Exposure to Indoor PM2.5 and Perception of Air Quality and Productivity in an Office Building: An Intervention Study

Jiaxu Zhou[1,*], Marcella Ucci[1], Gesche Huebner[1], Hong Wang[2,3]

[1] UCL Institute for Environmental Design and Engineering (IEDE), The Bartlett, University College London (UCL), Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK
[2] China Academy of Building Research (CABR), Beijing, 100020, China
[3] National Engineering Research Centre of Building Technology, Beijing, 100020, China

**Corresponding email: jiaxu.zhou.19@ucl.ac.uk*

SUMMARY
Health impacts of exposure to particulate matter can be wide-ranging, with some evidence suggesting potential impacts on cognition and productivity. This study was conducted in an urban mixed-mode ventilated office in China. Sixty eligible employees agreed to participate in the study and fifty-five valid responses were obtained. The perception of air quality, productivity and wellbeing were assessed via questionnaires during three conditions: intervention, control, and baseline (a week prior to the intervention). Portable air purifiers on the subjects' workstations were used as the intervention to control the $PM_{2.5}$ level at subjects' breathing zone. The air purifiers during the off and on status were considered as control and intervention conditions respectively. The same cohort was divided into four groups separately participating in each of three conditions on different workdays via a crossover design. The following $PM_{2.5}$ levels [Average (SD)] during the three conditions (Baseline/Control/Intervention) were:[26.7 (2.1)/18.0 (1.8)/3.7 (0.9)] μg/m³.These levels correspond to interim targets of WHO guidelines for $PM_{2.5}$. Analysis indicates significant differences between control and intervention regarding perception and satisfaction of air quality, thermal satisfaction and productivity.

KEYWORDS
Indoor air quality, Perception, Productivity, Exposure assessment, Healthy building

1 INTRODUCTION
$PM_{2.5}$, a well-known air pollutant, has been listed by the World Health Organization (WHO) as one of the top threats to human health. Research has made great strides in outdoors $PM_{2.5}$ exposure, yet comparatively less is known about impacts of indoor $PM_{2.5}$ exposure and how these relate to variations in perceptions of air quality, productivity and wellbeing for working-age adults in an office environment. Recent evidence suggests that poor air quality may affect work performance and productivity, which can then be directly related to economic outcomes (Ahmed *et al.*, 2022). Therefore, linking $PM_{2.5}$ exposure to perceptions of air quality, productivity and wellbeing may increase attention on indoor air quality and healthy building improvement (Cedeño Laurent *et al.*, 2021; de Oliveira, Rupp and Ghisi, 2021).

2 MATERIALS/METHODS
The study is an on-site randomised human-controlled cross over design conducted in an urban mixed-mode ventilated office in China. Sixty eligible employees agreed to participate to the study. The same cohort was divided into four groups each comprising 15 people participated in each of the three conditions on different weekdays via a crossover design. The perception of air quality, productivity and wellbeing were assessed via questionnaires during three conditions: intervention, control, and baseline (a week prior to the intervention). Portable air purifiers on

the subjects' workstations were used as the intervention to control the $PM_{2.5}$ level at subjects' breathing zone (Atem Desk Air Purifier, IQAir®, Switzerland). Portable air purifiers were placed in both control and intervention conditions to avoid potential placebo effects. The purifiers during the off and on status were considered as control and intervention conditions respectively. The lighting function of the air purifier was removed thus reducing the potential awareness of participants to the on/off condition. Real-time, commercial-grade, quality-certified environmental sensors Sensedge (Kaiterra®, Switzerland) and AirVisual Pro (IQ Air®, Switzerland) were respectively installed in the office workplace, and at the participants' working stations measuring $PM_{2.5}$, CO_2, temperature, and relative humidity. All loggers were pre-calibrated by manufacturer before data collection.

The questionnaire was largely based on standardized and validated questions translated by the researcher into the national language used in the case study building. The questions were about participants demographics including gender, age band and educational level; perception of air quality and thermal conditions; satisfaction with environmental parameters (air quality, temperature, lighting and acoustics); and productivity. Self-reported wellbeing was also included as a potential confounder affecting self-reported productivity.

The satisfaction ratings were evaluated based on a seven-point Likert scale; from very dissatisfied to very satisfied, where the mid denoted neutral state (neither satisfied nor dissatisfied) (Wargocki, 1999; Lan *et al.*, 2011). The perception of indoor air quality (IAQ) and thermal sensation were assessed by seven-point continuous scale ranging from stuffy to fresh (Bluyssen *et al.*, 2016), and from cold to hot (ASHRAE, 2005), respectively. The question on wellbeing included physical and emotional aspects (*How do you feel right now, mentally? And physically?)* answers on *Very bad to Very good*) (Elliot *et al.*, 2011). The question on self-reported productivity was used in the control and intervention condition only and was adapted using a seven-point Likert scale from a recent study (Licina and Yildirim, 2021): *How would you rate your productivity at the workplace during the working hours so far today? (Very unproductive to Very productive*).

