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Short-term exposure to indoor PM2.5 in office buildings and cognitive performance in adults: An intervention study

Jiaxu Zhou [a,*], Hong Wang [b,c], Gesche Huebner [a], Yu Zeng [b,c], Zhichao Pei [b,c], Marcella Ucci [a]

[a] *UCL Institute for Environmental Design and Engineering (IEDE), The Bartlett, University College London (UCL), Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK*
[b] *China Academy of Building Research (CABR), Beijing, 100020, PR China*
[c] *National Engineering Research Center of Building Technology, Beijing, 100020, PR China*

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ABSTRACT

Impacts of exposure to particulate matter can be wide-ranging, with some evidence suggesting potential impacts on nervous system, cognition, and productivity. However, most evidence to date addresses ambient exposure and chronic outcomes with limited research on indoor short-term exposure to PM2.5 and cognitive performance. Hence, the aim of this study was to evaluate if there is a relationship between short-term exposure to indoor PM2.5 within the workplace context and cognitive performance in adults.

A randomized single-blind cross-over trial was conducted in an urban mixed-mode ventilated office in Beijing (China). Sixty eligible employees participated in the study and fifty-five valid responses were obtained. Cognitive performance was assessed with a validated neurological battery test during intervention and control conditions. Portable air purifiers were placed on the subjects' workstations and used in the intervention condition to control PM2.5 levels at the subjects' breathing zone whereas in the control condition, the air purifiers were present but switched off. Average PM2.5 levels were respectively 18.0 μg/m^3 and 3.7 μg/m^3 in the control and intervention condition. In each condition, cognitive performance testing started five to 7 h after arriving in the office.

The results showed office workers had significantly better performance for 9 out of the 16 cognitive skills during the intervention, compared to the control condition, with the most consistent effect in the memory domain. This study adds evidence that elevated PM2.5 levels can detrimentally affect cognitive performance even during short-term indoor exposure. Further research is needed on the potential impact of other air pollutants, including ultrafine particles, and on the possible role of sound and air movement from the air purifiers.

1. Introduction

90% of the world's population breathes unhealthy air [1]. The air pollutant PM2.5 has been listed by the World Health Organization (WHO) as one of the top threats to human health [2]. In indoor environments, the use of polluting fuels in heating and cooking stoves, tobacco combustion and combustion for other purposes, such as cultural or religious practices or using candles on daily basis are a common source of PM2.5 emissions. Even in the absence of internal sources, PM2.5 levels can be elevated due to ambient air pollution penetrating indoors, whereby indoor PM2.5 levels are generally higher when outdoor PM2.5 are elevated [3]. In the second half of 2021, WHO issued new guidelines with stricter levels of PM2.5 as a new target (annual mean of 5 μg/m^3 and 24-h of 15 μg/m^3) in light of new evidence on mortality, as well as respiratory and cardiovascular morbidity. Studies suggest that indoor PM2.5 concentrations in office settings in developing and developed countries exceed the previous (2005 version) and latest WHO guidelines (2021 version) limits [4,5]. However, the levels recommended in the new WHO guidelines did not consider potential impacts on nervous system, productivity or cognitive performance.

Although the health impacts of particulate matter on cardiovascular disease and on mortality are well-established [6–9], emerging evidence supports associations between air pollution - such as PM2.5 exposure- and impairment of the central nervous system, including neurodegeneration through various pathways and mechanisms, e.g. neurotoxicity, neuroinflammation, oxidative stress, and damage in blood–brain barrier and neurovascular units [10]. Epidemiological studies also found that exposure to PM2.5 is associated with changes in

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* Corresponding author.
E-mail address: jiaxu.zhou.19@ucl.ac.uk (J. Zhou).

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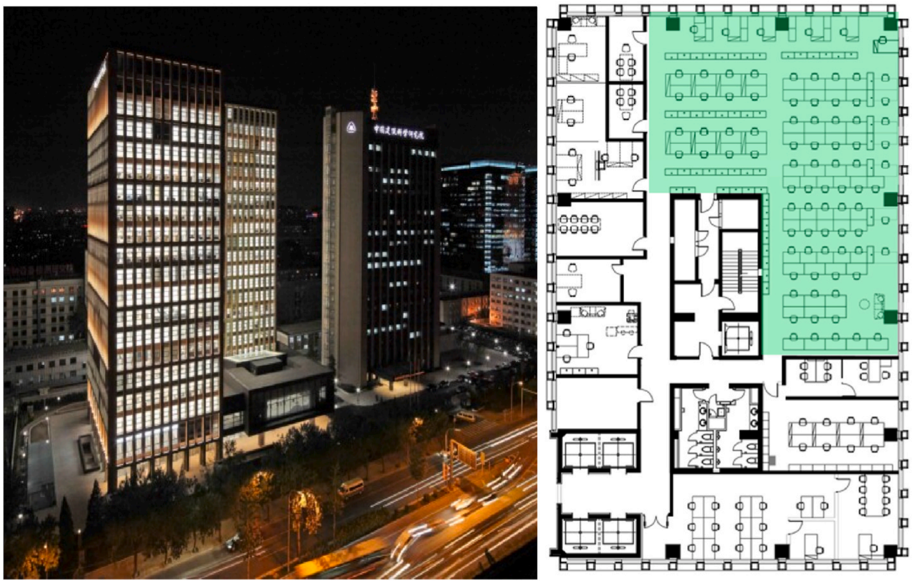


Fig. 1. External view and setting layout (Green for the living lab area). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

