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Heart rate variability, electrodermal activity and cognition in adults: Association with short-term indoor PM2.5 exposure in a real-world intervention study

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ABSTRACT

Background: Long-term effects of ambient fine particulate matter (PM2.5) exposure on mortality and morbidity are well established. The study aims to evaluate how short-term indoor PM2.5 exposure affects physiological responses and understand potential mechanisms mediating the cognitive outcomes in working-age adults.

Methods: This real-world randomized single-blind crossover intervention study was conducted in an urban office setting, with desk-based air purifiers used as the intervention. Participants ($N = 40$) were exposed to average PM2.5 levels of 18.0 μg/m3 in control and 3.7 μg/m3 in intervention conditions. Cognitive tests, heart rate variability (HRV), and electrodermal activity (EDA) measures were conducted after 5 h of exposure. Self-reported mental effort, exhaustion, and task difficulty were collected after the cognitive tests.

Results: Participants in the intervention condition had significantly higher HRV during cognitive testing, particularly in the standard deviation of normal-to-normal intervals (SDNN), root mean square of successive differences (RMSSD), and high-frequency power (HF) indices. Mediation analysis revealed that elevated PM2.5 exposure reduced HRV indices, which mediated the effect on two executive function-related cognitive skills out of 16 assessed skills. No significant differences were found in EDA, self-reported task difficulty, or exhaustion, but self-reported mental effort was higher in the control condition.

Conclusions: Lower indoor PM2.5 level was associated with reduced mental effort and higher HRV during cognitive testing. Furthermore, the association between indoor PM2.5 exposure and executive function might be mediated through cardiovagal responses. These findings provide insights on the mechanisms through which fine particle exposure adversely affects the autonomic nervous system and how this in turn affects cognition. The potential cardiovascular and cognitive health benefits of PM2.5 reduction warrants further research.

1. Introduction

Fine particulate matter (PM2.5) is an air pollutant recognized as one of the top risks to human health by the World Health Organization (WHO), which updated its PM2.5 guidelines in 2021, largely based on evidence from mortality and respiratory and cardiovascular disease (World Health Organization, 2021). However, many regions of the world still have PM2.5 levels that far exceed these guidelines, and around 90% of the global population is breathing unhealthy air (Health Effects Institute, 2020). PM2.5 can easily penetrate indoors, where people typically spend 90% of their time (US Environmental Protection Agency, 2011), and there are also indoor sources of PM2.5 beyond those that penetrate from outdoors, such as cooking, cleaning, candle burning and other household activities - although not all these are common in office buildings (Wei and Semple, 2023; Z. Zhang et al., 2020). The COVID-19 pandemic further demonstrated the importance of ventilation and indoor air quality (Nwanaji-Enwerem et al., 2020). Beyond COVID-19, there is growing awareness that exposure to pollutants in indoor environments has a substantial impact on general health, productivity and performance (Felgueiras et al., 2023).

The health impacts of particulate air pollution can be wide-ranging (Vos et al., 2020). Long-term exposure to high levels of PM2.5 can greatly increase the risk of cardiovascular events such as myocardial infarction and heart failure (Fiordelisi et al., 2017; La Rovere et al.,

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2003). To date, the range of PM2.5 concentrations around the world is still associated with mortality and premature deaths, with more than 4 million deaths per year attributed to ambient PM2.5 (Apte et al., 2015; Bowe et al., 2019; Thurston et al., 2016). The prevention and intervention strategies to reduce particulate air pollution and their efficacy and benefits for individual health are far from being fully understood (Brook et al., 2017), especially in office settings (Mandin et al., 2017). A growing body of studies show that reducing ambient and indoor PM2.5 air pollution may have overall health benefits and improve cardiovascular indicators (Allen and Barn, 2020; Kaufman et al., 2020; Laumbach & Cromar, 2022; Meng et al., 2016; Morishita et al., 2015; Rajagopalan et al., 2018, 2020; Zhao et al., 2021) with most studies focusing on the elderly population (over 50 years) (Sharma et al., 2020). For instance, a randomized clinical trial (RCT) conducted in a senior residential facility found that reducing indoor PM2.5 is beneficial to brachial blood pressure, aortic hemodynamic, and heart rate variability (HRV) (Morishita et al., 2018), a measure of the beat-to-beat variation in heart rate. HRV is predominantly under vagal control, and decreased HRV is generally interpreted to represent reduced vagal tone alongside increased sympathetic activity (Shaffer and Ginsberg, 2017). Exposure to PM2.5 may lead to reduced HRV levels, a proxy for relative autonomic nervous system dysfunction associated with an increased risk of cardiovascular disease (Fang et al., 2020; Kop et al., 2010), but previous evidence is heterogenous and not entirely conclusive (Niu et al., 2020) with limited studies on short-term indoor exposure in working-age adults, and mostly were observational approaches.

Recent studies found that air pollution, particularly PM2.5 exposure, also potentially affects cognitive performance and productivity in both long-term and short-term exposure (Ailshire et al., 2017; Gao et al., 2021; Graff Zivin and Neidell, 2012; Kulick et al., 2020; Schikowski and Altuğ, 2020; Shehab and Pope, 2019; Zhou et al., 2022, 2023). These effects may involve oxidative stress, inflammation, neuroinflammation, and autonomic nervous system dysfunction through many pathways (Genc et al., 2012; Hajipour et al., 2020; Sram et al., 2017; Zhang et al., 2018). A substantial body of research has revealed a direct connection between cognitive processing and the cardiovascular system through autonomic nervous system control, as measured using HRV (Luque-Casado et al., 2016; Thayer, 2009, 2016; Thayer et al., 2021). The possible physiological mechanisms on the association between short-term exposure to PM2.5 and cognition need further research.

Most findings on long-term exposure effects of PM2.5 (more than one year) on HRV are from cross-sectional and longitudinal observational studies (Huang et al., 2012; Lim et al., 2017; Mordukhovich et al., 2015; Schneider et al., 2010; Timonen et al., 2006; Xu et al., 2013), which show that elevated PM2.5 exposure was related to lower HRV (Wang et al., 2020). However, almost all previous studies used outdoor levels measured at the nearest monitoring stations as the long-term exposure variable. In contrast, findings from short-term exposure studies are mixed. For instance, a study (Sullivan et al., 2005) did not find a significant association between a 10μg/m3 increase in 1-h mean outdoor PM2.5 and a change in HRV. However, other studies observed significant associations between decreased HRV with ambient PM2.5 exposure within a few hours (Chuang et al., 2013; Devlin et al., 2003; Gold et al., 2000; Lipsett et al., 2006), suggesting a close temporal relationship between particulate air pollution and HRV effects within hours of exposure. Overall, the evidence for adverse effects of short-term indoor exposure to fine particulate air pollution on HRV is still scarce and inconsistent, considering different approaches to study design, population type, and exposure (i.e., concentration levels and duration). More importantly, given the connection between the heart and the brain (Elliot et al., 2011; Samuels, 2007; Thayer et al., 2021), the impact of short-term exposure to PM2.5 on the cardiovagal system and its potential relationship with cognition is poorly understood, especially in working adults (Brook et al., 2017).

