback). ANOVA and *Post Hoc* test were the main statistical approaches in terms of various analyses. The significance was achieved when $p<0.05$.

3.1 Measurement: Illuminance and CCT

Table 1 shows mean daylight illuminances and CCT measured near participants' eyes and their standard error of the mean (SEM). Apparently, there were differences of illuminance and CCT between the three glazing systems. The largest illuminance was found with the clear glazing, whilst the blue glazing can bring in the highest CCT.

Table 1: Mean and standard errors of the mean of Illuminance and CCT at eyes

	Mean ± SEM	
Glazing type	Illuminance_eye (lux)	CCT_eye (K)
Clear	1045.32 ±202.18	4472.23 ±26.85
Bronze	602.10 ±88.88	4007.39 ±59.36
Blue	711.03 ±102.90	5376.40 ±33.95

Figure 2 gives distributions of mean illuminance near eyes in terms of AQI levels. Based on one-way ANOVA analysis, it can be found: the indoor daylight illuminance received notable impact from AQI ($F(5, 673)=8.94$, $p<0.01$).

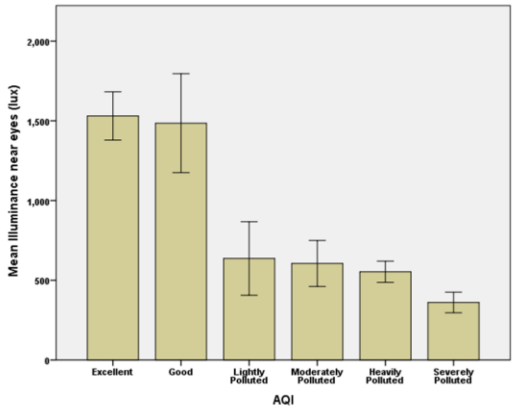

Figure 2: Mean illuminance values and external air quality.

Due to the unequal sample size of AQI, a *Post Hoc* test (Scheffe [12]) was conducted to compare various groups. Only the significant differences are reported in Table 2. 'Excellent' AQI had a significant difference in illuminance levels from 'Severely Polluted' & 'Heavily Polluted' conditions ($p<0.01$). There were also significant differences between 'Good' and 'Heavily Polluted' AQI ($p<0.05$). The measured illuminances between the groups without pollutions, and between the groups with pollutions, however, displayed no significant differences ($p>0.05$). The heavy air pollutions can significantly reduce the indoor daylighting levels near the eyes.

Table 2: Significant differences of mean illuminance between AQI groups (Post Hoc) (p<0.05)

AQI(I)	AQI(J)	Mean Difference (I-J)	Std. Error	Sig.
Excellent	Heavily Polluted	977.10	197.23	0.00
Excellent	Severely Polluted	1169.83	245.27	0.00
Good	Severely Polluted	1124.43	330.04	0.04

3.2 Subjective feedback: visual effects

The feedback of six visual performance questions was assessed based on three types of glazing in this section (only significant main effects or differences are presented in figures and tables).

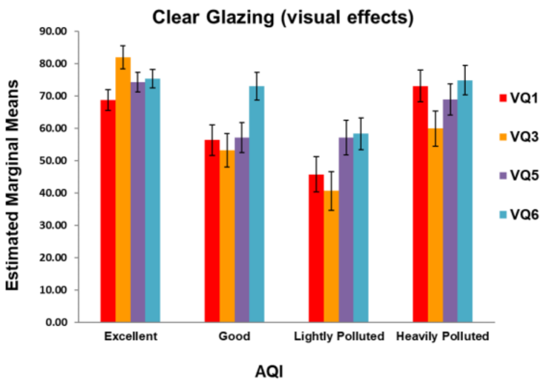

Figure 3: Mean values and standard errors of the mean of feedback of visual questions (clear glazing). (p<0.05)

Table 3: Post Hoc test of mean differences of AQI groups (visual, clear glazing). (p<0.05)

Q	AQI(I)	AQI(J)	Mean Difference (I-J)	Std. Error	Sig.
VQ1	Excellent	Lightly Polluted	22.97	6.32	0.01
VQ1	Lightly Polluted	Heavily Polluted	27.39	7.38	0.00
VQ3	Excellent	Good	28.78	6.29	0.00
VQ3	Excellent	Lightly Polluted	41.30	6.91	0.00
VQ3	Excellent	Heavily Polluted	21.98	6.46	0.01
VQ5	Excellent	Good	17.22	5.59	0.03
VQ6	Excellent	Lightly Polluted	17.08	5.73	0.03

