Environmental Science & Technology

pubs.acs.org/est

Article

Reducing Indoor Particulate Air Pollution Improves Student Test Scores: A Randomized Double-Blind Crossover Study

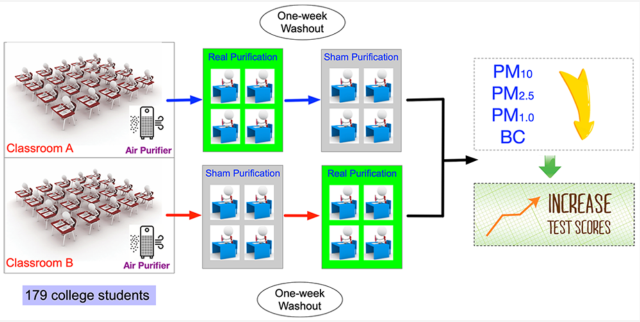
Jia Xu,[#] Hong Zhao,[#] Yujuan Zhang, Wen Yang, Xinhua Wang, Chunmei Geng, Yan Li, Yun Guo, Bin Han,* Zhipeng Bai,* Sverre Vedal, and Julian D. Marshall

Cite This: *Environ. Sci. Technol.* 2024, 58, 8207−8214

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Short-term exposure to air pollution is associated with a decline in cognitive function. Standardized test scores have been employed to evaluate the effects of air pollution exposure on cognitive performance. Few studies aimed to prove whether air pollution is responsible for reduced test scores; none have implemented a "gold-standard" method for assessing the association such as a randomized, double-blind intervention. This study used a "gold-standard" method—randomized, double-blind crossover—to assess whether reducing short-term indoor particle concentrations results in improved test scores in college students in Tianjin, China. Participants (n = 162) were randomly assigned to one of two similar classrooms and completed a standardized English test on two consecutive weekends. Air purifiers with active or sham (i.e., filter removed) particle filtration were placed in each classroom. The filtration mode was switched between the two test days. Linear mixed-effect models were used to evaluate the effect of the intervention mode on the test scores. The results show that air purification (i.e., reducing PM) was significantly associated with increases in the z score for combined (0.11 [95%CI: 0.02, 0.21]) and reading (0.11 [95%CI: 0.00, 0.22]) components. In conclusion, a short-term reduction in indoor particle concentration led to improved test scores in students, suggesting an improvement in cognitive function.



KEYWORDS: *Indoor air pollution, air purification, test score, intervention, randomized double-blinded crossover study*

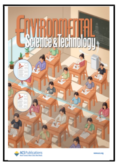
■ INTRODUCTIONS

Ambient air pollution, especially particulate matter (PM), is associated with adverse health effects, including hospitalization, mortality, and morbidity from cardiovascular and respiratory diseases.[1−4] Some recent studies have documented adverse effects of air pollution exposure on cognitive performance, such as on attention, visuo-construction, memory, math ability, reading comprehension, and verbal and nonverbal intelligence,[5−13] as well as the prevalence of some brain-related diseases, e.g., dementia and Alzheimer's disease.[14−16]

Among various measures of cognitive performance, standardized tests are important tools for evaluating students' academic performance. Because of their high demands on cognitive function, standardized tests are hypothesized to be susceptible to impacts of air pollution exposure.[17] Several recent studies have provided evidence that exposure to air pollution during testing days can affect test scores. Heissel et al.[18] found that children who experienced higher traffic-related air pollutant exposures during commuting had lower test scores than those with similar characteristics but lower traffic-related air pollutant exposures. In a longitudinal study of students taking multiple exams over time, Ebenstein and coworkers[6] found that contemporaneous $PM_{2.5}$ exposure was negatively associated with test performance. Others have also reported negative associations between PM and standardized test scores.[17,19−22] Most of these studies used air pollution data from administrative monitoring sites that were usually located several miles from the students taking the tests, raising possible concerns that the concentrations might not reflect the true exposures. Roth,[23] however, used indoor air pollutant measurements to estimate pollutant impacts on test scores and found that a 1 $\mu g/m^3$ increase in indoor PM_{10} reduced students' test scores by 0.3 standard deviations. Stafford[10] found that standardized test scores were significantly improved after indoor renovation projects.

These existing studies provide evidence that exposure to air pollution is linked to reduced test scores. However, all were observational studies of associations that suggest but do not prove that air pollution exposure is directly responsible for the

Received: December 11, 2023
Revised: April 10, 2024
Accepted: April 11, 2024
Published: April 22, 2024



ACS Publications

https://doi.org/10.1021/acs.est.3c10372

reduced test scores. Furthermore, because air pollutants are part of an air pollution mixture, it is difficult to identify which component(s) of the mixture might have been responsible for the observed effects.