In contemporary workplaces, indoor air quality has emerged as a critical concern for occupational health and wellbeing (Bluyssen et al., 2016; Chen et al., 2023; Mandin et al., 2017). Among the various airborne contaminants, PM2.5 holds particular relevance due to its potential to impact respiratory health and overall productivity (Chuang et al., 2012; Khan et al., 2019; Zhou et al., 2022). These fine particles possess the capacity to remain suspended in the air for extended periods, allowing them to be easily inhaled deep into the respiratory tract (Lee et al., 2019). As employees typically spend a substantial portion of their day within the workplace, understanding and mitigating PM2.5 levels within offices is crucial for safeguarding the health and wellbeing of the workforce (Jones et al., 2021). Moreover, addressing PM2.5 in the workplace aligns with broader efforts towards creating healthier indoor environments, ultimately fostering greater productivity and job satisfaction among employees (Cedeño Laurent et al., 2021). Overall, indoor PM2.5 could represent an important contributor to overall population exposure to air pollution and to health, wellbeing and cognitive performance inequalities (Cooper et al., 2021, 2022; Dong et al., 2023; Ferguson et al., 2020, 2021, 2023; Wang et al., 2021; Zhang et al., 2021a,b). However, to date the role of PM2.5 in the work environment, its physiological effects and the mechanisms underlying occupational work performance decline are not well established.

This paper builds upon a previously published study (Zhou et al., 2023) which investigated the impact of short-term PM2.5 exposure on cognitive performance among office workers, based on a real-world intervention using air purifiers to reduce PM2.5 exposures via a randomized repeated measure crossover intervention approach. Our previous work found that in the intervention condition, office workers demonstrated significantly better performance in 9 out of 16 cognitive skills, with the most notable effects observed in memory and attention domains. In this paper, we report the relationship between short-term indoor PM2.5 exposure and physiological responses (i.e. HRV and EDA) and aim to understand whether these represent potential mediating mechanisms of cognitive outcomes within the workplace context.

2. Method

2.1. Overview

Details of the study have been previously described (Zhou et al., 2023). In this methods section, we summarize key study elements and add information on physiological measures (HRV and EDA) that were conducted in conjunction with the cognitive testing in a sub-sample of N = 40 participants. Following the cognitive assessment, a standalone questionnaire was administered to evaluate self-reported test difficulty, mental effort, and feeling of exhaustion.

2.2. Setting

The study was conducted in an urban office setting in Beijing, China, which featured a mixed-mode ventilation system. The experiment took place within a designated office area where employees engaged in their routine work-related tasks.

2.3. Subjects

60 non-smoking eligible employees were enrolled for the whole study. The inclusion criteria were as follows: being an employee of working age (18–65 years) in the case study building, non-smoking, healthy, not using prescription medications or antiarrhythmic drugs (including beta-blockers, calcium channel blockers, digitalis etc.), not having psychiatric or learning disorders, and not experiencing COVID-19 symptoms. The study was approved by the institutional review board of University College London (UCL), Bartlett School of Environment Energy and Resources, with the registration number for Ethics (No. 20210715_IEDE_PGR_ETH). It also adhered to UCL data protection rules, as indicated by Data Protection (No. Z6364106/2021/07/29). All participants gave written informed consent ahead of the study.

Due to the limited availability of wearable sensors, a subset of subjects (N = 40, randomly selected from the 60 participants of the whole study) were equipped with HRV and EDA wearable sensors, the results of which are presented in this paper.

2.4. Study design and procedure

A randomized, single-blind, two-way crossover intervention study was conducted over four consecutive days in a non-heating season, The study adopted a repeated measure design across a control and an intervention condition. The 40 participants were divided randomly into four groups, each comprising 10 people.

The experimental procedure is shown in Fig. 1. First, subjects were asked to fill out a pre-test questionnaire covering demographic information (age band, sex, education level), questions on well-being and productivity, as well as perceptions and satisfaction with environmental factors (air quality, thermal conditions, light, sound) (Zhou et al., 2022). Subsequently, physiological response monitoring was conducted using wearable sensors, measuring HRV and EDA. First, the researcher helped participants to put on the EDA and HRV sensors and ensured that the wireless signals were connected. Next, EDA and HRV measures were collected in each session during the rest period (5 min) followed by cognitive testing (45 min). Lastly, participants were asked to self-report on mental effort, exhaustion, and task difficulty via a post-test questionnaire. On each study day, the desk-based air purifiers were activated at 8:30 a.m. for the desks assigned to the intervention condition. Participants arrived at the office around 9:00 a.m. The cognitive and physiological measures were conducted in the afternoon. Consequently, both groups were exposed to either the control or intervention condition for a period of approximately 5 h prior to cognitive and physiological measurements based on the counterbalanced crossover design.

2.5. Physiological measurements and outcomes

HRV and EDA responses were monitored using wireless wearable sensors (ErgoLab, King-far Inc., Beijing, China). Electrodes were attached to left-hand fingers to measure EDA, and a photoplethysmography (PPG) sensor was worn on the left arm and clipped to the left earlobe to record HRV as shown in Fig. 1a. HRV indices include time domain metrics (standard deviation of normal-to-normal intervals [SDNN]; root mean square of the successive differences [RMSSD]; percentage of successive R-R intervals that differ by more than 50 ms [pNN50]), and a frequency domain metric (high-frequency spectral power [HF]). The RMSSD and HF HRV indices are proposed to be more specific to the parasympathetic (vagal) modulation of heart rate, whereas SDNN and pNN50 are considered to represent both vagal and sympathetic influences (Shaffer and Ginsberg, 2017). These metrics have been widely used in previous studies on air pollution in relation to HRV-related health effects (Mallach et al., 2023; Niu et al., 2020; Wang et al., 2020). EDA was measured by the changes in skin conductivity due to sweat gland activity, which consists of two components: the phasic (Skin Conductance Response [SCR]) and tonic (Skin Conductance Level [SCL]) component (Choi et al., 2019; Greco et al., 2016). The tonic part (SCL) measures changes in skin conductance and represents activity of the sympathetic nervous system on sweat glands induced by a longer-term duration of stress, whilst the phasic component (SCR) is a faster-changing component of skin conductance serving as an indicator of immediate responses to external stressors (Braithwaite et al., 2013; Mir et al., 2023). The exposure to higher PM2.5 levels during the experiments over a defined period of time can rather be seen as a longer-term stressor than an immediate stimulus, hence, the tonic component (SCL) of the EDA response of participants across both conditions might be the more relevant EDA variable. However, for clarity, here we also report SCR. The above-mentioned methods and instruments have been widely used in previous studies on environment and human health and behaviours (Ding et al., 2020; Elsadek et al., 2021; K. Y. Liu et al., 2022; Shi et al., 2023; Yan et al., 2020; Zahmat Doost and Zhang, 2023). Participants' physiological data were processed by ErgoLAB software, which removes noise and interfering elements such as ectopic beats (Shi et al., 2023). The processing details and sensor technical specifications are available in the supplementary material (Fig. S2, and Table S1).