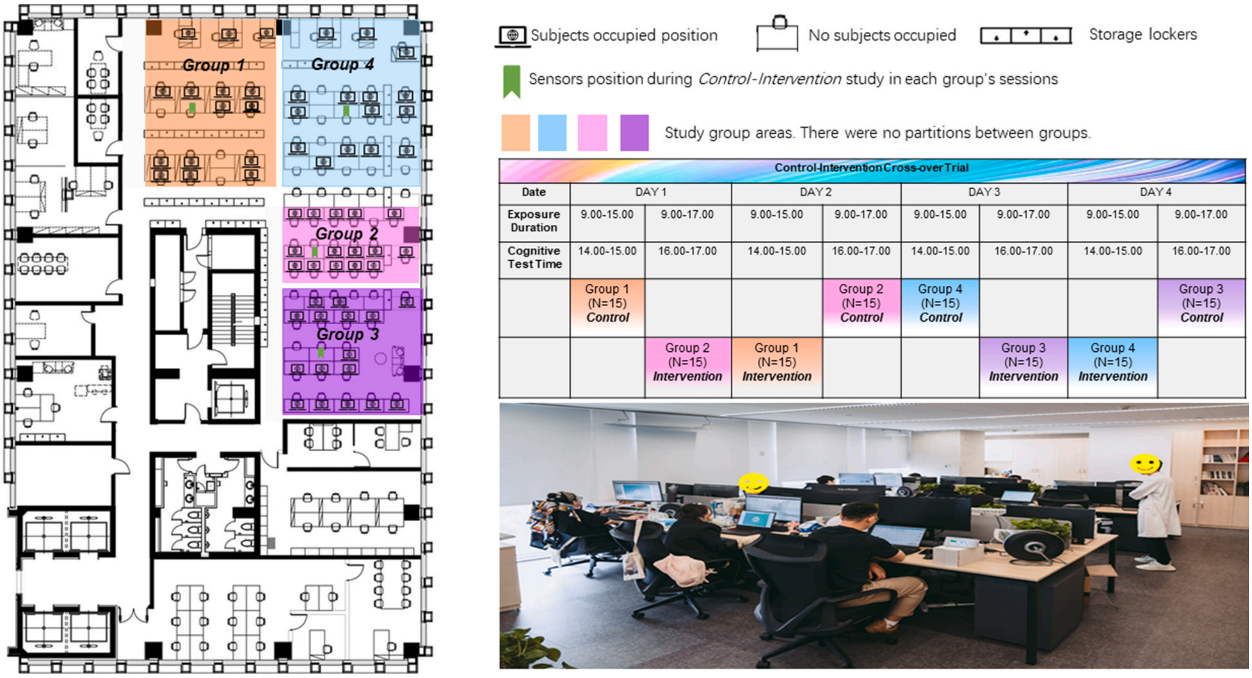
brain morphology such as smaller total cerebral brain volume, deep-grey brain volumes, and decrease hippocampal volumes [11–14]. Evidence also suggests that exposure to particulate air pollution may worsen cognitive decline and impairment, with most studies focusing on older adults (over 50 years). However, evidence is heterogenous and not fully conclusive [15].

Cognitive performance refers to the performance associated with the multi-mental processes involved in knowing, learning, memorizing, and understanding things [15,16]. Given that cognitive performance is critical to people's daily life, the effect of air pollution on human cognition has attracted increased scientific interest and has become a prospective area of environmental and epidemiological research [17–24]. Cognitive performance is affected by various factors, such as ageing and mental disorders [25–28], and can be measured in different ways such as task-based methods used previously in environment-related research [29–31] as well as physiological measures [32–34].

There is some evidence on long-term exposure (i.e., one year or more) to particulate matter air pollution as a potential risk factor for cognition [35–39]. In addition, an intervention study investigated air cleaner use during pregnancy and children's cognitive performance at four-years of age, via a single-blind parallel-group randomized controlled design [40]. The air cleaners were used from 11 weeks gestation until the end of pregnancy. They found that reducing indoor particulate matter air pollution during pregnancy improved cognitive performance in childhood. A smaller number of studies have also found evidence of an effect for relatively short-term exposures on cognitive performance, although some effects were found for specific outcome metrics only [5,41,42]. Specifically, a longitudinal observation study investigated the association of 28-days home address PM2.5 exposure (assumed by using ambient PM2.5 concentrations) with the cognitive performances of 954 white aging males via the Global Cognitive Function (GCF) and the Mini-mental State Examination evaluation (MMSE) scores. They found that higher short-term exposure to PM2.5 had negative non-linear associations with cognitive function [42]. Similarly, another one-year longitudinal prospective observational study across several countries worldwide found that higher indoor PM2.5 levels in office buildings were significantly associated with decreased performance in the Stroop Color-Word test and an Addition-Subtraction test in office workers [5]. Moreover, a double cross-over experimental study [41] including thirty university participants found that when subjects were exposed for 1-h to elevated indoor candle-generated PM2.5, there was a statistically significant reduction in cognitive performance as measured via the MMSE but no statistically significant reduction when considering the Stroop Word-Colour test or the Ruff 2 and 7 test. Changes in MMSE and in Ruff 2 and 7 scores were statistically significant in a separate experiment with 30-min exposure to traffic pollution, with no statistical differences in the Stroop Word-Colour test. Despite the emerging evidence suggesting PM2.5 exposure potentially impacting cognitive function and productivity, most studies focused on chronic rather than short-term effects and outdoor-based exposure instead of indoors, whereas people spend a large amount of their time indoors [43]. Whilst there are several studies exploring the impacts of indoor air quality more on office workers' performance for a review see Ref. [30]; the potential role of PM2.5 in office settings on cognitive performance has been largely under-investigated with limited understanding of the impacts of exposures on specific cognitive domains.

Given that particulate matter exposure not only affect neurological disease but may also cognitive performance and thus productivity, the hidden impacts of PM2.5 exposure have raised concerns related to potential negative consequences on economic productivity at national and individual level for working age adults, both those working outdoor as well as indoor [44]. Specifically, some preliminary findings suggest impacts of particulate matter pollution on indoor workers productivity in manufacturing sectors [45,46] and offices [47]. For instance, an observation study found that productivity of call centre workers in two Chinese cities was negatively affected by ambient fine particulate matter exposure and these impacts were not limited to extreme ambient pollution days [48]. In addition, exposure to PM2.5 in indoor environments has been found to be a stronger predictor of personal exposure than outdoor concentrations [49] and the variation in exposure also raises concerns of social inequalities, e.g. higher indoor PM2.5 levels within residential settings are estimated to be associated with lower-income families in high-income countries [50]. These results suggest that indoor PM2.5 could represent an important contribution to overall population exposure and may be contributing to aspects of health, wellbeing and cognitive performance inequalities. However, the role of PM2.5 in work environments is not well understood.

Therefore, this paper aims at further understanding how short-term exposure to indoor PM2.5 affects various domains of cognitive performance in working-age adults within the workplace context via an intervention approach.