In this study, we hypothesize that exposure to indoor PM adversely affects cognition, as assessed by standardized test scores. To implement a "gold-standard" approach for assessing the association, we designed a randomized, double-blind, crossover intervention trial using indoor air purifiers to evaluate the short-term effects of indoor PM exposure on test scores. Specifically, we investigated standardized English language tests in college students in Tianjin, China. To our knowledge, this is the first such "gold standard" study of air pollution and test scores.

■ METHODS

Study Participants and Design. We recruited 180 healthy college students from the main campus of Nankai University in Tianjin, China. The number of students was based on a sample size calculation of noninferiority tests (PASS 11 software [NCSS, LLC. Kaysville, Utah]).[24] The significance level (alpha) was set at 0.01 with 95% power, with noninferior margins at 0.5. Most participants were in their first year of university. We selected two nearly identical classrooms located on the first and second floors of a university building, each approximately 200 m^2 in area.

The study was designed as a randomized, double-blind crossover intervention study. Participants were equally divided and then randomly assigned to one of the two classrooms. Students took the English language tests (see below) twice: once on November 30th and once on December 7th, 2019 (consecutive Saturdays). Both classrooms had two air purifiers (Honeywell KJ900F, China, Text S1) in the center of the classroom that were turned on starting 3 h before the test and continued running throughout the test. On one test day, the air purifiers included filters ("active"), and on the other test day, the filters were removed ("sham"). The air purifiers were otherwise operated identically across days and rooms. The filter was first "real" (day one) and then "sham" (day two) in one classroom, and in reverse order ("sham" then "real") in the other classroom.

All study participants and investigating staff were blinded to the filter status of the air purifiers except for the exposure engineer, who stayed away from the classrooms for the entirety of the testing periods. The test started at 9:00 am each day and finished at 12:00 pm. The participants were required to sit in the same seat during the two tests. The Medical Ethics Committee of the Second Hospital of Tianjin Medical University approved the study protocol. All participants provided written informed consent before enrollment. The study was registered with the Chinese Clinical Trial Registry (registration number: ChiCTR1900027773).

To evaluate the students' perception of the exposure, all participants were required to answer a question after each test as to whether or not they perceived the air in the classroom during the test to be purified. Responses to this question were used to evaluate the students' perception of exposure, which could potentially affect test performance.[25]

Exposure Assessment. Classroom windows were kept open throughout the night before the test days. At 6:00 a.m., the windows were closed, and the air purifiers began operating; the purifiers were left on until 12:00 pm, when the exam ended. At 8:50 am, the windows were again opened and kept open to prevent levels of indoor CO_2 from increasing during tests. Study participants were first allowed to enter the classrooms from 8:50 am to 9:00 am.

Real-time indoor PM monitors (Grimm Model 11-A 1.109, GRIMM Aerosol Technik Pouch GmbH, Germany) were placed at least 1 m from the air purifiers. Gaseous air pollutants and particulate black carbon (BC) were also monitored (Table S1). Before the study, all monitoring devices were calibrated in our laboratory in accordance with the respective standard operating procedures. They were consistently placed in the same classroom each sampling time.

English Language Test. The English language test administered in this study was the mock test paper of the College English Test band 4 ("CET-4"), which is the national English language test in the People's Republic of China, typically used for undergraduate and graduate students.[26] CET-4 includes four sections (see Text S2), two of which are "subjective" (graded manually: writing, translation) and two of which are "objective" (multiple-choice listening and reading, scored by machine). Here, we investigated only the "objective" sections (listening and reading) and the overall combined (four-section) test score. The test order and duration of the two sections are described in the Supporting Information (Text S3).

Statistical Analysis. The three test scores (listening, reading, and four-section combined) were analyzed both as raw (original) scores and also as z scores, with the three test scores for each student being converted into three z scores (calculated in the standard manner: individual score minus mean score of all participants, divided by the standard deviation of all participants) in order to allow comparisons across the three tests (listening, reading, and four-section combined). To test crude (i.e., unadjusted) effects due to the testing period and perception, original scores and z scores between the two intervention groups (active and sham air purification) were compared using the two-sample Wilcoxon rank sum test. Linear mixed-effect models were used to estimate the effect of the intervention on test scores; this approach accounts for repeated tests within individuals.[25] A hierarchical approach to model building was used, beginning with univariable models and progressing to more complex multivariable models. The simplest models (base models) included a random effect of the study participant and an indicator variable as a fixed effect for the intervention (sham intervention is the reference group). The next set of models added fixed effects for the test period (first or second) and order of intervention (active intervention first or second) to the base models. The most complex full models added terms for gender, age, university department, perception of exposure (see below), indoor gaseous pollutant concentrations (CO, CO_2, SO_2, and NO_2), and temperature. Study participants were slightly more likely to incorrectly identify the active vs sham intervention (44.6% correct, 55.4% incorrect; see Table S2). To address potential effects of perception on our outcome measures, we adjusted for it in the full model. In a further analysis, the intervention indicator variable was replaced by either the indoor $PM_{2.5}$ concentration or the indoor BC concentration in the mixed-effects models.