2.6. Cognitive stimuli and assessment

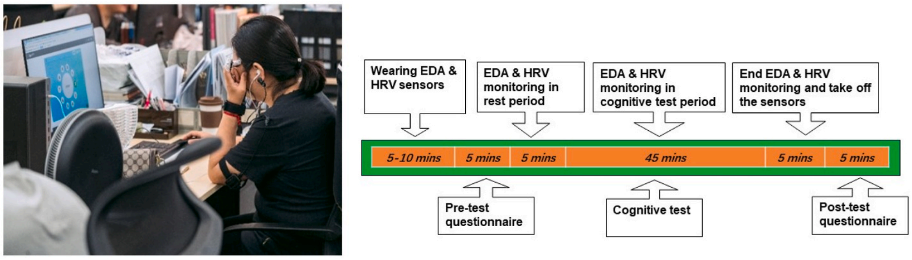
Cognitive performance was tested with the commercially available computer-based neurological test battery General Cognitive Assessment Battery, CogniFit® (CogniFit Inc., San Francisco, USA). In order to control for learning effects and level of task complexity, parallel versions of the same cognitive test battery were used as cognitive performance measures in the two conditions. The detailed cognitive performance results have been reported recently including task descriptions and validation information of the assessment details (Zhou et al., 2023).

2.7. Survey

Shortly after completing the cognitive assessment, participants were required to fill in a questionnaire on self-reported test difficulty, mental effort and exhaustion. The question on self-reported mental effort related to completion of the cognitive tests was based on the NASA Task Load Index for mental demand with a scale ranging from No Effort At All (0) to The Most Possible Effort (100) (Hart and Staveland, 1988), which was "How do you feel your mental efforts during cognitive test?". The question on exhaustion, "Are you experiencing exhaustion during the test?", was assessed based on a categorical Yes or No response (Wargocki, 1999; Wargocki et al., 2000). The self-reported rating to the task-difficulty question "How do you feel about the difficulty level of the test?" was based on a seven-point Likert scale from very difficult to very easy (Joshi et al., 2015; L. Xu et al., 2022). All items were translated into Chinese by the first author of the paper.

2.8. Intervention and exposure assessment

The intervention involved a high-efficiency particulate air filtration



a) Desk set-up

b) Procedure

Fig. 1. Experimental procedure: a) Desk set-up, b) Procedure.

(HEPA) method using personal desk-based air purifiers (Atem Desk Air Purifier, IQAir®, Switzerland) with a 30 m^3/h clean air delivery rate (CADR), and placed on the participants' workstation to reduce the PM2.5 concentration within the participants' breathing zone in the office. The air purifiers were presented but switched off in the control condition. Participants were naïve to the study hypothesis. Prior to the experiment, they were informed that even if the air purifier was operating, the research team might remove the filters, which could render it ineffective. However, in reality, no filters were removed. In addition, participants wore earphones to reduce noise interference during the cognitive tests (see Fig. 1).

Indoor environmental parameters, including PM2.5, CO_2, temperature, and relative humidity, were monitored at 1-min intervals in the office using real-time environmental sensors Sensedge (Kaiterra®, Switzerland), which were placed in the centre of the experimental space to monitor exposure levels in the respiratory zone of the subjects during each trial. The screen of the sensors' monitors was turned off. All sensors were calibrated before experimental data collection. The sensor specification and calibration protocol have been described previously (Zhou et al., 2023).

2.9. Statistical analysis

Summary statistics were calculated across participants under each experimental condition. Differences in self-reported task difficulty and mental effort in the control vs. intervention condition were evaluated via a paired *t*-test. To test if the presence of exhaustion - coded categorically as "presence of exhaustion" vs. "absence of exhaustion" - differed across control and intervention condition, Chi-square testing was used.

Physiological EDA and HRV indices were log10 transformed to improve the normality distribution. The study tested whether HEPA filtration (intervention) improved physiological outcomes compared to the control condition using a Generalized Linear Mixed Effect Model (GLMM), adjusting for sex as a covariate. We treated PM2.5 condition and sex as fixed effects (coded categorically), and fitted Subject ID as a random intercept term in each mixed-effects model. Whilst age may affect HRV, this was not included as a covariate since the distribution of participants were similar across the two age categories (Chi-Square test, $p = 0.752$), and participants were all classified as young adults with high educational background. The model was formulated as:

$$Y_{ic} = \beta_1 * \mathit{Condition}_c + \beta_2 * \mathit{Sex} + v_i + \varepsilon_{ic}$$

where Y_{ic} represented physiological metrics of individual i measured at condition c; β_1 and β_2 were fixed-effect coefficients respectively for PM2.5 experimental conditions and Sex; $\mathrm{Condition}_c$ was experimental condition (coded categorically); v_i was a random-effect intercept at individual level for individual i; and ε_{ic} was a normally distributed residual term that represented the random variation of individual i at condition c. For variables demonstrating significant effects, Cohen's d and the standardized coefficient (std β) were calculated (Cohen, 1988; Fey et al., 2023; Nieminen, 2022). In secondary analyses, the models were adjusted for baseline resting HRV scores. Statistical significance was evaluated at the level of $\alpha = 0.05$ and analysis was implemented using SPSS software.