Control-Intervention Cross-over Trial								
Date	DAY 1		DAY 2		DAY 3		DAY 4	
Exposure Duration	9.00-15.00	9.00-17.00	9.00-15.00	9.00-17.00	9.00-15.00	9.00-17.00	9.00-15.00	9.00-17.00
Cognitive Test Time	14.00-15.00	16.00-17.00	14.00-15.00	16.00-17.00	14.00-15.00	16.00-17.00	14.00-15.00	16.00-17.00
	Group 1 (N=15) ***Control***			Group 2 (N=15) ***Control***	Group 4 (N=15) ***Control***			Group 3 (N=15) ***Control***
		Group 2 (N=15) ***Intervention***	Group 1 (N=15) ***Intervention***			Group 3 (N=15) ***Intervention***	Group 4 (N=15) ***Intervention***	

Fig. 2. Experimental procedure.

2. Material and methods

2.1. Setting

This study was conducted in an urban common sized mixed-mode ventilated office in Beijing, China. The experiment was conducted in the office area on the 15th floor, a space (living lab) that is used for the daily work-related activities of the employees and can also occasionally be used for productivity-related experiments (Fig. 1 green area).

2.2. Participants

The sample size was calculated based on Cohen's study in behavioral research [51]. Method of analysis was set to paired t-tests. The recommended sample size for detecting a small effect was at least 55 participants, with alpha set to 0.05 and a desired power of 0.95 (see supplementary material for details). Therefore, this study recruited 60 participants to account for potential dropouts or invalid data. Inclusion criteria were: being the case study's employee of working-age (18–65 years), not smoking, healthy, not using prescription medications, no mental and learning disorders as well as not having COVID-19 symptoms. The coffee machine was temporally removed during the project time cycle to avoid variations of caffeine consumption between subjects. Participants were not paid for their participation but received an umbrella and a tote bag as souvenir for participation.

2.3. Study design and procedures

This study adopted an on-site randomized single-blind cross over design. 60 participants were divided randomly into four groups, each comprising 15 people taking the cognitive test twice, once during the control and once in the intervention conditions, on different weekdays via a crossover design (Fig. 2). Specifically, on any study day, regardless of the cognitive test start time (i.e., "14.00–15.00 slot" or "16.00–17.00 slot"), the air purifier was switched on at 8:30 for those desks where the intervention group was being studied. Participants arrived at the office around 9.00 a.m. Therefore, the two groups were exposed (to the control or the intervention condition) for 5–7 h depending on which group they belonged (Fig. 2).

Four parallel versions of cognitive tests were used to avoid learning effects. Prior to taking the cognitive test, participants were required to complete a questionnaire on demographic details (age band, gender, education level) and their perceptions of and satisfaction with environmental parameters (air quality, thermal conditions, light, sound) as well as self-reported wellbeing and productivity. For a subset of participants (n = 40), the cognitive battery test was supplemented with physiological response monitoring (i.e., electrodermal activity, EDA and heart rate variability, HRV) through wearable sensors, however, results on physiological measures are not reported here.

The questionnaire results including self-reported productivity and IAQ perception and satisfaction have been reported previously [47]. All participants participated in a baseline study a week before the intervention trial. The baseline also served as a pilot of the entire project's procedures and its findings will be analyzed separately. A subset of participants (N = 30) used wearable loggers to measure PM2.5 personal exposure to/from work but results are not presented here.

2.4. Intervention and exposure assessment

Personal desk-based air purifiers on the subjects' workstations were used as the intervention to control the PM2.5 level at the subject's breathing zone. The air purifier used in this study (Atem Desk Air Purifier, IQAir®, Switzerland) had a HEPA filter with >99% removal efficiency for particles at 0.3 μm, and with customizable clean air delivery rates (from 4 to 66 m^3/h). 30 m^3/h was used in this study, as the rate has a low sound level during operation. The air purifiers were placed on the desks in both control and intervention conditions to avoid potential placebo effects due to equipment visibility but were switched off in the control condition (remotely controlled). To reduce the risk of participants being aware of the times when the air purifiers were switched on, the lighting function was turned off during all experimental conditions, with sound level being 35 dB during operations. In addition, participants were naïve to the study hypothesis. Prior to the experiment, participants were told that even when there was airflow from the air purifier, the filters might be removed which would render the air purifier ineffective. But in reality, no filters were removed.

Table 1
Environmental monitoring equipment specifications.

$PM_{2.5}$	Sensor type	Light scattering (350 nm)
	Measuring range	1–1000 μg/m^3
	Resolution	1 μg/m^3
	Accuracy	0–30 μg/m^3; ±3 μg/m^3 30–1000 μg/m^3; ±10%
CO_2	Sensor type	Non-dispersive infrared
	Measuring range	400–2000 ppm
	Resolution	1 ppm
	Accuracy	±3%; ±50 ppm
Temperature	Sensor type	Digital
	Measuring range	−20-100 °C
	Resolution	1 °C
	Accuracy	±1 °C
Relative humidity	Sensor type	Digital
	Measuring range	0–99%
	Resolution	1%
	Accuracy	±5%

Real-time environmental sensors Sensedge (Kaiterra®, Switzerland) were placed on different desks according to the group location for monitoring the exposure levels within a subject's breathing zone during the experiment (see Fig. 2, green dots), measuring PM2.5, CO2, temperature, and relative humidity at 1-min intervals (see logger specifications in Table 1). The screen of the sensors' monitors was turned off. Thus, subjects did not know the actual environmental conditions. The loggers are fully compliant with various air quality standards, including WELL V2, LEED, RESET, the Living Building Challenge, and Fitwel. All loggers were calibrated before experimental data collection. Briefly, first one logger was sent to the manufacturer for calibration against a reference instrument (i.e., TSI DustTrak, TSI Instruments, USA) in a typical office room in central Beijing. The office room for calibration work had a similar air temperature (27 °C) and relative humidity (52%) as in the experiment office setting (Relative humidity 54%, Temperature 27 °C). Subsequently, before the experiment, all loggers were placed together on a desk within the experiment office setting, at an air temperature of 29 °C and relative humidity of 51%, with the aim to compare the real-time data from each logger against the data from the co-located recently calibrated one. Appropriate correction values were applied as required, based on suggestions from the manufacturer.