With the clear glazing (Figure 3), significant main effects of four AQI levels (Excellent, Good, Lightly Polluted, and Heavily Polluted) can be found on four aspects of visual performance (p<0.05), including 'Lighting Comfort' (VQ1, F(3, 124)=6.42); 'Darkness' (VQ3, F(3, 124)=15.38); 'Colour comfort' (VQ5, F(3, 124)=4.56); 'Colour appearance' (VQ6, F(3, 124)= 3.17). There were no significant main effects on the 'Brightness (VQ2) & Glare (VQ4)' (p>0.05). As shown in Table 3, pairwise comparisons using Scheffe model demonstrated the differences. For VQ1, first, significant differences can be found between 'Excellent' and 'Lightly Polluted', and between 'Lightly Polluted' and 'Heavily Polluted' (p<0.05). The excellent air quality could make occupants feel more comfortable than the slightly polluted condition. The heavy pollutions did not bring in significant differences from the conditions of good & excellent air quality based on this issue (p>0.05). Second, the feedback of darkness (VQ3) was significantly different between 'Excellent' and 'Good' (p<0.05), and between 'Lightly Polluted' and 'Heavily Polluted' (p<0.05). For colour comfort and appearance (VQ5 & 6), third, the feedback with excellent air quality was significantly different from that with 'Good' (p<0.05) or 'Lightly Polluted' (p<0.05), and had no significant difference from 'Heavily Polluted' (p>0.05).

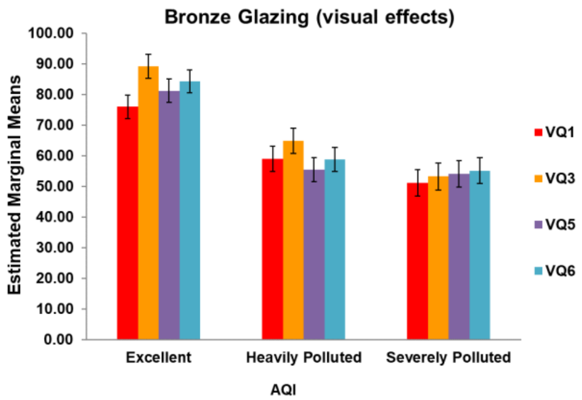

Figure 4: Mean values and standard errors of the mean of feedback of visual questions (bronze glazing). (p<0.05)

Table 4: Post Hoc test of mean differences of AQI groups (visual, bronze glazing). (p<0.05)

Q	AQI(I)	AQI(J)	Mean Difference (I-J)	Std. Error	Sig.
VQ1	Excellent	Heavily Polluted	17.00	5.58	0.01
VQ1	Excellent	Severely Polluted	24.79	5.82	0.00
VQ3	Excellent	Heavily Polluted	24.23	5.64	0.00
VQ3	Excellent	Severely Polluted	35.82	5.89	0.00
VQ5	Excellent	Heavily Polluted	25.77	5.52	0.00
VQ5	Excellent	Severely Polluted	27.15	5.76	0.00
VQ6	Excellent	Heavily Polluted	25.43	5.45	0.00
VQ6	Excellent	Severely Polluted	29.13	5.68	0.00

For the bronze glazing, in Figure 4, only three AQI levels of were available during the test: Excellent, Heavily Polluted and Severely Polluted. Similarly, the main effects of AQI on four visual aspects have been found as significant (p<0.05), such as 'Lighting Comfort' (VQ1, F(2, 121)=9.85); 'Darkness' (VQ3, F(2, 121)=19.95); 'Colour comfort' (VQ5, F(2, 121)=15.11); 'Colour appearance' (VQ6, F(2, 121)= 16.54). It seems that no significant links can be observed between

'Brightness (VQ2) & Glare (VQ4)' and external pollution levels. Given Scheffe pairwise comparisons (Table 4), 'Excellent' air condition led to significantly different feedback from both 'Heavily and Severely Polluted' conditions in terms of VQ1, 3, 5 and 6 ($p<0.05$). In general, higher comfort levels of both lighting and colour (VQ1 & 5), fewer complaints of darkness (VQ3), more acceptance of light colour (VQ6) can be found with 'Excellent' AQI than the heavy pollution conditions ($p<0.05$). However, there were no significant differences of these issues between the two pollution conditions ($p>0.05$).