Mediation analyses were conducted to explore whether PM2.5 exposure impacted any cognitive performance outcomes through an HRV-mediated pathway. In addition, since the airflow might not be the same when the air purifier was on or off - which could affect thermal satisfaction - we also assessed self-reported thermal satisfaction rating (TR) as another parallel mediator in the mediation models. As the study utilized repeated measures to evaluate cognitive and physiological responses within the same individuals across two conditions, and employed a randomized counterbalanced crossover design, the mediation analysis was considered to examine causal effects as the design was free of no confounding assumption (Hafeman, 2009; Valeri and VanderWeele, 2013; VanderWeele, 2011). The mediation analysis, covering direct and indirect effects, was performed via SPSS software with the mediation PROCESS package (Hayes, 2017). The outputs cover traditional regression analyses recommended by Baron and Kenny (1986) and a bootstrapping approach proposed by Preacher and Hayes (2004) for identifying direct and indirect effects. The bootstrapping approach implies that if zero falls outside the bootstrap 95% confidence interval, the indirect effect is significant at a level of $p < 0.05$ (two-tailed).

3. Results

3.1. Descriptive statistics

The 40 randomly selected subjects did not differ significantly from the total sample ($N = 60$) in terms of socio-demographics (Zhou et al., 2023) (see Table 1). The majority (70%) were female, all subjects were young adults aged 18–40, with a master's degree or above (87.5%). Environmental parameters for each condition are described in Table 2. The average PM2.5 levels were 18.0 ($SD = 1.8$) during the control and 3.7 ($SD = 0.9$) μg/m3 during the intervention condition, while RH, CO_2, and temperature were similar across both conditions. It should be noted that due to the nature of the case study building (office) and the lack of typical indoor sources of PM2.5 (e.g. cooking or smoking) within the vicinity of the monitored areas, the indoor PM2.5 levels were predominantly influenced by outdoor traffic-related air pollution penetrating the indoor office environment, as there were no filters in the building's ventilation system. The outdoor PM2.5 level was obtained from an outdoor monitoring station located 5 km away from the office, with a 1-h logging interval. The average outdoor PM2.5 concentration (19.0 $\mu g/m^3$) for the same time period exceeded the mean indoor PM2.5 concentration (18.0 $\mu g/m^3$), with an indoor/outdoor (I/O) ratio of 0.94 for PM2.5. Detailed data by condition per day can be found in our previous work (Zhou et al., 2023).

3.2. HRV

The HRV findings are shown in Fig. 2 and Table 3 across the control and intervention conditions. There was no significant effect of PM2.5 exposure on HRV indices in the rest period prior to cognitive testing ($p > 0.1$). However, the findings revealed significant differences in the fixed effect of PM2.5 on certain HRV indices ($p < 0.05$), specifically SDNN, RMSSD and HF, during the cognitive testing period (i.e. when there was a cognitive demand). The changes in SDNN, RMSSD, HF were moderate in magnitude with Cohen's d varying from 0.43 to 0.65 (Table 3). In secondary analyses, where models were adjusted for baseline resting HRV, the HRV results remained statistically significant for SDNN ($\beta = 0.123$ [95% CI: 0.009, 0.237], $p = 0.035$), RMSSD ($\beta = 0.188$ [95% CI: 0.039, 0.336], $p = 0.014$), and HF ($\beta = 0.312$ [95% CI: 0.073, 0.551], $p = 0.011$) across the two conditions. The fixed effect of sex on the outcomes was not significant in any model in this study ($p > 0.1$).

Table 1
Demographics for both intervention and control conditions (same cohort of participants, $N = 40$).

Parameters	Answers	N (%)
Total Participants		40
Sex	Male	12 (30.0)
	Female	28 (70.0)
Age Band	18–30	21 (52.5)
	31–40	19 (47.5)
Education Level	Bachelor	5 (12.5)
	Master and above	35 (87.5)

Table 2
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)

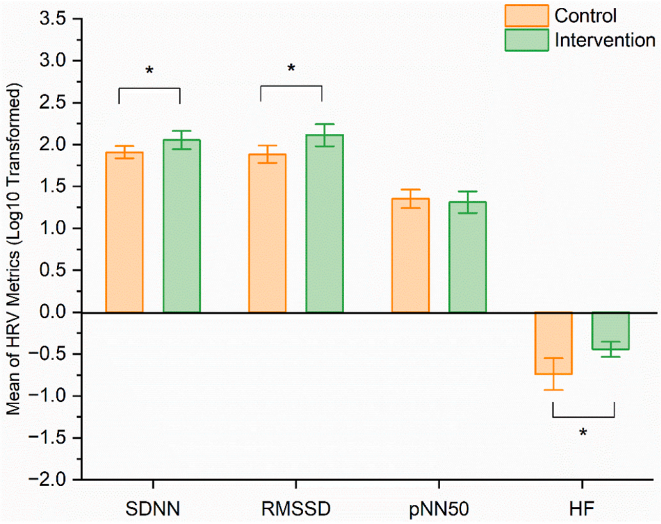


Fig. 2. Intervention and control average HRV metrics during the cognitive testing period with error bars indicating 95% confidence interval.

3.3. EDA

Table 4 provides results for EDA measures across control and intervention conditions. No significant fixed effects of PM2.5 on SCL and SCR were found during the rest or cognitive testing periods ($p > 0.05$).

3.4. Self-reported outcomes

Participants' self-reported mental effort was significantly higher in the control (M = 73.5% [SD = 17.17]) compared with the intervention (M = 64.25% [SD = 15.17]) condition, t(39) = 2.437, p = 0.019. No significant differences in self-reported task difficulty (p = 0.426) or exhaustion (p = 0.204) was found between the two conditions.

3.5. Mediation analysis

The cognitive test outcomes have been reported previously (Zhou et al., 2023). The cognitive results showed that office workers performed significantly better on 9 out of 16 cognitive skills during the intervention compared to the control condition, defined either as lower reaction time or higher accuracy depending on the task, with most of the significant effects found in memory and attention domains. In the current paper, we performed a mediation analysis to explore potential HRV-related mechanisms underlying these cognitive effects. RMSSD and HF are highly correlated and are proposed to reflect the parasympathetic influence, whereas SDNN represents both sympathetic and parasympathetic influences on the heart (Shaffer and Ginsberg, 2017), thus we chose SDNN and RMSSD to examine the influence of both aspects of the autonomic nervous system (Koch et al., 2019; Niu et al., 2020;

Table 4
Statistical analysis of EDA measures.

		SCL β (95% CI), p-value	SCR β (95% CI), p- value
Period of Rest	Control	Ref	Ref
	Intervention	−0.081 (-0.242, 0.081), p = 0.322	−0.096 (-0.325,0.133), p = 0.408
	Control Mean (SD)	6.80 (4.78)	0.41 (0.33)
	Intervention Mean (SD)	5.77 (4.94)	0.43 (0.53)
Period of Cognitive Test	Control	Ref	Ref
	Intervention	−0.028 (-0.172, 0.117), p = 0.703	−0.191 (-0.387,0.005), p = 0.056
	Control Mean (SD)	7.25(5.17)	0.46 (0.29)
	Intervention Mean (SD)	7.11(5.80)	0.45 (0.62)

The coefficient-β adjusted Sex as covariable.
SCL: the Tonic component EDA refers to Skin Conductance Level in micro siemens (µS).
SCR: the Phasic component EDA refers to Skin Conductance Response in micro siemens (µS).