2.5. Cognitive assessment

Cognitive performance was tested with the commercially available computer-based neurological battery test General Cognitive Assessment Battery, CogniFit® (CogniFit Inc., San Francisco, USA). Testing was performed via an online platform which is available in multiple languages, here, Chinese was used. CogniFit measures various aspects of cognitive performance covering five cognitive domains: memory, attention, perception, coordination, and reasoning. In each domain, various sub-skills are assessed, with 16 skills in total included. The time it takes to complete the whole battery is 30–45 min. The tasks have parallel versions that allow researchers to test subjects repeatedly and avoid the risk of learning effects within the context a crossover within-subject design. Task metrics considered for the analysis were: *Reaction Time of an accurate response* ($RT_{correct}$, in Milliseconds), *Reaction Time of any response* for tests where no accuracy was assessed (RT_{all}, in Milliseconds), and, where available depending on the task, *Accuracy* (ACC, % correct answers). RT_{all} was measured in milliseconds/pixels in The Circles and Hexagons Task for assessing Visual Scanning skill. Inverse Efficiency Score, which combines RT and ACC, considered a comprehensive metric and it was calculated where ACC was available (IES = $RT_{correct}$/ACC) [52–54]. Moreover, based on the CogniFit® manual some tasks fall under more than one domain, e.g., The Pictures and Words task falls under Working Memory skill and is marginally relevant to Visual Perception skill. Therefore, we report the task outcomes under the memory domain only as it is more relevant and can avoid reporting the same data twice. In addition, The Circles and Hexagons task falls under Focused Attention skill and Visual Scanning skill, but different metrics were used to assess them. Thus, for clarity, we report the results of two metrics for the same task separately under these two skills. The details of cognitive tasks descriptions and metrics are provided in the Supplementary Materials Table S2.

The CogniFit neuropsychological evaluation has been validated in healthy people against major standard neuropsychological tests, including the full Cambridge Neuropsychological Test Automated Battery, Raven's Standard Progressive Matrices, the Wisconsin Card Sorting Test, the Continuous Performance Test, the STROOP test, and other tests [55]. Tests of its reliability have been demonstrated in previous studies, yielding adequate measures of internal consistency (Chronbach's alpha = 0.70) and test—retest reliability (intra-class correlation coefficient = 0.80) [55,56]. It has been used as a cognitive function measure in previous research [56–62].

Table 2
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)
	41–65	3 (5.4)
Education Level	Bachelor	28 (50.9)
	Master and above	27 (49.1)

2.6. Statistical analysis

Data cleaning was done separately for both conditions and the raw data of the cognitive tests were z-transformed prior to use in analyses. If the z value was outside the range from −3 to 3, it was considered an outlier and hence excluded. The normality assumption was checked by Q-Q plots and Kolmogorov-Smirnov test and the data largely follows a normal distribution with about 70% of task metrics meeting the normality assumption. The paired *t*-test served to assess statistical differences across conditions in repeated measures. Statistical significance was evaluated at a level of $\alpha = 0.05$. Non-parametric Wilcoxon Signed Ranks Test was additionally performed as a sensitivity check, and the results are in line with the paired *t*-test, which are provided in the Supplementary Materials Table S4. Relevant outcome metrics were $RT_{correct}$, RT_{all}, and where available ACC and IES (see section 3.2). Cohen's *d* was calculated via G*Power 3.1.9.7 (Universität Kiel, Germany) as indicator of whether the difference was of practical importance [63], with *d* values of 0.2, 0.5, and 0.8 indicating small, moderate, and large changes in pairwise comparisons [51]. Findings pertaining all outcome metrics are presented in tabular format. In addition, since RT was available for most tasks, RT results are presented for each cognitive domain in figures illustrating average RT, with error bars indicating 95% confidence interval.

2.7. Ethics and data protection

The study Ethics protocol was approved as low risk by University College London, Bartlett School of Environment Energy and Resources (ref: No. 20210715_IEDE_PGR_ETH) and registered for data protection (ref: Z6364106/2021/07/29 social research). Informed consent was obtained from all participants involved in this study.

Table 3
Average environmental parameters (SD) for all sessions under control and intervention conditions.

Parameter	Control	Intervention
$PM_{2.5}$ (μg/m^3)	18.0 (1.8)	3.7 (0.9)
Relative Humidity (%)	54.3 (0.4)	51.5 (0.4)
Air Temperature (°C)	27.8 (0.06)	27.6 (0.04)
CO_2 (ppm)	707.1 (38.6)	723.7 (23.0)

Control sessions: Day 1 (9–15.00); Day 2(9–17.00); Day 3(9–15.00); Day 4 (9–17.00).
Intervention sessions: Day 1 (9–17.00); Day 2 (9–15.00); Day 3(9–17.00); Day 4 (9–15.00).

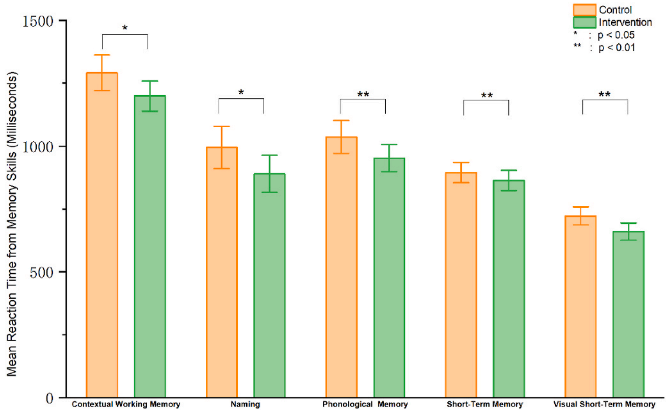


Fig. 3. Intervention and control average reaction time of a correct response for memory skills (the lower the better).

3. Results

Five participants did not complete all parts of the study. Hence, the statistical analysis was based on data from 55 participants. A CONSORT diagram showing the participant flow throughout the study is provided in the Supplementary Materials Fig. S1.

3.1. *Participant demographics and environmental parameters*

Table 2 shows the general characteristics of respondents: the majority (69%) were female, mostly aged 18–40 (only 5% aged 41–65), with a master's degree or above (49%) or a bachelor (51%).