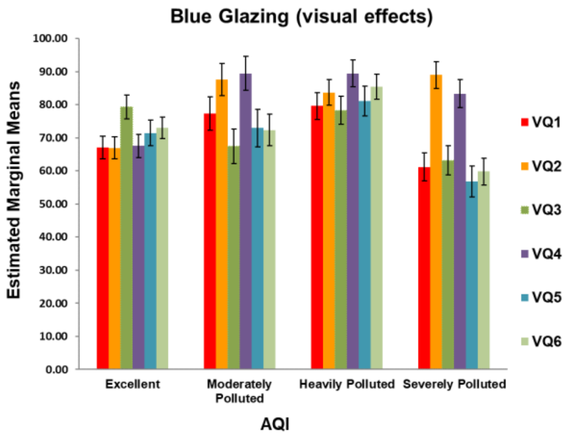

Figure 5: Mean values and standard errors of the mean of feedback of visual questions (blue glazing). (p<0.05)

Table 5: Post Hoc test of mean differences of AQI groups (visual, blue glazing). (p<0.05)

Q	AQI(I)	AQI(J)	Mean Difference (I-J)	Std. Error	Sig.
VQ1	Heavily Polluted	Severely Polluted	18.46	5.85	0.02
VQ2	Excellent	Moderately Polluted	-20.59	5.86	0.01
VQ2	Excellent	Heavily Polluted	-16.72	5.11	0.02
VQ2	Excellent	Severely Polluted	-22.01	5.25	0.00
VQ3	Excellent	Severely Polluted	16.22	5.69	0.05
VQ4	Excellent	Moderately Polluted	-27.66	6.17	0.00
VQ4	Excellent	Severely Polluted	-23.15	5.53	0.00
VQ5	Heavily Polluted	Severely Polluted	24.31	5.70	0.00
VQ6	Heavily Polluted	Severely Polluted	25.64	5.84	0.00

When using the blue glazing, four AQI levels were available: Excellent, Moderately Polluted, Heavily Polluted and Severely Polluted. In Figure 5, significant main effects of AQI were found for all six questions ($p<0.05$): 'Lighting Comfort' (VQ1, $F(3, 129)=4.27$); 'Brightness' (VQ2, $F(3, 129)=7.85$); 'Darkness' (VQ3, $F(3, 129)=3.61$); 'Glare' (VQ4, $F(3, 129)=10.35$); 'Colour comfort' (VQ5, $F(3, 129)=6.21$); 'Colour appearance' (VQ6, $F(3, 129)=6.44$). Furthermore, the *Post Hoc* (Scheffe) test in Table 5 displayed some results different from the clear and bronze glazing. For the feedback of lighting and colour comfort (VQ1, 5) and colour appearance (VQ6), there were no significant differences between 'Excellent' AQI and the three pollution conditions ($p>0.05$), while 'Heavily Polluted' significantly receives higher acceptance rates than 'Severely Polluted' ($p<0.05$). Normally, the feedback of 'Brightness & Darkness (VQ2 &3)' showed 'Excellent' brought in a brighter lighting environment than other pollution conditions ($p<0.05$). Therefore, the pollutions (moderate & severe) conditions might deliver a lower possibility to get glare problem (VQ4) ($p<0.05$).

3.3 Subjective feedback: non-visual effects

The feedback of four non-visual questions was evaluated with three types of glazing as follows (only significant main effects or differences are presented in figures and tables).

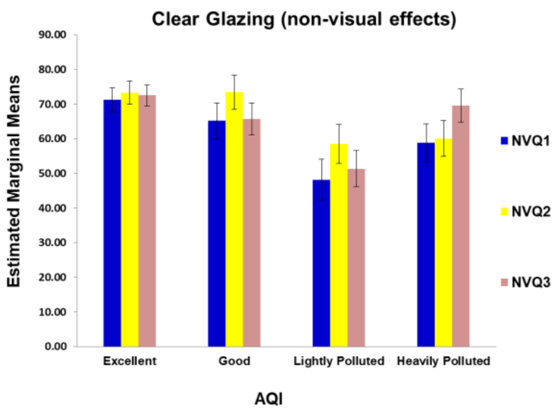

Figure 6: Mean values and standard errors of the mean of feedback of non-visual questions (clear glazing). (p<0.05)

Table 6: Post Hoc test of mean differences of AQI groups (non-visual, clear glazing). (p<0.05)