All statistical tests were two-sided, with an alpha of 0.05 considered to be statistically significant. Analyses were conducted using R statistical software (version 4.0.3, R Development Core Team).

https://doi.org/10.1021/acs.est.3c10372
Environ. Sci. Technol. 2024, 58, 8207−8214

■ RESULTS

Basic Information on Participants. Table 1 presents descriptive statistics. Initially, 180 college students were recruited from eight colleges of Nankai University. Of these, 179 took at least one test (88 males, 91 females): 162 took both tests, and 17 took the test only once. All participants declared that they had no clinically diagnosed cognition-related diseases. No participants said they had never taken CET-4 before the study.

Table 1. Characteristics of the Participants ($N = 179$)

variable	median (5th−95th percentiles) or number (percentage)	
sex	male ($N = 88$)	female ($N = 91$)
age (years)	18.6 (17−21)	18.5 (16−20)
university discipline		
STEM[a]	80 (87.9%)	63 (69.2%)
chemistry	55 (69.6%)	35 (38.5%)
mathematics	14 (17.7%)	10 (11.0%)
statistics	5 (6.3%)	17 (18.7%)
physics	6 (7.6%)	1 (1.1%)
non-STEM	8 (8.8%)	28 (30.8%)
economics	2 (2.5%)	5 (5.5%)
business	1 (1.3%)	3 (3.3%)
language	5 (6.3%)	20 (22.0%)

[a] STEM is Science, Technology, Engineering, and Mathematics.

Indoor Air Pollutant Concentrations During the Tests. Figure 1 and Table 2 show the indoor pollutant concentrations with active and sham interventions. The concentrations of PM for all three size ranges (PM_{10}, $PM_{2.5}$ and PM_1) gradually declined during the test periods. Table 2 shows the indoor air pollutant concentrations and temperatures during the test periods. The indoor $PM_{2.5}$ concentrations in the classrooms with a sham air purifier were significantly higher on both test days (41.5 and 40.2 $\mu g/m^3$, respectively) than in the classrooms with an active air purifier (12.5 and 13.4 $\mu g/m^3$, respectively). The sudden changes in particulate concentrations between 10:00 and 10:20 across days and rooms were caused by an unexpected autocalibration event and brief powering off of the PM monitors, respectively. BC concentrations paralleled those of PM (1.20 (day 1) and 2.76 (day 2) $\mu g/m^3$ with active filtration; 3.01 (day 1) and 5.39 (day 2) $\mu g/m^3$ with sham filtration). There was no effect of active filtration on concentrations of the gaseous pollutants (SO_2, NO_2, CO_2), as is expected, because the filter removes only particles, not gases.

The Distributions of Test Scores. Supporting Figures S1 and S2 show the distributions of test scores as z scores (Figure S1) and raw scores (Figure S2) for the two interventions, test periods, and perception of air purification. In these crude analyses, there were no statistically significant differences in the z scores of listening, reading, and combined tests between interventions (Figure S1a,d,g), test period (Figure S1b,e,h), or perception of air purification (Figure S1c,f,i ; Wilcoxon rank sum tests, $p > 0.05$).

The Effects of PM Purification on the Test Scores. Linear mixed effects model results are shown in Table 3 for the base model (random effect for subject and fixed effect for intervention); the base model with added fixed effects for test period and intervention order (full model); and the full model with additional fixed effects for sex, age, university department, intervention perception, and indoor gaseous pollutant concentrations. For the base model, compared with participants in the sham purification group, those who experienced active air purification (reduction in indoor PM) showed a significant increase in z score for the combined score ($p < 0.05$), and a marginal increase in z score for the reading test ($0.05 < p < 0.10$). There was a suggestion that the listening test score was also higher with active air purification relative to sham purification ($p > 0.10$). The results of the models with added fixed effects for test period and intervention order, as well as those of the full models, were not substantially different from the base models.

With the intervention variable replaced by pollutant concentrations (Table S4), lower indoor PM concentrations were significantly associated with elevated CET-4 test z scores. Lower particulate BC concentrations were not significantly associated with test z scores.