Table 3
Statistical analysis of the HRV parameters in the control and interventions conditions in the periods of rest and cognitive testing.

		SDNN β (95% CI), p-value	RMSSD β (95% CI), p-value	pNN50 β (95% CI), p-value	HF β (95% CI), p-value
Period of Rest	Control	Ref	Ref	Ref	Ref
	Intervention	0.041 (-0.053,0.136), p = 0.389	0.067 (-0.066,0.201), p = 0.318	−0.078 (-0.271,0.114), p = 0.421	0.067 (-0.085,0.218), p = 0.383
	Control Mean (SD)	83.31 (35.11)	92.57(53.96)	31.29 (19.11)	0.45 (0.20)
	Intervention Mean (SD)	91.19 (37.39)	105.98(58.61)	28.05(18.14)	0.50(0.16)
Period of Cognitive Testing	Control	Ref	Ref	Ref	Ref
	Intervention	0.145 (0.014,0.277), p = 0.031*	0.228 (0.060, 0.396), p = 0.008*	−0.041 (-0.209,0.128), p = 0.633	0.295 (0.092,0.499), p = 0.005*
	Standardized beta (std β)	0.4838	0.5856		0.6108
	Cohen's d	0.581	0.653		0.433
	Control Mean (SD)	85.82 (44.06)	91.15 (67.72)	28.85(17.88)	0.32 (0.24)
	Intervention Mean (SD)	128.65 (94.44)	162.76(139.43)	27.78 (18.11)	0.41 (0.17)

The coefficient-β adjusted Sex as covariable.
SDNN: standard deviation of normal-to-normal intervals in millisecond (ms); RMSSD: root mean square of the successive differences in millisecond (ms); pNN50: Percentage of successive R-R intervals that differ by more than 50 ms in percentage (%); HF:normalized high-frequency spectral power in normalized units (nu).

Shaffer et al., 2014).

The mediation analyses were conducted for all 16 cognitive skills. We present the two tasks with significant mediation relationships in Fig. 3 for SDNN and RMSSD; all models are included in Tables 5 and 6. The analysis suggests that mediating effects of HRV via SDNN and RMSSD occurred in the two executive related skills (i.e. divided attention and inhibition). A bootstrap CI for the specific average causal mediation effect (indirect effect), did not include zero providing evidence for statistically significant mediation. The analysis overall showed that decreased HRV indices mediated the effect of elevated PM2.5 exposure on longer average response time in correct trials for the divided attention and inhibition tasks. In addition, there was no relevant mediating effect via differences in thermal satisfaction rating (TR) pathway.

4. Discussion

Our real-world intervention study sheds light on an interaction between short-term PM2.5 indoor exposure and autonomic nervous system function, and its effects on cognitive performance in working age adults. Analyses showed that during cognitive testing, HRV was significantly higher in the intervention condition of lower PM2.5 levels than in the control condition with higher PM2.5 levels, whereas there were no significant effects on HRV during baseline resting period before the cognitive testing. Mediation analysis showed reduced HRV mediated effects of elevated indoor PM2.5 exposure on cognitive performance decline in two executive-related tasks, which warrants further research. The effects of PM2.5 were not observed in either tonic or phasic EDA measures. Overall, our findings suggest that elevated indoor PM2.5 could have acute effects and be detrimental to cardiovagal and cognitive health in working age adults.

Previous studies with different approaches to study design, population type and exposure (i.e., concentration levels and duration) yielded mixed results of HRV in relation to PM2.5. Our study found an effect of PM2.5 on relevant HRV indicators (SDNN, RMSSD and HF) during a period of cognitive demand when controlling for task complexity and learning effects (via parallel test versions). This negative impact on HRV is consistent with previous cross-sectional and longitudinal studies suggesting that elevated long-term PM2.5 exposure decrease HRV (Huang et al., 2012; Lim et al., 2017; Mordukhovich et al., 2015; Schneider et al., 2010; Timonen et al., 2006; Xu et al., 2013) with some findings also confirmed by short term exposure studies (Chuang et al., 2013; Devlin et al., 2003; Gold et al., 2000; Lipsett et al., 2006; Paoin et al., 2020). In contrast, one previous study using ionization air purifier reported significantly lower HRV during intervention in 44 school children (Dong et al., 2019), which may reflect an adverse cardiovascular effect of the ozone produced by electrostatic and ionization air purifiers, as suggested by a previous review (Xia et al., 2021). Another study found no significant changes in HRV outcomes with the use of air purifiers in 38 college students in a student accommodation but observed significant changes in blood pressure and blood oxygen saturation (Xia et al., 2023). However, none of these studies included cognitive measures or explored the effects under cognitively demanding conditions. In our study, HRV indices were higher during cognitive testing in the lower PM2.5 condition, suggesting that participants had a higher parasympathetic relative to sympathetic influence on cardiac response, which may indicate better stress resilience. Although this aligns with the finding that participants in the intervention condition reported reduced mental effort, we performed a Pearson's correlation analysis that showed no significant correlation between self-reported mental effort and HRV, which is consistent with findings from previous study (Zhang et al., 2021a,b). Although significant effects of PM2.5 on HRV were observed for SDNN, RMSSD and HF, the largest effect sizes was found for RMSSD, which is considered to represent vagally-mediated HRV (Camm et al., 1996; Shaffer and Ginsberg, 2017).