This study is a part of a large research project whose main aim is to investigate $PM_{2.5}$ exposure and cognitive performance, and the cognitive results will be presented separately. Here only the survey results are presented. The productivity question was added in the second tranche of the entire project schedule (after baseline) because the local partner indicated that they were interested and willing for us to include this question, which can be a sensitive subject in the workplace. The baseline served effectively as a pilot of the entire project for all the procedures, but we are reporting this for clarity and transparency.

General linear model (GLM) repeated measures ANOVA served to assess differences in repeated measures and the Greenhouse-Geisser method was used to adjust the violation of sphericity. Bonferroni adjustment was used in post hoc analysis. Productivity outcomes were analysed via Paired-t test since the question was only asked in control and intervention conditions. All the statistical analyses were performed using IBM SPSS Statistics 23 (SPSS Inc, Chicago, IL, USA).

3 RESULTS and DISCUSSION

Five participants did not complete all parts of the study hence the statistical analysis was based on data from 55 participants. Table 1 shows the general characteristics of respondents. 17 male subjects (30.9%) and 38 female subjects (69.1%) participated in the surveys. Most of the participants have a higher education level.

Environmental parameters in three conditions are described in Table 2. The $PM_{2.5}$ levels [Average (SD)] during the baseline, control and intervention were 26.69 (2.08), 17.99 (1.78), 3.67 (0.94) µg/m³, respectively. These levels correspond to interim targets of WHO guidelines for $PM_{2.5}$. Differences between baseline and control $PM_{2.5}$ indoor concentrations are driven by outdoor $PM_{2.5}$ levels, since there are no filters in the building's ventilation system and outdoor $PM_{2.5}$ levels during the baseline were higher than outdoor levels during the control condition. The lowest $PM_{2.5}$ concentration was found under the intervention condition, which we interpret as an effect attributed to the air purifiers. Therefore, the portable air purifier could be an effective method for reducing $PM_{2.5}$ level in indoors.

Table 1. Demographics information

Parameters	Answers	N (%)
Total participants		55
Gender	Male	17 (30.9)
	Female	38 (69.1)
Age band	18-30	25 (45.5)
	31-40	27 (49.1)
	41-50	2 (3.6)
	51-65	1 (1.8)
Education level	High school	2 (3.6)
	Bachelor	26 (47.3)
	Master and above	27(49.1)

Table 2. Environment Parameters in Conditions.

Parameter	Baseline	Control	Intervention
$PM_{2.5}$(µg/m³)	26.7(2.1)	18.0 (1.8)	3.7 (0.9)
Relative Humidity (%)	52.8(0.2)	54.3(0.4)	51.5(0.4)
Temp(°C)	27.9(0.04)	27.8(0.06)	27.6(0.04)
CO_2 (ppm)	708.8(64.8)	707.1(38.6)	723.7(23.0)

The relationship between air quality perception, satisfaction, or productivity under three conditions are illustrated in Fig.1 and Table3. Statistically significant differences were found in participants' perceptions and satisfaction of IAQ, and productivity between control and intervention conditions. However, the IAQ perception was not statistically significant between baseline and control conditions. A possible reason is that there is a threshold effects in $PM_{2.5}$ exposure beyond which there is no difference in perception. Perception of other environmental parameters (i.e. thermal sensation and satisfaction, light and noise satisfaction) did not vary significantly across the three conditions, except for 'thermal satisfaction' with significant differences between control and intervention which is consistent with a recent study conducted in domestic buildings suggesting that air purifiers could enhance the occupants' thermal comfort (Cooper *et al.*, 2021). In terms of other confounders, no statistically significant differences were found in self-reported wellbeing across the three conditions.

Table 3. Outcomes under Different Conditions.

Parameter	Main effect P-value	Baseline-Control P-value (95%CI)	Control-Intervention P-value (95%CI)	Baseline-Intervention P-value (95%CI)
Air quality perception	0.000**	>0.1	0.000** (-1.776, -0.733)	0.000** (-1.776, -0.733)
Air quality satisfaction	0.000**	0.043* (-1.077, -0.014)	0.000** (-1.799, -0.783)	0.004 ** (0.197,1.294)
Thermal sensation	0.084	>0.1	0.061 (-0.011, 0.629)	>0.1
Thermal satisfaction	0.007**	>0.1	0.004** (-1.262, -0.193)	>0.1
Sound satisfaction	>0.1	>0.1	0.083	>0.1
Lighting satisfaction	0.059	0.087	>0.1	>0.1
Physical wellbeing	>0.1	>0.1	>0.1	>0.1
Emotional wellbeing	0.082	>0.1	>0.1	>0.1
Productivity			0.000** (-1.004, -0.305)	