■ DISCUSSION

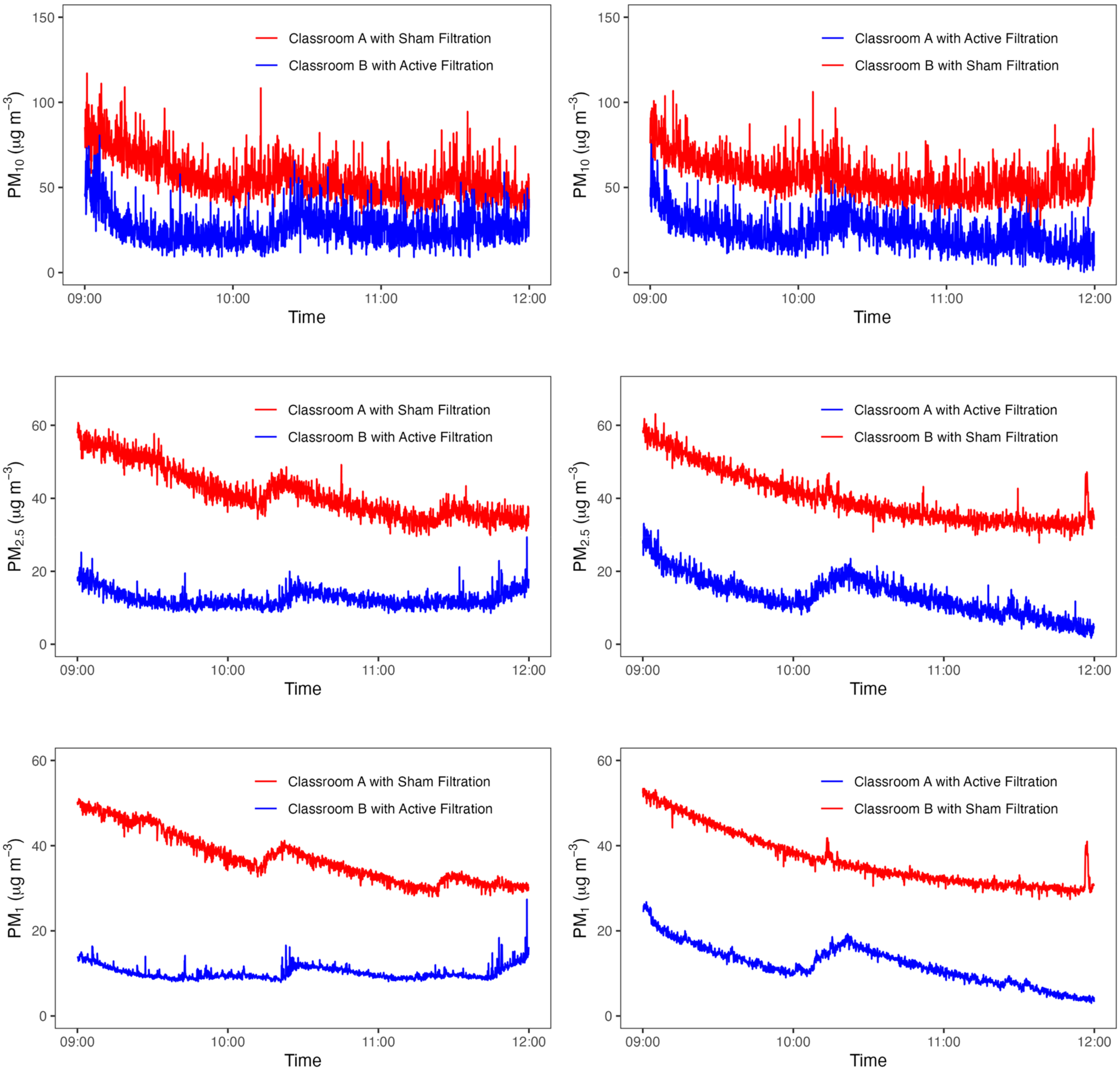
In this study, it was hypothesized that exposure to high levels of PM decreases cognitive function in healthy young adults as reflected by reduced test scores and therefore that reductions in concentrations would result in an improvement in test scores. To address the hypothesis, we employed a randomized, double-blind, crossover design with sham and effective air purifier interventions that selectively filtered out indoor PM. We found that the air filtration intervention resulted in a statistically significant increase in combined test scores, a marginal increase in reading scores, and a suggestion of an increase in listening scores.

Air purifiers have been used as an intervention method for reducing indoor particulate concentrations, and several studies have reported them to have cardiopulmonary benefits.[25,27,28] However, no studies have investigated the association between air purification and cognitive function. The results of this study support our hypothesis and provide the first "gold standard" evidence to date regarding air pollution exposure being associated with decreased test scores.