Vagally-mediated HRV indices in particular are consistently associated with better cognitive and behavioral outcomes (Holzman and Bridgett, 2017; L. Liu et al., 2022), and increasing evidence supports a bidirectional relationship with the integrity of prefrontal self-regulatory regions (Mather and Thayer, 2018; Thayer et al., 2012). Consistent with findings on vagally-mediated HRV and prefrontal executive self-regulatory capacity, our study found that the mediation effect of HRV metrics on cognitive outcomes occurred within two executive related attention tasks: divided attention and inhibition. Our findings also align with a 3-days PM2.5 exposure observational study in China (Ke et al., 2022), which reported a statistically significant difference in Stroop test executive performance, mediated through electroencephalogram (EEG) oscillations. It should be acknowledged that in our study the assessment comprised 16 distinct tasks, thus analysing them individually could potentially elevate the occurrence of false positives. Should the Bonferroni correction be applied, this would set the significance threshold at α = 0.0031 (16/0.05), which would then mean the mediation effects are no longer statistically significant. However, there are known limitations to Bonferroni adjustment, i.e. overly

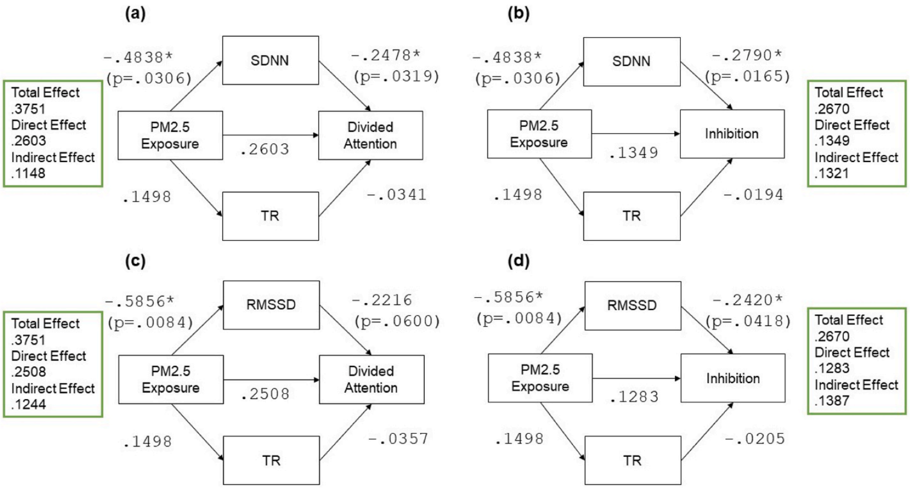


Fig. 3. Mediation effect analysis on the relationship of PM2.5, HRV (SDNN, RMSSD), and executive attention skills. a) SDNN and divided attention reaction times, b) SDNN and inhibition reaction times, c) RMSSD and divided attention reaction times, and d) RMSSD and inhibition reaction times. The path coefficients are standardized regression coefficients, adjusted by sex as covariable. Asterisk indicates statistical significance. Inhibition skill is assessed by the Stroop test. Divided Attention skill requires test-taker to accurately follow a ball moving and turning in all directions on the screen while, at the same time, performing a Stroop test.

Table 5
Mediation effect of variables on the relationship between PM2.5 exposure, SDNN-HRV, and task performance.

Domain	Skill	Variable	Total effect (95% bootstrap CI) [standardized effect]	Direct effect (95% bootstrap CI) [standardized effect]	Mediator	Indirect effect (95% bootstrap CI) [standardized effect]
Attention	Divided Attention	Correct Reaction Time	55.77 (-9.84, 121.39) [0.38]	38.70 (-27.88, 105.29) [0.26]	M1: SDNN	17.82[a] (0.85, 41.92) [0.12]
					M2:TR	−0.76 (-8.86, 9.25) [-0.01]
	Inhibition	Correct Reaction Time	40.50 (-27.2, 108.23) [0.27]	20.46 (-47.74, 88.68) [0.14]	M1: SDNN	20.47[a] (0.69, 48.85) [0.14]
					M2:TR	−0.44 (-12.68,7.80) [-0.003]
	Sustained Attention	Correct Reaction Time	1.76 (-64.30, 67.83) [0.01]	8.52 (-59.63, 76.69) [0.06]	M1: SDNN	−3.16 (-26.82, 21.10) [-0.02]
					M2:TR	−3.59 (-19.46, 9.27) [-0.03]
	Updating	Correct Reaction Time	28.54 (-22.89, 79.97) [0.25]	27.65 (-25.56, 80.87) [0.24]	M1: SDNN	3.42 (-8.49, 18.90) [0.03]
					M2:TR	−2.53 (-15.95, 6.35) [-0.02]
Memory	Visual Short-Term Memory	Correct Reaction Time	73.69 (17.39, 129.98) [0.55]	69.42 (10.84, 127.99) [0.52]	M1: SDNN	5.61 (-14.48, 26.56) [0.04]
					M2:TR	−1.34 (-14.96, 3.70) [-0.01]
		Accurate Answers	−0.51 (-0.93, −0.09) [-0.52]	−0.46 (-0.88, −0.04) [-0.47]	M1: SDNN	−0.077 (-0.21, 0 0.03) [-0.08]
					M2:TR	0.03 (-0.05, 0.15) [0.03]
	Phonological Short-term Memory	Correct Reaction Time	110.08 (2.91, 217.26) [0.45]	104.84 (-7.05, 216.74) [0.43]	M1: SDNN	6.94 (-17.60, 39.51) [0.03]
					M2:TR	−1.70 (-20.29, 17.51) [-0.01]
	Contextual Working Memory	Correct Reaction Time	97.52 (-11.69, 206.74) [0.39]	122.86 (10.94, 234.77) [0.50]	M1: SDNN	−23.89 (-68.31, 4.50) [-0.10]
					M2:TR	−1.44 (-17.09, 14.58) [-0.01]
		Accurate Answers	−0.90 (-1.51, −0.28) [-0.63]	−0.97 (-1.6167, −0.03) [-0.68]	M1: SDNN	0.10 (-0.03, 0.32) [0.07]
					M2:TR	−0.02 (-0.15, 0.08) [-0.02]
	Short-Term Memory	Correct Reaction Time	46.16 (-19.08, 111.41) [0.32]	40.48 (-27.59, 108.56) [0.28]	M1: SDNN	5.90 (-12.14, 21.23) [0.04]
					M2:TR	−0.22 (−9.15, 11.60) [-0.002]
	Naming	Correct Reaction Time	114.46 (-28.63, 257.56) [0.35]	104.56 (-44.91, 254.04) [0.32]	M1: SDNN	10.30 (-35.91, 48.05) [0.03]
					M2:TR	−0.3971 (-18.88, 25.15) [-0.001]
Perception	Estimation	Correct Reaction Time	334.86 (-185.56, 855.28) [0.28]	292.09 (-250.54, 834.74) [0.25]	M1: SDNN	48.66 (-68.27, 202.90) [0.04]
					M2:TR	−5.90 (-96.42, 52.21) [-0.01]

(*continued on next page*)

Table 5 (*continued*)