Q	AQI(I)	AQI(J)	Mean Difference (I-J)	Std. Error	Sig.
NVQ1	Excellent	Lightly Polluted	23.07	6.91	0.01
NVQ3	Excellent	Lightly Polluted	21.17	6.05	0.01

As regards the clear glazing (Figure 6), significant main effects of four AQI levels (Excellent, Good, Lightly Polluted, and Heavily Polluted) can be observed on three aspects ($p<0.05$): 'Alertness' (NVQ1, $F(3, 124)=4.09$); 'Mood' (NVQ2, $F(3, 124)=2.97$); 'Physical well-being' (NVQ3, $F(3, 124)=4.20$). The 'Relaxation (NVQ4)' was not significantly affected by AQI ($p>0.05$). The pairwise comparisons using Scheffe model (Table 6) supported that significant differences were only found for 'Alertness' and 'Physical well-being' between 'Excellent' and 'Lightly Polluted' conditions ($p<0.05$).

It is normal that 'Excellent' AQI led to a more positive feedback on alertness and physical well-being. Similar to the visual feedback analysis above, there were no significant differences between 'Excellent' or 'Good' AQI and 'Heavily Polluted' condition for all the four aspects (p>0.05).

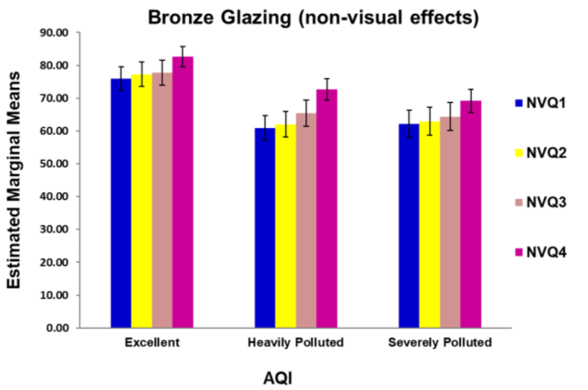

Figure 7: Mean values and standard errors of the mean of feedback of non-visual questions (bronze glazing). (p<0.05)

Table 7: Post Hoc test of mean differences of AQI groups (non-visual, bronze glazing). (p<0.05)

Q	AQI(I)	AQI(J)	Mean Difference (I-J)	Std. Error	Sig.
NVQ1	Excellent	Heavily Polluted	14.99	5.31	0.02
NVQ1	Excellent	Severely Polluted	13.78	5.53	0.05
NVQ2	Excellent	Heavily Polluted	15.24	5.47	0.02
NVQ2	Excellent	Severely Polluted	14.32	5.70	0.05
NVQ4	Excellent	Severely Polluted	13.47	4.67	0.02

For the bronze glazing (Figure 7), significant main effects of AQI were found for four non-visual aspects as follows (p<0.05): 'Alertness' (NVQ1, F(2, 121)=4.90); 'Mood' (NVQ2, F(2, 121)=4.85); 'Physical well-being' (NVQ3, F(2, 121)=3.54); 'Relaxation (NVQ4, F(2, 121)=4.67). Three AQI levels (Excellent, Heavily Polluted and Severely Polluted) were available for this test. In Table 7, the Scheffe process displayed that significant differences between 'Excellent' and 'Heavily Polluted' or 'Severely Polluted' occurred at the questions of NVQ1, 2 and 4 (p<0.05). For occupant's alertness and mood, normally, excellent air quality will achieve more positive feedback than seriously polluted air conditions. In addition, occupants will feel less stressful with the improved air quality than the conditions of heavily polluted air. However, the NVQ3 'Physical well-being' did not see significant differences between various AQI levels (p>0.05).

In Figure 8, the experiment using the blue glazing has four AQI levels available: Excellent, Moderately Polluted, Heavily Polluted and Severely Polluted. Similar to the bronze glazing, significant main effects of AQI were found at four non-visual questions (p<0.05): 'Alertness' (NVQ1, F(3, 129)=4.93); 'Mood' (NVQ2, F(3, 129)=5.0); 'Physical well-being' (NVQ3, F(3, 129)=5.16); 'Relaxation (NVQ4, F(3, 129)=3.37). As the pairwise comparisons (Scheffe) in Table 8, for 'Alertness & Mood', there were significant differences between 'Excellent' and 'Heavily Polluted' (p<0.05), and between 'Moderately Polluted' and 'Heavily Polluted' (p<0.05). In comparison to excellent and moderately polluted air, interestingly, the heavy pollution conditions would significantly get participants' feedback of alertness and mood moving towards the positive side. For 'Physical Well-being & Relaxation', significant differences can be found between 'Moderately Polluted' and 'Heavily Polluted' (p<0.05). The heavy pollution could achieve more positive feedback than moderate pollution condition based on the two aspects. However, 'Severely Polluted' level can give rise to a significantly lower score on 'Mood and Physical well-being' than 'Heavily Polluted' condition (p<0.05). Generally, for all non-visual aspects, the effects of excellent air quality were similar to moderately polluted air quality (p>0.05).