Environmental parameters for each condition are described in Table 3. Average $PM_{2.5}$ levels during the control were 18.0 (SD = 1.8) and in the intervention 3.7 (SD = 0.9) μg/m^3, respectively, whereas RH, CO_2 and temperature were similar across the two conditions. Hence, PM2.5 levels were substantially lower when the air purifier was switched on. The detailed data by condition per day is shown in the Supplementary Materials Fig. S3.

3.2. *Cognitive performance results*

3.2.1. *Memory domain*

The memory domain includes five skills: *Phonological Short-term Memory; Contextual Working Memory; Short-Term Memory; Visual Short-Term Memory; Naming.* Fig. 3 shows the average correct reaction time (available for all five skills) for memory tasks in the control and intervention condition with error bars indicating 95% confidence interval. Table 4 shows all available metrics for the memory skills. There were statistically significant differences in RT between conditions, with all five memory skills consistently higher in the intervention compared to the control condition. The changes in $RT_{correct}$ were small to moderate magnitude with Cohen's d varying from 0.21 to 0.48. Similarly, ACC and IES across memory skills showed consistent effects (see Table 4), with

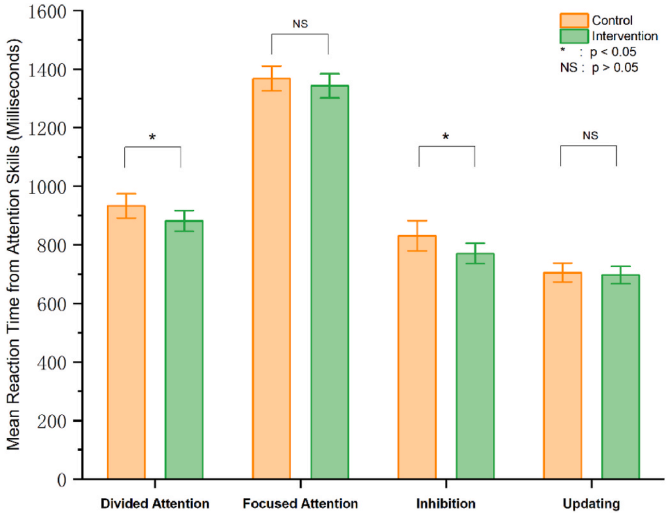


Fig. 4. Intervention and control average reaction time of a correct response for attention skills (the lower the better).

Table 4
Statistical analysis from memory domain.

Skills	Skills assessed by task	Metrics	Control vs. Intervention *p* (*d*)	Control Mean (SD)	Intervention Mean (SD)
Phonological Short-term Memory	Objects Seen or Heard Before	$RT_{correct}$ (Milliseconds)	0.006** (0.38)	1036.60 (240.82)	952.57 (199.34)
Contextual Working Memory	Pictures and Words	IES	<0.001*** (0.62)	147.79 (40.04)	125.21 (32.61)
		ACC (Correct answers/Total answers)	0.001** (0.55)	9.02/12 (1.59)	9.82/12 (1.32)
		$RT_{correct}$ (Milliseconds)	0.014* (0.38)<	1291.34 (263.16)	1199.05 (221.78)
Short-Term Memory	The Numbers	$RT_{correct}$ (Milliseconds)	0.009** (0.21)	894.93 (148.70)	863.55 (148.66)
Visual Short-Term Memory	Glowing Circles	IES	<0.001*** (0.62)	111.62 (30.83)	95.06 (22.36)
		ACC (Number sequences/Total sequences)	0.013* (0.41)	6.67/10 (1.03)	7.06/10 (0.88)
		$RT_{correct}$ (Milliseconds)	0.003** (0.48)	722.62 (134.13)	660.34 (126.21)
Naming	The Letters	$RT_{correct}$ (Milliseconds)	0.010* (0.36)	994.71 (309.74)	890.42 (272.68)

$p < 0.001$***; $p < 0.01$**; $p < 0.05$*.
$RT_{correct}$: Reaction time of a correct response; ACC: Accuracy; IES (Inverse Efficiency Score) = $RT_{correct}$/ACC.
The Cohen's effect size (d) was calculated as an indicator of whether the difference between control and intervention condition. The Cohen's effect sizes d with values of 0.2, 0.5, and 0.8 indicate small, moderate, and large changes.

Table 5
Statistical analysis from attention domain.

Skills	Skills assessed by task	Metric (Milliseconds)	Control vs. Intervention *p (d)*	Control Mean (SD)	Intervention Mean (SD)
Divided Attention	The Ball and the Colors	$RT_{correct}$	0.013* (0.36)	933.07 (152.00)	881.72 (129.18)
Focused Attention	The Circles and Hexagons	$RT_{correct}$	>0.05 (N/A)	1368.36 (155.59)	1343.12 (153.70)
Inhibition	The Words and the Colors	$RT_{correct}$	0.01* (0.27)	830.95 (191.27)	770.40 (128.78)
Updating	Numbers and Shapes	$RT_{correct}$	>0.05 (N/A)	705.59 (117.31)	697.31 (110.24)

$p < 0.001$***; $p < 0.01$**; $p < 0.05$*.
N/A: not applicable, no significance($p > 0.05$).
$RT_{correct}$: *Reaction time of a correct response.*
Cohen's effect size (d) was calculated as an indicator of whether the difference between control and intervention condition. The Cohen's effect sizes d with values of 0.2, 0.5, and 0.8 indicate small, moderate, and large changes.

moderate effect sizes for Contextual Working Memory and Visual Short-Term Memory.