These findings are consistent with evidence from several association studies. Amanzadehand co-workers[17] found that a one standard deviation (SD) increase in ambient $PM_{2.5}$ corresponded to a 0.029 SD decrease in test scores in mock exams of the Iran high-stakes matriculation exam. Similar improvements in standardized test scores were also observed for Israeli matriculation exams,[6] California public school children,[20] and high school students in Chile.[21] These results suggest that taking exams on more polluted days could have a negative effect on the test scores. To minimize exposure measurement errors in using daily variation in ambient air pollutant concentrations, Roth[23] instead used the concentrations of indoor air pollutants; he found that a one unit increase in indoor PM_{10} ($\mu g/m^3$) in a London university was associated with a 0.003 SD reduction in students' test scores. Although the results in those studies are not necessarily comparable, they reflect growing evidence that exposure to higher PM levels can result in reduced test scores.

As observational studies of association, the studies mentioned above are susceptible to a number of biases that could produce confounded results. Furthermore, the uncontrolled exposures in those studies make it difficult to identify the specific air pollutants or factors associated with these pollutants that might be responsible for the observed effects. Our study used a "gold standard" approach to investigate a

https://doi.org/10.1021/acs.est.3c10372
Environ. Sci. Technol. 2024, 58, 8207−8214



(1st test day) (2nd test day)

Figure 1. Concentrations of PM$_{10}$, PM$_{2.5}$, and PM$_1$ in the two classrooms during the tests (left panel, 1st test day; right panel, 2nd test day).

direct link. The results of several intervention studies have been reported using interventions such as air filters installed in vehicles[29−31] or homes[25,27,32] or using respirators.[33−37] To the best of our knowledge, this study is the only study in which an intervention was used to experimentally manipulate concentrations of inhaled air pollutants to examine the effects of PM reduction on test scores.

While our study did not aim to investigate mechanisms by which short-term exposure to indoor PM could have near-immediate effects on test performance, the existing literature suggests at least two plausible pathways.[38,39] First, PM can infiltrate the central nervous system (CNS) directly with a fraction of the particles that deposit in the nasal airways being absorbed through the nasal epithelium and transported retrogradely along the olfactory bulb to the brain.[40,41] Second, inhaled PM activates lung airway irritant receptors, producing near-immediate systemic inflammation and oxidative stress through afferent autonomic nervous system pathways.[42,43]

Toxicological evidence also suggests that short-term exposures to PM can produce neuroinflammation.[44,45] An acute exposure to PM of 6 h in adult mice induced neuroinflammation, with the most notable effects observed in the hippocampus and olfactory bulb.[46] This resultant neuroinflammation likely involved one or both of the above pathways.

While these investigations provide evidence of a connection between short-term exposure to air pollution and abrupt initiation of neuroinflammation, the precise nature of this relationship remains uncertain. The extent to which it is attributed to particles directly entering brain tissue, systemic inflammatory reactions, or a combination of both mechanisms has yet to be determined.

In addition to neurophysiological pathways, air pollution could also disrupt cognitive functioning through psychological pathways. For example, exposure to high concentrations of PM may increase the risk of depression,[47,48] although the time course of this effect, if it occurs, is likely to be relatively

Table 2. Summary of Test Scores and Indoor Air Pollutant Concentrations (mean ± SD) for the Sham and Active Air Purifier Interventions by Test Period

	first test			second test		
score/air pollutants	classroom A (sham)	classroom B (active)	p value	classroom A (active)	classroom B (sham)	p value
			score			
listening (original score)	30.8 (32.0)	31.3 (32.5)	0.93	29.6 (32.0)	29.0 (30.0)	0.24
listening (z score)	−0.03 (0.12)	0.03 (0.18)		0.04 (0.35)	−0.04 (0.09)	
reading (original score)	43.2 (44.0)	50.1 (53.5)	0.002	50.5 (54.0)	54.7 (58.0)	0.14
reading (z score)	−0.22 (−0.17)	0.22 (0.44)		−0.13 (0.08)	0.12 (0.32)	
combined (original score)	73.9 (76.0)	81.3 (83.0)	0.03	80.2 (86.0)	83.7 (86.0)	0.46
combined (z score)	−0.18 (−0.08)	0.18 (0.25)		−0.08 (0.18)	0.08 (0.22)	
			air pollutants			
PM_{10} ($\mu g/m^3$)	56.1 (53.6)	26.3 (24.5)	<0.001	23.5 (22.6)	55.8 (54.4)	<0.001
$PM_{2.5}$ ($\mu g/m^3$)	41.5 (39.9)	12.5 (12.0)	<0.001	13.4 (13.1)	40.2 (37.9)	<0.001
$PM_{1.0}$ ($\mu g/m^3$)	37.1 (36.0)	10.2 (9.7)	<0.001	12.0 (11.8)	36.8 (34.6)	<0.001
BC (ng/m^3)	3008 (2876)	1202 (1146)	<0.001	2764 (2870)	5391 (5472)	<0.001
SO_2 (ppb)	3.60 (3.30)	3.40 (3.35)	0.13	1.89 (1.78)	1.72 (1.75)	0.05
NO_x (ppb)	27.75 (24.10)	26.81(26.30)	0.26	93.17 (83.30)	99.16 (97.35)	0.85
CO_2 (ppm)	1579 (668)	1643 (501)	0.57	1628 (657)	1608 (567)	0.86
temperature (°C)	23.8 (1.4)	23.5 (2.0)	0.29	23.4 (1.5)	23.5 (1.1)	0.72