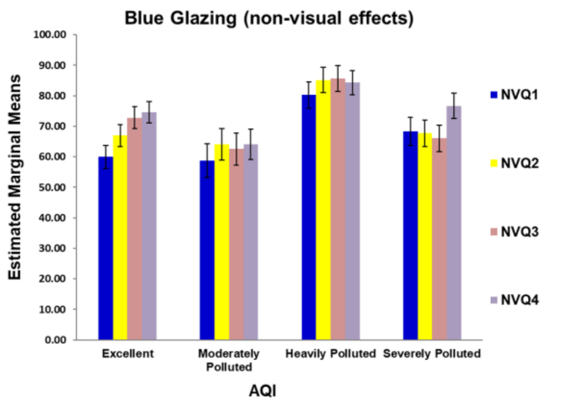

Figure 8: Mean values and standard errors of the mean of feedback of non-visual questions (blue glazing). (p<0.05)

Table 8: Post Hoc test of mean differences of AQI groups (non-visual, blue glazing). (p<0.05)

Q	AQI(I)	AQI(J)	Mean Difference (I-J)	Std. Error	Sig.
NVQ1	Excellent	Heavily Polluted	-20.24	5.81	0.01
NVQ1	Moderately Polluted	Heavily Polluted	-21.51	7.03	0.03
NVQ2	Excellent	Heavily Polluted	-18.19	5.51	0.01
NVQ2	Moderately Polluted	Heavily Polluted	-21.06	6.67	0.02
NVQ2	Heavily Polluted	Severely Polluted	17.44	6.05	0.04
NVQ3	Moderately Polluted	Heavily Polluted	-23.10	6.72	0.01
NVQ3	Heavily Polluted	Severely Polluted	19.61	6.10	0.02
NVQ4	Moderately Polluted	Heavily Polluted	-20.20	6.42	0.02

3.4 Discussions

Results above could be explained based on psychological adaptation [13], daylight illuminances, and light colour (CCT). Participants easily noticed any change of external air quality through the clear and blue glazing (reflected by atmospheric visibility [14]). Given the finding of air pollution adaptation [15], visual detection of air pollution is a complex problem, and the perceptual sensitivity of air pollution would tend to decrease with the increasing exposure time. The lightly pollution situation was newly developed from the stage of good air quality, while the heavy pollution was the pollution accumulation across a period. In addition, heavily polluted external air might influence participants' perceptions and cognitions so that they might feel more satisfied with staying indoors. The bronze glazing delivered low mean illuminances and CCT to participants' eyes (Table 1). In a relatively darker space, participants might be highly sensitive to the incident daylight. Since the higher external air quality can lead to higher daylighting availability (Figure 2), excellent AQI would improve participants' satisfaction via increasing the daylight illuminances [1]. The blue glazing brought in a higher CCT (5300K) (Table 1). It has been found that the dominant short-wave stimulus would enhance sensitivities of visual functions (brightness, glare), and improve the alertness and mood [16]. Even with the heavy air pollutions, CCT above 5000k would keep participants with higher alertness and good mood in the working space.

Limitations: The impact of weather conditions on daylight illuminance was not fully considered in the discussion. The measures used for non-visual feedback could be relatively simple.

4. CONCLUSION

Several finding can be drawn as follows: 1) Urban air pollutions can reduce indoor daylight availability. Significant reduction could be only found with the heavy air pollution. 2) Urban air pollution would significantly impact on occupants' visual performance, alertness, physical wellbeing, and mood in offices. The effects vary in the window glazing type and colour. With the clear glazing, significant effects on comfort, mood, and alertness were only observed when the lightly polluted air occurred. However, the heavy air pollution combined with the bronze glazing would bring in significant detrimental effects on occupants' visual performances. Interestingly, the blue glazing might mitigate the negative effects of heavy urban air pollution on occupants' performances, especially in terms of comfort, alertness and mood.

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