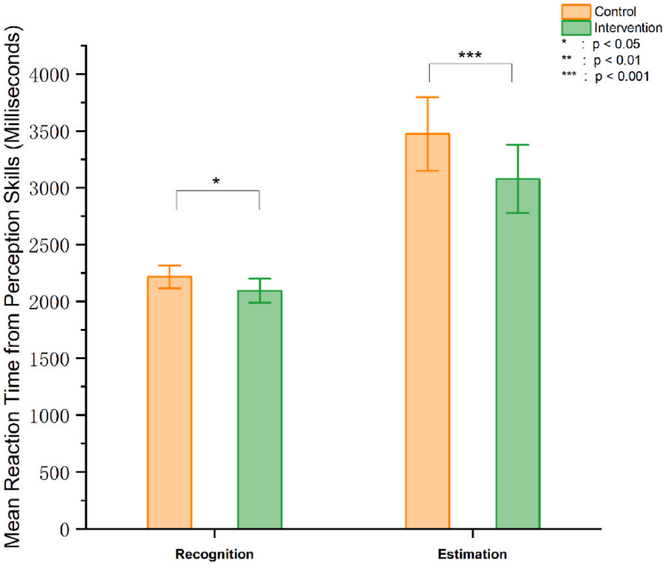


Fig. 5. Intervention and control average reaction time of a correct response for perception skills (the lower the better).

3.2.2. *Attention domain*

The attention domain includes *Divided attention; Focused attention; Inhibition; and Updating skills*. There was a statistically significant difference between the control and intervention conditions in 'divided attention' and in 'inhibition' (Fig. 4) with small effect sizes (Table 5). No statistically significant difference was found in 'updating' and 'focused attention' between the two conditions.

3.2.3. *Perception domain*

There are multiple skills within the perception domain: *Auditory perception; Estimation; Recognition; Visual Scanning.* Fig. 5 shows $RT_{correct}$ in the intervention and control conditions when available for perception skills: Recognition, Estimation skills. Table 6 described numerical values and effect sizes across the five perception sub-skills. There is a statistically significant difference in $RT_{correct}$ for Estimation, and Recognition skill between control and intervention ($p < 0.05$), with higher ACC in the intervention compared with the control, and effect sizes are generally small except for ACC in Estimation ($d = 0.51$). No statistical difference was found in Auditory Perception and Visual Scanning skill.

3.2.4. *Coordination domain*

The coordination domain includes *Hand-eye Coordination and Response Time skill*, with no statistically significant differences found in either between the intervention and control (Table 7).

Table 6
Statistical analysis from perception domain.

Skills	Skills assessed by task	Metrics	Control vs. Intervention *p (d)*	Control Mean (SD)	Intervention Mean (SD)
Auditory perception	Musical Notes	ACC (%)	>0.05 (N/A)	85.06 (5.66)	87.15 (7.64)
Estimation	Fast and Curious	IES	<0.001*** (0.54)	61.48 (23.33)	50.04 (17.05)
		ACC (%)	<0.001*** (0.51)	58.65 (9.68)	63.66 (9.81)
		$RT_{correct}$ (Milliseconds)	0.003** (0.36)	3491.51 (1198.43)	3076.00 (1108.17)
Recognition	Three Shapes	$RT_{correct}$ (Milliseconds)	0.011* (0.38)	2234.60 (348.28)	2094.88 (393.09)
Visual Scanning	The Circles and Hexagons	RT_{all} (Milliseconds/pixels)	>0.05 (N/A)	3.24 (0.69)	3.14 (0.80)

$p < 0.001$***; $p < 0.01$**; $p < 0.05$*.
N/A: not applicable, no significance($p > 0.05$).
IES (Inverse Efficiency Score) = $RT_{correct}$/ACC.
$RT_{all:}$ Average speed when responding to stimuli located at the top of the screen, Milliseconds/pixels. The lower the better (Milliseconds/pixels).
The Cohen's effect size (d) was calculated as an indicator of whether the difference between control and intervention condition. The Cohen's effect sizes d with values of 0.2, 0.5, and 0.8 indicate small, moderate, and large changes.

Table 7
Statistical analysis from coordination domain.

Skills	Skills assessed by task	Metrics	Control vs. Intervention *p (d)*	Control Mean (SD)	Intervention Mean (SD)
Hand-eye Coordination	Follow the ball	Accuracy (%)	>0.05 (N/A)	94.62 (3.04)	95.030 (3.18)
Response time	A big Circle	RT_{all}	>0.05 (N/A)	165.78 (17.69)	166.79 (17.49)

N/A: not applicable, no significance($p > 0.05$).
RT_{all}: *Reaction Time of any response for tests where no accuracy was assessed (Milliseconds).*

Table 8
Analysis from the reasoning task.

Skills	Skills assessed by task	Metrics	Control vs. Interventionp (d)	Control Mean (SD)	Intervention Mean (SD)
Planning	The Mazes	ACC (Number solved mazes/ Total mazes)	>0.05 (N/A)	1.76/3 (0.98)	1.91/3 (0.93)

$p < 0.001$***; $p < 0.01$**; $p < 0.05$*.
N/A: not applicable, no significance($p > 0.05$).
The Cohen's effect size (d) was calculated as an indicator of whether the difference *between control and intervention condition.* The Cohen's effect sizes d with values of 0.2, 0.5, and 0.8 indicate small, moderate, and large changes.

Table 9
A summary of effect sizes of cognitive results.

Domain	Skill	Task	RT	ACC	IES
Memory	Phonological Short-term Memory	Objects Seen or Heard Before	0.38**		
	Contextual Working Memory	Pictures and Words	0.38*	0.55**	0.62***
	Short-Term Memory	The Numbers	0.21**		
	Visual Short-Term Memory	Glowing Circles	0.48**	0.41*	0.62***
	Naming	The Letters	0.36*		
Attention	Divided Attention	The Ball and the Colors	0.36*		
	Inhibition	The Words and the Colors	0.27*		
	Focused Attention	The Circles and Hexagons✓	ns		
	Updating	Numbers and Shapes	ns		
Perception	Auditory Perception	Musical Notes		ns	
	Estimation	Fast and Curious	0.36**	0.51***	0.54***
	Recognition	Three Shapes	0.38*		
	Visual Scanning	The Circles and Hexagons✓※	ns		
Coordination	Hand-eye Coordination	Follow the ball		ns	
	Response Time	A big Circle※	ns		
Reasoning	Planning	The Mazes		ns	

$p < 0.001$***; $p < 0.01$**; $p < 0.05$*.
ns: no significance ($p > 0.05$).
Tasks using RT_{all} as the metric are marked with ※, others use $RT_{correct}$ as the metric.
The tasks marked as ✓ are the same task, which we reported separately by using different metrics in different domains.

3.2.5. *Reasoning domain*

The average reasoning skill indicators and effect size analysis are provided in Table 8. There was no significant effect in Planning skill for the relevant outcome (ACC).