**P <0.01; *P < 0.05

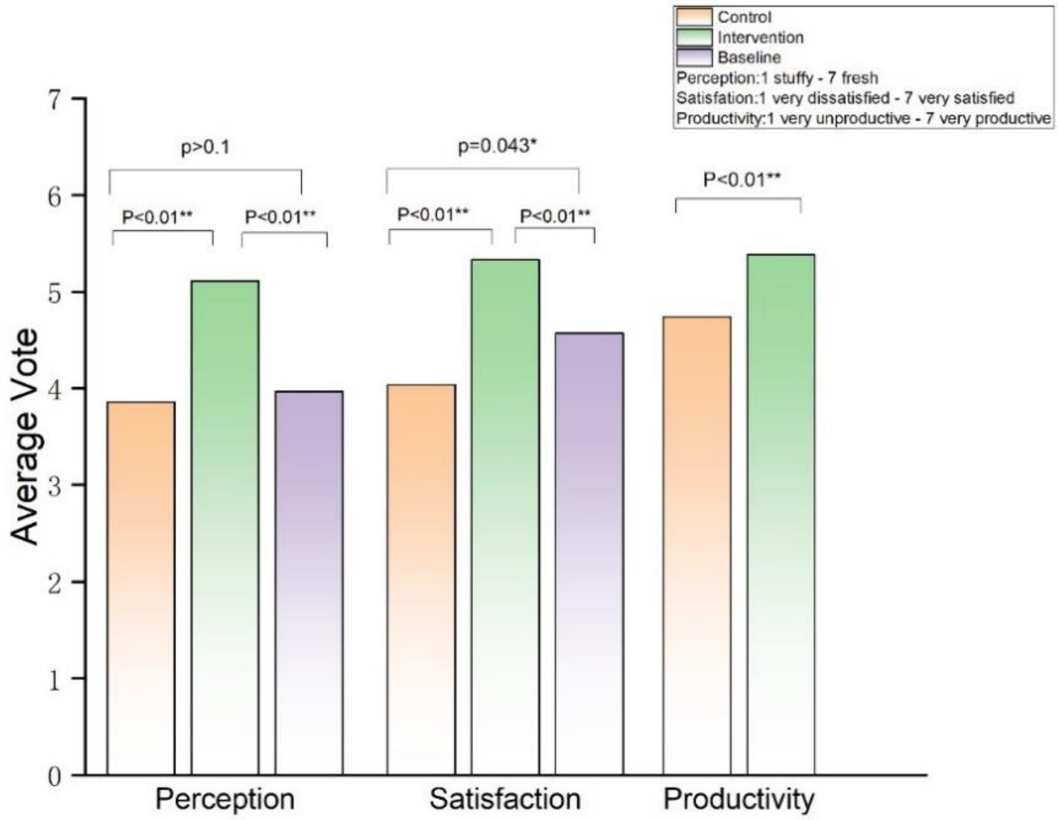

Figure 1. IAQ Perception, IAQ Satisfaction, and Productivity under Different Conditions

Table 4 represents the correlation analysis of IAQ perception and satisfaction, thermal satisfaction and productivity in the experimental conditions. The results pointed out that: 1) perception and satisfaction of IAQ are correlated in all three conditions; 2) productivity is in turn correlated with IAQ perception as well as with IAQ satisfaction in the control and in the intervention condition (no productivity data in the baseline condition);3)Thermal satisfaction correlated with productivity across intervention and control conditions. And thermal satisfaction also correlated with IAQ perception and satisfaction across three conditions. Other studies have also found links between air quality and thermal perception/satisfaction (Bourikas *et al.*, 2021; de Oliveira, Rupp and Ghisi, 2021; Oliveira, Rupp and Ghisi, 2021).

Table 4. Pearson Correlation Analysis outcomes

	IAQ Perception Baseline	IAQ Satisfaction Baseline	IAQ Perception Control	IAQ Satisfaction Control	IAQ Perception Intervention	IAQ Satisfaction Intervention	Productivity Control	Productivity Intervention	Thermal Satisfaction Baseline	Thermal Satisfaction Control	Thermal Satisfaction Intervention
IAQ Perception Baseline	1										
IAQ Satisfaction Baseline	.797**	1									
IAQ Perception Control	-.093	.046	1								
IAQ Satisfaction Control	-.068	.053	.844**	1							
IAQ Perception Intervention	-.231	-.184	.069	.012	1						
IAQ Satisfaction Intervention	-.225	-.152	-.006	-.063	.826**	1					
Productivity Control	-.096	.011	.617**	.615**	.027	.053	1				
Productivity Intervention	-.114	-.160	-.033	.004	.410**	.520**	.131	1			
Thermal Satisfaction Baseline	.582**	.808**	.025	.032	-.008	.019	-.035	-.033	1		
Thermal Satisfaction Control	-.100	.002	.757**	.770**	-.050	-.105	.509**	-.071	.015	1	
Thermal Satisfaction Intervention	-.322*	-.276*	-.022	-.196	.667**	.589**	-.066	.494**	-.043	-.056	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