Table 3. Linear Mixed Effects Model Effect Estimates (z Scores and 95% Confidence Intervals) of the Intervention, Test Period, and Intervention Order by Model Complexity

test	variable	base model[a]	base + period + order[b]	full model[c]
listening	intervention	0.07 (−0.07, 0.20)	0.07 (−0.06, 0.20)	0.07 (−0.06, 0.20)
	period		0.02 (−0.11, 0.15)	0.02 (−0.12, 0.16)
	order		0.01 (−0.25, 0.28)	−0.08 (−0.37, 0.21)
reading	intervention	0.10 (0.00, 0.21)[d]	0.10 (−0.01, 0.21)[d]	0.11 (0.00, 0.22)[d]
	period		0.01 (−0.10, 0.11)	−0.02 (−0.14, 0.09)
	order		−0.34 (−0.62, 0.07)	−0.47 (−0.75, −0.19)
combined	intervention	0.10 (0.01, 0.20)[e]	0.10 (0.01, 0.20)[e]	0.11 (0.02, 0.21)[e]
	period		0.02 (−0.08, 0.11)	−0.01 (−0.11, 0.09)
	order		−0.25 (−0.53, 0.03)	−0.30 (−0.58, −0.03)

[a]Model includes random effect for subject and fixed effect for intervention. [b]Test period and order of intervention fixed effects added to base model. [c]Fixed effects added for sex, age, university department, intervention perception, and indoor gaseous pollutant concentrations. [d]$p < 0.10$. [e]$p < 0.05$.

prolonged. Some studies have also suggested that air pollution may affect an individual's performance by inducing minor irritation, which may produce a rapid reduction in cognitive function.[49−51]

Our study has important strengths. First, by employing an experimental design (a double-blind, randomized crossover design), this study was able to show that reduced indoor PM pollution results in improved standardized test scores. Second, CET-4 is the only test that each college student takes in China. By using the scores of a CET-4 mock exam to reflect cognitive function, differences among several disciplines in the college can be minimized. Third, the experimental intervention only targeted particulate matter; therefore, possible confounding effects of gaseous air pollutants should be excluded.

There are nevertheless some limitations to the study. First, the complete representation of cognitive function may not be adequately captured by test scores alone. Relying solely on the CET-4 test score as the primary outcome in this study may be somewhat limited. Incorporating standardized scales that assess various aspects of cognitive function, such as math, logic, and creative problem-solving, could more fully assess cognitive function. Second, we conducted mock tests only twice; more repetitions of the tests may have enhanced the certainty of the results. Third, because PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ concentrations were affected similarly by the intervention, the study was unable to determine which PM size range had the largest impact on test scores. Fourth, opening windows may cause a heterogeneous indoor environment with varying levels of air pollutants and temperature in different locations in the classroom and thus potentially affect the results. Future studies should consider a better ventilation method to exclude heterogeneous influences from the outdoor environment.

In conclusion, this intervention study found cognitive benefits of indoor PM purification among young college students using a "gold standard" study design that allows an inferential claim of an effect that is not merely an association. Future research could make use of other academic tests (e.g., math, creative reasoning, etc.) or nonacademic tests of cognitive performance (e.g., agility, reaction time, and visual accuracy),[51] employ more vulnerable populations (e.g., children, the elderly), study other locations or settings, use interventions that allow other concentrations, or allow investigation of pollutants other than PM.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c10372.