3.3. *Summary of cognitive outcomes*

A summary of all cognitive results is shown in Table 9.

Table 10 shows the correlation analysis of the cognitive variables in the intervention condition. Memory abilities are positively correlated with each other in general, and also with several skills within the Attention domain. The Perception and Coordination domains also had some correlated skills.

4. Discussion

This on-site experimental trial examined a wide range of cognitive functions and their relationship with short-term indoor exposures to PM2.5 within workplace settings. A comprehensive analysis covering five cognitive domains including 16 cognitive skills was presented. We found office workers had significantly lower reaction times for a correct response indicating higher cognitive performance in 9 out of 16 skills when working in comparatively lower PM2.5 concentrations. Within those 9 skills, the accuracy in 3 of the 9 skills (where available as the metric) was also statistically significant different (better) in the intervention. The effect sizes ranged from small to moderate, with the largest effect sizes found for ACC and IES in Contextual Working Memory and Visual Short-Term Memory.

The Memory domain showed the most consistent impact related to PM2.5 exposure. This finding is consistent with previously published work from cross-sectional [35,36,64,65] and longitudinal [37,66,67] studies across the world, but all these studies were using outdoor levels as the exposure variable. A longitudinal study from China found lower memory ability in a Word-recognition task after higher exposure to long-term exposure to air pollution including particulate air pollution in an older population [38]. Our RCT cross-over work showed a similar result that short-term exposure to indoor PM2.5 in adults also affect Naming skill and others in the memory domain.

The correlation analysis indicates that memory abilities positively correlated with each other in general, and also with skills within the attention domain. A possible reason is that memory is closely related to attention, which has been broadly demonstrated in previous studies [68–71]. Moreover, attention as a resource for storage and processing is also empirically well supported [71–77]. For example, the role of memory in cognitive control contributes to controlling perceptual attention and controlling action [78]. Therefore, if memory is affected, the performance in other areas may also be affected to varying degrees e.g., attention and perception abilities.

Previous studies with different approaches to study design, task assessment, population type and exposure (i.e., concentration levels and duration) yielded inconsistent results. We found clear effects for some cognitive domains, but not for others. For example, the performance for the Memory domain was significantly influenced in a consistent manner across all relevant tasks and the Coordination domain was not. Findings for the sub-skills within the Attention and the Perception domains were mixed. Hence, there might be domain-specific effects, which may however be also affected by thresholds effects in the exposure and/or the population characteristics as suggested by other studies [5,42]. Some of our findings are consistent with the findings from Cedeño Laurent et al. *(*2021) where, after adjusting for several covariates, a statistically significant difference in the Stroop test metrics was found, as our study also found within the corresponding tasks (see: Attention domain, Inhibition skill). Their study also established via a sensitivity analysis that associations between indoor PM2.5 levels and cognitive performance were stronger in magnitude and significance at concentrations above the US annual ambient air quality standard (12 $\mu g/m^3$), whereby our study compared differences in cognitive performance at PM2.5 concentration levels of 3.7 and 18.0 $\mu g/m^3$. On the other hand [41], did not find a statistically significant difference in Stroop test scores (adjusted by age and education level) when comparing candle-generated means of $PM_{2.5}$ 41.4 $\mu g/m^3$ against conditions without candles (mean PM2.5: 1.6 $\mu g/m^3$). However, the exposure time was relatively short (1 h) compared to our study, where exposure times to indoor office settings prior to cognitive performance testing was approximately 5–7 h.

There is prior research on the use of air purifiers as an intervention for the purpose of improving air quality by lowering PM2.5 [79,80] as

Table 10
Correlations among the cognitive variables at intervention.

Correlation analysis		*Attention*				*Memory*		
		Divided Attention (RT)	Inhibition (RT)	Focused Attention (RT)	Updating (RT)	Phonological Short-term Memory (RT)	Contextual Working Memory (ACC)	Contextual Working Memory (RT)
Attention	Divided Attention (RT)	1						
	Inhibition (RT)	**.277***	1					
	Focused Attention (RT)	.079	.054	1				
	Updating (RT)	−.053	.121	−.191	1			
Memory	Phonological Short-term Memory (RT)	**.371****	.072	**.427****	−.143	1		
	Contextual Working Memory (ACC)	−.139	.185	.031	.144	−.148	1	
	Contextual Working Memory (RT)	.108	−.037	.235	−.074	**.273***	**−.268***	1
	Short-Term Memory (RT)	**.287***	.128	**.385****	.104	**.478****	−.149	.079
	Visual Short-Term Memory (ACC)	−.074	.028	.103	−.161	.045	−.142	**.290***
	Visual Short-Term Memory (RT)	−.051	.007	**.338***	.131	.221	−.052	−.121
	Naming (RT)	**.430****	.102	.107	−.070	**.346****	−.162	−.009
Perception	Auditory perception (ACC)	−.014	−.056	.052	.013	−.150	.033	**−.333***
	Estimation (ACC)	.134	−.093	−.139	−.058	−.152	−.117	.024
	Estimation (RT)	.069	.001	.199	−.072	**.358****	.130	.155
	Recognition (RT)	**.321***	.222	.048	−.132	**.404****	.092	−.019
	Visual Scanning (RT)	.071	.136	.181	**−.311***	.053	−.134	.039
Coordination	Hand-eye Coordination (ACC)	−.238	−.047	.145	.136	−.176	.146	−.063
	Response time (RT)	−.071	−.001	.062	−.022	.017	−.032	.030
Reasoning	Planning (ACC)	−.178	−.006	−.088	.197	−.044	.198	.014

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

well as health and wellbeing outcomes [81,82], in offices [83], schools [84] and domestic buildings [85]. Our work found that the use of air purifiers as an intervention lowered the PM2.5 levels and affected both perception of indoor air quality and productivity [47] as well as cognitive performance as shown in this paper. It should be acknowledged that further research is needed to establish to what extent the effect of PM2.5 exposure on cognitive outcomes should be attributed to the perceived air quality pathway and/or to bio-physiological mechanisms.

5. Strengths and limitations

The study design has several notable strengths, including repeated measures of cognitive function on the same individual controlling for between-subject variability. This is the first on-site work that examined the PM2.5 exposure on a wide range of cognitive domains via a validated PC-based measure and an onsite intervention approach in adults within office buildings.