4 CONCLUSIONS

The results show that the intervention successfully lowered indoor concentrations of $PM_{2.5}$ levels and that self-reported productivity was significantly higher in the intervention than the control group. Perception and satisfaction with IAQ were also significantly higher in the intervention than in the control group, and also compared to baseline. Thermal satisfaction was also significantly different between intervention and control. IAQ satisfaction and perception were positively correlated with each other. They also positively correlated with self-reported productivity and thermal satisfaction. Self-reported productivity correlated positively with thermal satisfaction. Hence, the study shows that PM levels are significantly related to a number of subjective measures, indicating that it needs to be taken seriously as a pollutant since it impacts on a variety of outcomes and not disease only. Further studies should evaluate how objectively measured productivity of working-age adults may relate to $PM_{2.5}$ exposures as well as with IAQ satisfaction and perception. The role of thermal satisfaction in affecting IAQ perception and/or productivity should also be considered. The relevant findings may provide useful references for future air quality and healthy indoor environment policymaking and promotion and understanding optimal operation for occupants and stakeholders.

ACKNOWLEDGEMENT

We are grateful to the people who participated in the experiment and to the Living Lab for Healthy Building and Workplace Productivity (China Academy of Building Research, CABR) for providing the experimental site.

5 REFERENCES

ASHRAE. 2005. ASHRAE Handbook: Fundamentals, Atlanta, GA, American Society of Heating, Refrigerating and Air- Conditioning Engineers, Inc.

Ahmed, R. et al. (2022) ‘Combined effects of ventilation rates and indoor temperatures on cognitive performance of female higher education students in a hot climate’, Indoor Air, 32(2), pp. 1–15. doi: 10.1111/ina.13004.

Bluyssen, P. M. et al. (2016) ‘Self-reported health and comfort in “modern” office buildings: First results from the European OFFICAIR study’, Indoor Air, 26(2), pp. 298–317. doi: 10.1111/ina.12196.

Bourikas, L. et al. (2021) ‘Effect of thermal, acoustic and air quality perception interactions on the comfort and satisfaction of people in office buildings’, Energies, 14(2). doi: 10.3390/en14020333.

Cedeño Laurent, J. G. et al. (2021) ‘Associations between acute exposures to PM2.5 and carbon dioxide indoors and cognitive function in office workers: a multicountry longitudinal prospective observational study’, Environmental Research Letters, 16(9), p. 94047. doi: 10.1088/1748-9326/ac1bd8.

Cooper, E. et al. (2021) ‘Use of portable air purifiers in homes: Operating behaviour, effect on indoor PM2.5 and perceived indoor air quality’, Building and Environment, 191(December 2020), p. 107621. doi: 10.1016/j.buildenv.2021.107621.

Elliot, A. J. et al. (2011) ‘A subtle threat cue, heart rate variability, and cognitive performance’, Psychophysiology, 48(10), pp. 1340–1345. doi: 10.1111/j.1469-8986.2011.01216.x.

Lan, L. et al. (2011) ‘Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance’, Indoor Air, 21(5), pp. 376–390. doi: 10.1111/j.1600-0668.2011.00714.x.

Licina, D. and Yildirim, S. (2021) ‘Occupant satisfaction with indoor environmental quality, sick building syndrome (SBS) symptoms and self-reported productivity before and after

relocation into WELL-certified office buildings', Building and Environment, 204(July), p. 108183. doi: 10.1016/j.buildenv.2021.108183.
de Oliveira, C. C., Rupp, R. F. and Ghisi, E. (2021) 'Influence of environmental variables on thermal comfort and air quality perception in office buildings in the humid subtropical climate zone of Brazil', Energy and Buildings, 243, p. 110982. doi: 10.1016/j.enbuild.2021.110982.
Oliveira, C. C. De, Rupp, R. F. and Ghisi, E. (2021) 'Assessment of Air Quality Perception and Its Effects on Users' Thermal Comfort in Office Buildings', Sci, 3(4), p. 47. doi: 10.3390/sci3040047.
Wargocki, P. (1999) 'Perceived air quality, sick building syndrome (SBS) symptoms and productivity in an office with two different pollution loads', Indoor Air, 9(3), pp. 165–179. doi: 10.1111/j.1600-0668.1999.t01-1-00003.x.