Detailed information on experiment design: the basic information on the air purifier (Text S1), the introduction of the CET-4 (Text S2), the order of the English tests (Text S3), and monitoring equipment and parameters (Table S1). Additional results of the study:

assessment of subject blinding by the perception of purification status (Table S2); distributions of z scores and original scores by intervention, test period, or perception of the intervention (Figures S1 and S2); linear mixed-effects model effect estimates of the intervention, test period, and intervention order by model complexity (Table S3); and change in z score associated with an IQR change of continuous indoor PM and particulate BC concentration (Table S4) (PDF)

AUTHOR INFORMATION

Corresponding Authors

Bin Han − *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China;* orcid.org/0000-0002-0499-1767; Email: hanbin@craes.org.cn

Zhipeng Bai − *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China; Department of Environmental and Occupational Health Sciences, School of Public Health, University of Washington, Seattle, Washington 98105, United States;* orcid.org/0000-0002-1816-2353; Email: baizp@craes.org.cn

Authors

Jia Xu − *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China;* orcid.org/0000-0003-4243-079X

Hong Zhao − *College of Computer Science, Nankai University, Tianjin 300071, China*

Yujuan Zhang − *Department of Family Planning, The Second Hospital of Tianjin Medical University, Tianjin 300211, China;* orcid.org/0000-0002-7125-4505

Wen Yang − *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China*

Xinhua Wang − *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China*

Chunmei Geng − *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China*

Yan Li − *College of Computer Science, Nankai University, Tianjin 300071, China*

Yun Guo − *College of Computer Science, Nankai University, Tianjin 300071, China*

Sverre Vedal − *Department of Environmental and Occupational Health Sciences, School of Public Health, University of Washington, Seattle, Washington 98105, United States;* orcid.org/0000-0002-1309-3627

Julian D. Marshall − *Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington 98195, United States;* orcid.org/0000-0003-4087-1209

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.est.3c10372

Author Contributions

[#]J.X. and H.Z. contributed equally to this work.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This study was funded by the National Key R&D Program of China (2023YFC3708305), the National Natural Science Foundation of China (42277429), and the Budget Surplus of Central Financial Science and Technology Plan (2022YSKY-44).

REFERENCES

(1) Dai, L.; Zanobetti, A.; Koutrakis, P.; Schwartz, J. D. Associations of fine particulate matter species with mortality in the United States: a multicity time-series analysis. *Environ. Health Perspect.* **2014**, *122* (8), 837−842.

(2) Chen, R.; Kan, H.; Chen, B.; Huang, W.; Bai, Z.; Song, G.; Pan, G. Association of particulate air pollution with daily mortality: the China Air Pollution and Health Effects Study. *American Journal of Epidemiology* **2012**, *175* (11), 1173−1181.

(3) Wong, C.-M.; Vichit-Vadakan, N.; Kan, H.; Qian, Z. Public Health and Air Pollution in Asia (PAPA): a multicity study of short-term effects of air pollution on mortality. *Environ. Health Perspect.* **2008**, *116* (9), 1195−1202.

(4) Katsouyanni, K.; Samet, J. M.; Anderson, H. R.; Atkinson, R.; Le Tertre, A.; Medina, S.; Samoli, E.; Touloumi, G.; Burnett, R. T.; Krewski, D. *Air Pollution and Health: a European and North American Approach (APHENA)*; Research Report, Health Effects Institute, 2009; vol *142*, pp 5−90.

(5) Lu, J. G. Air pollution: a systematic review of its psychological, economic, and social effects. *Current Opinion in Psychology* **2020**, *32*, 52−65.

(6) Ebenstein, A.; Lavy, V.; Roth, S. The long-run economic consequences of high-stakes examinations: Evidence from transitory variation in pollution. *American Economic Journal: Applied Economics* **2016**, *8* (4), 36−65.

(7) Chiu, Y.-H. M.; Bellinger, D. C.; Coull, B. A.; Anderson, S.; Barber, R.; Wright, R. O.; Wright, R. J. Associations between traffic-related black carbon exposure and attention in a prospective birth cohort of urban children. *Environ. Health Perspect.* **2013**, *121* (7), 859−864.

(8) Kicinski, M.; Vermeir, G.; Van Larebeke, N.; Den Hond, E.; Schoeters, G.; Bruckers, L.; Sioen, I.; Bijnens, E.; Roels, H. A.; Baeyens, W.; Viaene, M. K.; Nawrot, T. S. Neurobehavioral performance in adolescents is inversely associated with traffic exposure. *Environ. Int.* **2015**, *75*, 136−143.

(9) Mohai, P.; Kweon, B.-S.; Lee, S.; Ard, K. Air pollution around schools is linked to poorer student health and academic performance. *Health Affairs* **2011**, *30* (5), 852−862.

(10) Stafford, T. M. Indoor air quality and academic performance. *Journal of Environmental Economics and Management* **2015**, *70*, 34−50.