There is a potential limitation that the cognitive testing was done on different days which could be associated with variations in outdoor exposure. However, given that control and intervention testing sessions were balanced to happen on the same days this should only marginally if at all affect results. There was limited variation in the sample population in age band and educational level, with the majority of participants being females. Although all attempts were made to reduce the potential for the placebo effect (e.g., participants were told the filters may be removed), this cannot be completely excluded. Furthermore, there might be some differences between the two conditions in terms of noise and airflow when the air purifier was in operation. Regarding noise, it should be noted that sound levels arising from the air purifier during operation was below 40 dB which suggests it could be considered a quiet office setting [86]. Moreover, the self-reported sound environment satisfaction was assessed by questionnaire in this study, whereby no significant difference was found across the control and intervention [47]. These aspects mentioned above are encouraging, but since the impact of noise canceling on concentration is relatively well established [87–89], the role of sound cannot be fully excluded. Moreover, airflow would be different across the two conditions, and this may indirectly impact on thermal comfort. Whilst the aforementioned questionnaire did not ask about airflow as such, there was a difference in thermal satisfaction between the two conditions [47]. Further research is needed to establish if the use of air purifiers is overall beneficial for cognitive performance or actual work performance/outcomes and to evaluate if our findings are confirmed by studies where other methods for reducing PM2.5 exposure are utilized to further evaluate if there is a causative association, and/or to what extent airflow or noise may play a pivotal role. More broadly speaking, Cognitive performance may also be influenced by other individual-level factors including overall wellbeing and sleep quality [90–92]. The questionnaire results that were collected during this study and published previously did not find significant differences in self-reported wellbeing [47]. Future studies may consider addressing other areas which may impact cognitive performance, such as mental load as potentially leading to fatigue [93]. Furthermore, the presence and role of other air pollutants may need to be considered, although in this study CO2 levels, which can be considered a proxy for ventilation, were similar across control and intervention conditions [94,95]. It should be acknowledged that the air purifiers used in this study did not control gaseous pollutants such as NO2 or O3, hence there is little scope to disentangle effects specifically related to PM2.5 versus any synergistic effects with other pollutants.

IES used in the presented study was an appropriate measure as both variables ($RT_{correct}$ and ACC) in our studies are in unison [52]. This study has used multiple, partly correlated outcome variables but analyzed them separately which may increase the chance of false positives. We additionally performed Bonferroni correction of p-values. Here, the adjusted alpha level is $\alpha = 0.0031(0.05/16)$, and seven tests remained significant (Bonferroni adjusted value is reproduced in Supplementary Materials Table S6). Bonferroni adjustment is overly conservative when

Memory				*Perception*					*Coordination*		*Reasoning*
Short-Term Memory (RT)	Visual Short-Term Memory (ACC)	Visual Short-Term Memory (RT)	Naming (RT)	Auditory perception (ACC)	Estimation (ACC)	Estimation (RT)	Recognition (RT)	Visual Scanning (RT)	Hand-eye Coordination (ACC)	Response time (RT)	Planning (ACC)
1											
−.057	1										
.441**	−.059	1									
.549**	−.199	.161	1								
−.190	−.136	.135	−.187	1							
−.156	−.160	−.241	−.061	−.049	1						
.098	−.044	−.090	.043	−.201	.134	1					
.244	−.188	.108	.144	.128	−.271	.056	1				
−.074	.026	.055	−.023	.009	.013	.084	.159	1			
−.042	.217	.048	**−.294***	**.360****	−.042	**−.312***	.053	−.204	1		
.218	−.057	.169	.195	**−.327***	**−.279***	−.068	.052	.070	−.262	1	
−.186	.189	.010	**−.316***	.071	−.067	.246	−.145	−.001	−.037	−.023	1

the tested hypotheses are related, leading to an unnecessary loss of power (i.e., the Bonferroni adjustment would lead to the conclusion of a non-significant result.) [96,97]. Moreover, there are known limitations to the quality of real-time, commercial-grade environmental sensors [98]. For instance, these are low-cost monitors with low absolute accuracy and the varying size of PM exposures levels (e.g., ultrafine particles) cannot be monitored. Despite their limitations, the use of low-cost sensors (i.e., relative measurements) can make an appropriate contribution in certain areas, particularly when looking at relative changes in exposures. Future work including use of high-quality monitor instrument might become necessary to investigate the impacts of varying size of PM exposures on cognitive and health related study.

6. Conclusions

This study aimed to understand how short-term exposure to indoor PM2.5 within offices affects cognitive performance across various domains in working-age adults. Using a case study building in an urban setting with elevated PM2.5 levels, the study found that office workers had significantly improved cognitive performance in some cognitive skills when working at relatively lower indoor PM2.5 concentrations (3.7 $\mu g/m^3$) achieved via an air purifier, compared with higher PM2.5 exposure without the air purifier (18.0 $\mu g/m^3$). The results showed that there were differences in effect size and statistical significance levels across domains, with memory domain showing consistently lower performance under higher PM2.5 levels. However, results were more mixed for some domains such as attention and perception. No difference was found for the coordination domain. This study adds to the evidence pertaining short-term effects of indoor air quality, particularly indoor PM2.5, on cognitive function, and contributes to the body of evidence demonstrating the relevance of PM2.5 to a healthy and productive built environment, building performance, and human cognitive performance. Reducing significantly indoor elevated PM2.5 levels can improve some cognitive abilities in office workers. Hence, the impacts of PM2.5 should be considered more broadly, not solely pertaining disease and mortality. Future research is needed to investigate the role of ultrafine particle exposure, sound and air flows on cognitive effects and also some work in including experiments conducted by well-controlled chamber, exploring potential mechanisms of physiological responses to PM2.5 exposure, and cognitive outcomes regarding personal exposure are needed.

CRediT authorship contribution statement

Jiaxu Zhou: Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hong Wang:** Writing – review & editing, Resources, Conceptualization. **Gesche Huebner:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Yu Zeng:** Writing – review & editing, Resources, Conceptualization. **Zhichao Pei:** Writing – review & editing, Resources, Conceptualization. **Marcella Ucci:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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