Domain	Skill	Variable	Total effect (95% bootstrap CI) [standardized effect]	Direct effect (95% bootstrap CI) [standardized effect]	Mediator	Indirect effect (95% bootstrap CI) [standardized effect]
	Auditory Perception	Accuracy	−2.27 (-5.45, 0.91) [-0.31]	−1.95 (-5.25, 1.34) [-0.27]	M1: SDNN	−0.173 (-1.27, 1.24) [-0.02]
					M2:TR	−0.147 (-0.89, 0.29) [-0.02]
	Recognition	Correct Reaction Time	173.05 (8.57, 337.54) [0.45]	143.22 (-26.60, 313.05) [0.37]	M1: SDNN	30.00 (-5.16, 83.16) [0.08]
					M2:TR	−0.16 (-22.04, 28.39) [-0.0004]
	Visual Scanning	Reaction Speed	0.15 (-0.15, 0.47) [0.22]	0.16 (-0.16, 0.49) [0.24]	M1: SDNN	0.01 (-0.11, 0.08) [0.01]
					M2:TR	−0.01 (-0.10, 0.04) [-0.03]
Coordination	Hand-eye Coordination	Accuracy	−0.65 (-2.06, 0.74) [-0.21]	−0.57 (-2.04, 0.88) [-0.18]	M1: SDNN	−0.10 (-0.48, 0.43) [-0.04]
					M2:TR	0.02 (-0.1926, 0 0.24) [0.008]
	Response Time	Reaction Time	−0.51 (-8.34, 7.31) [-0.03]	−1.75 (-9.87, 6.36) [-0.10]	M1: SDNN	1.13 (-0.68, 3.62) [0.06]
					M2:TR	0.10 (-0.80, 1.94) [0.01]
Reasoning	Planning	Accurate Answers	−0.17 (-0.61, 0.26) [-0.18]	−0.14 (-0.59, 0.30) [-0.15]	M1: SDNN	−0.01 (-0.12, 0.14) [-0.01]
					M2:TR	−0.01 (-0.11, 0.05) [-0.02]

SDNN: standard deviation of all normal-to-normal intervals (ms).

TR: thermal satisfaction rate.

[a] Mediation effect significance at 0.05 level. A bootstrap CI for the specific average causal mediation effect (indirect effect), did not include zero providing evidence for statistically significant mediation.

conservative, which can lead to an unnecessary loss of statistical power, potentially resulting in ignoring significant findings (Blakesley et al., 2009; Hollestein et al., 2021; VanderWeele and Mathur, 2019). It would be important for future studies to further investigate the impact of PM2.5 exposure on negative cognitive, emotional and behavioral outcomes through changes in cardiovagal activity, and explore the potential of autonomic nervous system-based interventions as a protective factor. We found no differences between control and intervention in HRV metrics during rest periods. It should be acknowledged that the rest period measured in this study was 5 min, whereas the cognitive testing lasted 45 min. Short-term physiological measurements are widely used due to their practical advantages and reproducibility (Min et al., 2008). Nonetheless, the length of time of physiological response collection still needs more consideration. For example, a previous study suggested that 5-min HRV measurements are not sufficient to predict adverse effects on cardiovascular health (Min et al., 2008; Paoin et al., 2020). Future studies may consider using the same duration for the rest and cognitive testing periods, i.e., extending the rest period to equal the duration of the cognitive testing.

HRV may also be influenced by individual-level factors including overall wellbeing, sleep quality, and activity (Geisler et al., 2010; Rennie et al., 2003; van den Berg et al., 2005), as well as measurement factors such as body posture and duration of measurement (Laborde et al., 2017). The questionnaire results that were collected during this study and published previously did not find significant differences in self-reported wellbeing (Zhou et al., 2022), as well as sleep hours during the previous night, nor meal status across the control and intervention condition. In our experiment, the subjects' activity level was low as they were sedentary, performing typical office work while seated during the exposures. The study additionally incorporated age as another covariate in the models. The findings remained robust for HRV outcomes (see Supplementary material).

5. Strengths, limitations, and future research

The presented study has several strengths and novelties, including repeated measures of physiological responses and cognition within the same individual controlling for between-subject variability through a real-world intervention approach. The study also expands beyond cognitive endpoints to delve into potential underlying mechanisms. What sets this work apart is its examination of the relationship between indoor air quality-PM2.5 and cognition within office environments, in particularly regarding insights into how these effects may be mediated through cardiovagal responses. Not all cognitive skills showed a mediation effect, highlighting the need to understand the differential effects of PM2.5 on varying cognitive abilities associated with HRV pathways. This study also points towards potential future pathways for implementing targeted interventions aimed at improving indoor air quality in office environments, developing specialized strategies for mitigating the adverse effects of air pollution on co-benefits of health, cognitive performance, productivity etc.

Due to limited availability of sensors, only a subset of participants (N

Table 6
Mediation effect of variables on the relationship between PM2.5 exposure, RMSSD-HRV, and task performance.

Domain	Skill	Variable	Total effect (95% bootstrap CI) [standardized effect]	Direct effect (95% bootstrap CI) [standardized effect]	Mediator	Indirect effect (95% bootstrap CI) [standardized effect]
Attention	Divided Attention	Correct Reaction Time	55.77 (-9.84, 121.39) [0.37]	37.28 (-30.75, 105.31) [0.25]	M1: RMSSD	19.29 [a] (0.77, 44.64) [0.13]
					M2:TR	−0.80 (−11.09, 7.69) [-0.01]
	Inhibition	Correct Reaction Time	40.50 (-27.22, 108.23) [0.27]	19.46 (-50.48, 89.41) [0.13]	M1: RMSSD	21.50 [a] (1.23, 53.65) [0.14]
					M2:TR	−0.47 (-11.84, 8.87) [-0.003]
	Sustained Attention	Correct Reaction Time	1.76 (-64.30, 67.83) [0.01]	9.39 (-59.74, 78.54) [0.06]	M1: RMSSD	−4.06 (-31.92, 23.02) [-0.03]
					M2:TR	−3.58 (-18.20, 9.83) [-0.02]
	Updating	Correct Reaction Time	28.54 (-22.89, 79.97) [0.25]	31.66 (-22.41, 85.74) [0.28]	M1: RMSSD	−0.69 (-19.33, 15.17) [-0.01]
					M2:TR	−2.44 (-15.63, 5.99) [-0.02]
Memory	Visual Short-Term Memory	Correct Reaction Time	73.69 (17.39, 129.98) [0.55]	69.22 (9.73, 128.71) [0.52]	M1: RMSSD	5.82 (-16.49, 25.63) [0.04]
					M2:TR	−1.35 (-12.75, 3.35) [-0.01]
		Accurate Answers	−0.51 (-0.93, −0.09) [-0.52]	−0.46 (-0.89, −0.02) [-0.47]	M1: RMSSD	−0.08 (-0.22, 0.067) [-0.08]
					M2:TR	0.03 (-0.05, 0.16) [0.03]
	Phonological Short-term Memory	Correct Reaction Time	110.08 (2.91, 217.26) [0.45]	105.44 (-8.16, 219.04) [0.43]	M1: RMSSD	6.34 (-25.16, 45.58) [0.03]
					M2:TR	−1.69 (-21.94, 18.31) [-0.01]
	Contextual Working Memory	Correct Reaction Time	97.52 (-11.69, 206.74) [0.39]	128.36 (14.86, 241.87) [0.52]	M1: RMSSD	−29.54 (-79.73, 3.13) [-0.12]
					M2:TR	−1.31 (−20.89, 14.44) [-0.01]
		Accurate Answers	−0.90 (-1.51, −0.28) [-0.62]	−0.99 (-1.64, −0.35) [0.69]	M1: RMSSD	0.12 (-0.05, 0.41) [0.08]
					M2:TR	−0.02 (-0.14, 0.07) [-0.02]
	Short-Term Memory	Correct Reaction Time	46.16 (-19.08, 111.41) [0.32]	41.04 (-28.12, 110.21) [0.28]	M1: RMSSD	5.33 (-16.02, 24.14) [0.04]
					M2:TR	−0.21 (-10.91, 11.07) [-0.001]
	Naming	Correct Reaction Time	114.46 (-28.63, 257.56) [0.36]	106.45 (-45.36, 258.27) [0.33]	M1: RMSSD	8.36 (-48.92, 49.18) [0.03]
					M2:TR	−0.35 (-20.89, 25.22) [-0.001]
Perception	Estimation	Correct Reaction Time	334.86 (-185.56, 855.28) [0.29]	275.62 (-274.46, 825.70) [0.24]	M1: RMSSD	65.55 (-69.94, 276.20) [0.06]
					M2:TR	−6.30 (-103.39, 59.34)

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Table 6 (*continued*)

Domain	Skill	Variable	Total effect (95% bootstrap CI) [standardized effect]	Direct effect (95% bootstrap CI) [standardized effect]	Mediator	Indirect effect (95% bootstrap CI) [standardized effect]
						[-0.005]
	Auditory Perception	Accuracy	−2.27 (-5.45, 0.91) [-0.32]	−1.89 (-5.23, 1.45) [-0.26]	M1: RMSSD	−0.24 (-1.39, 1.54) [-0.03]
					M2:TR	−0.15 (-0.95, 0.30) [-0.02]
	Recognition	Correct Reaction Time	173.05 (8.57, 337.54) [0.45]	136.37 (-35.89, 308.64) [0.36]	M1: RMSSD	37.01 (-10.78, 101.78) [0.10]
					M2:TR	−0.33 (-24.34, 27.42) [-0.009]
	Visual Scanning	Reaction Speed	0.15 (-0.15, 0.47) [0.22]	0.15 (−0.18, 0.48) [0.21]	M1: RMSSD	0.03 (−0.11, 0.12) [0.04]
					M2:TR	−0.02 (−0.09, 0.03) [-0.03]
Coordination	Hand-eye Coordination	Accuracy	−0.65 (-2.06, 0.74) [-0.21]	−0.53 (-2.01, 0.95) [-0.17]	M1: RMSSD	−0.15 (−0.63, 0.32) [-0.05]
					M2:TR	0.03 (−0.19, 0.26) [0.01]
	Response Time	Reaction Time	−0.51 (-8.34, 7.31) [-0.02]	−1.98 (-10.22, 6.24) [-0.11]	M1: RMSSD	1.37 (−0.73, 4.43) [0.08]
					M2:TR	0.10 (−0.74, 2.21) [0.01]
Reasoning	Planning	Accurate Answers	−0.17 (-0.61, 0.26) [-0.18]	−0.16 (−0.62, 0.29) [-0.17]	M1: RMSSD	0.01 (-0.14, 0.18) [0.01]
					M2:TR	−0.02 (−0.11, 0.04) [-0.02]

RMSSD: the root mean square of successive differences between normal heartbeats.
TR: thermal satisfaction rate.

[a] Mediation effect significance at 0.05 level. A bootstrap CI for the specific average causal mediation effect (indirect effect), did not include zero providing evidence for statistically significant mediation.

= 40 out of the total N = 60 involved in cognitive performance testing) had their physiological responses measured. Further research might consider a large cohort to examine our findings where other intervention efforts on PM2.5 reduction are utilized. Other general limitations of this study have been previously discussed (Zhou et al., 2022, 2023), including limited variability in the study population, for example regarding age and educational level. The equipment used in this fieldwork did not allow for the use of a sham filter, as the HEPA filter was integrated with Radio Frequency Identification (RFID) Chips in the equipment and removing the filter would cause the device to report an error. However, prior to the experiment participants were informed that even if the air purifier was operating, the research team might remove the filters, which could render it ineffective and thus minimizing their awareness of the actual conditions. Furthermore, the self-reported sound environment satisfaction and thermal sensation, assessed by questionnaire in this study, showed no significant difference between the control and intervention (Zhou et al., 2022), suggesting that findings were not influenced by sound or thermal sensation effects during the interventions. In addition, while the operation of the air purifier may indirectly impact thermal comfort, the mediation analysis conducted in this study revealed no mediation effects through the thermal satisfaction pathway in this fieldwork. Overall, we consider that the potential for a functional unblinding effect was minimized. The study primarily considered 5 h average exposure between the two conditions, as this approach captures the overall exposure over a substantial portion of the working day. We acknowledge that this method may not fully capture potential shorter-term spikes or immediate effects of PM2.5 exposure variation, although our fieldwork revealed that average exposures in shorter-time frames (30 min, 1hr, 3hr, and 5hr prior to testing protocol) were similar (see supplementary material). Future studies could benefit from more temporal analysis of PM2.5 levels variations and their immediate effects on health and cognition measures.

6. Conclusion

This randomized controlled experimental crossover study in a real-world setting is the first to show that short-term exposure to indoor PM2.5 within offices lowers HRV in the context of cognitive testing in working-age adults. The results suggest that reducing indoor PM2.5 levels led to significant and potentially beneficial changes in health indices such as HRV, which may mediate improvements on cognitive performance skills related to executive and self-regulatory capacity. The potential benefits of reducing short-term indoor PM2.5 exposure on cardiac and cognitive health through a relative increase in vagal activity in the central autonomic nervous system during cognitive exertion warrant further research.

CRediT authorship contribution statement

Jiaxu Zhou: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gesche Huebner:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Kathy Y. Liu:** Writing – review & editing, Validation, Resources. **Marcella Ucci:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.120245.

Data availability

Data will be made available on request.

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