(11) Suglia, S. F.; Gryparis, A.; Wright, R. O.; Schwartz, J.; Wright, R. J. Association of black carbon with cognition among children in a prospective birth cohort study. *American Journal of Epidemiology* **2007**, *167* (3), 280−286.

(12) Sunyer, J.; Esnaola, M.; Alvarez-Pedrerol, M.; Forns, J.; Rivas, I.; Lopez-Vicente, M.; Suades-Gonzalez, E.; Foraster, M.; Garcia-Esteban, R.; Basagana, X.; Viana, M.; Cirach, M.; Moreno, T.; Alastuey, A.; Sebastian-Galles, N.; Nieuwenhuijsen, M.; Querol, X. Association between traffic-related air pollution in schools and cognitive development in primary school children: a prospective cohort study. *PLoS Med.* **2015**, *12* (3), No. e1001792.

(13) Wang, S.; Zhang, J.; Zeng, X.; Zeng, Y.; Wang, S.; Chen, S. Association of traffic-related air pollution with children's neurobehavioral functions in Quanzhou China. *Environ. Health Perspect.* **2009**, *117* (10), 1612−1618.

(14) Zhang, X.; Chen, X.; Zhang, X. The impact of exposure to air pollution on cognitive performance. *Proc. Natl. Acad. Sci. U. S. A.* **2018**, *115* (37), 9193−9197.

(15) Chen, H.; Kwong, J. C.; Copes, R.; Hystad, P.; van Donkelaar, A.; Tu, K.; Brook, J. R.; Goldberg, M. S.; Martin, R. V.; Murray, B. J.; Wilton, A. S.; Kopp, A.; Burnett, R. T. Exposure to ambient air

pollution and the incidence of dementia: A population-based cohort study. *Environ. Int.* **2017**, *108*, 271−277.

(16) Power, M. C.; Adar, S. D.; Yanosky, J. D.; Weuve, J. Exposure to air pollution as a potential contributor to cognitive function, cognitive decline, brain imaging, and dementia: A systematic review of epidemiologic research. *NeuroToxicology* **2016**, *56*, 235−253.

(17) Amanzadeh, N.; Vesal, M.; Ardestani, S. F. F. The impact of short-term exposure to ambient air pollution on test scores in Iran. *Population and Environment* **2020**, *41*, 253.

(18) Heissel, J.; Persico, C.; Simon, D. *Does pollution drive achievement? The effect of traffic pollution on academic performance*; National Bureau of Economic Research, 2019.

(19) Lavy, V.; Ebenstein, A.; Roth, S. *The impact of short term exposure to ambient air pollution on cognitive performance and human capital formation*; 0898−2937; National Bureau of Economic Research, 2014.

(20) Zweig, J. S.; Ham, J. C.; Avol, E. L. Air pollution and academic performance: Evidence from California schools. *National Institute of Environmental Health Sciences* **2009**, 1−35.

(21) Miller, S.; Vela, M. *The Effects of Air Pollution on Educational Outcomes: Evidence from Chile*; Department of Research and Chief Economis, Inter-American Development Bank, 2013.

(22) Carneiro, J.; Cole, M. A.; Strobl, E. The Effects of Air Pollution on Students' Cognitive Performance: Evidence from Brazilian University Entrance Tests. *Journal of the Association of Environmental and Resource Economists* **2021**, *8* (6), 1051−1077.

(23) Roth, S. *The Effect of Indoor Air Pollution on Cognitive Performance: Evidence from the UK*; The London School of Economics and Political Science: London, United Kingdom, 2018.

(24) Head, S. J.; Kaul, S.; Bogers, A. J.; Kappetein, A. P. Non-inferiority study design: lessons to be learned from cardiovascular trials. *European Heart Journal* **2012**, 33 (11), 1318−1324.

(25) Chen, R.; Zhao, A.; Chen, H.; Zhao, Z.; Cai, J.; Wang, C.; Yang, C.; Li, H.; Xu, X.; Ha, S.; Li, T.; Kan, H. Cardiopulmonary benefits of reducing indoor particles of outdoor origin: a randomized, double-blind crossover trial of air purifiers. *Journal of the American College of Cardiology* **2015**, *65* (21), 2279−2287.

(26) Zheng, Y.; Cheng, L.Y. Test review: college English test (CET) in China. *Language Testing* **2008**, *25* (3), 408−417.

(27) Morishita, M.; Adar, S. D.; D'Souza, J.; Ziemba, R. A.; Bard, R. L.; Spino, C.; Brook, R. D. Effect of Portable Air Filtration Systems on Personal Exposure to Fine Particulate Matter and Blood Pressure Among Residents in a Low-Income Senior Facility: A Randomized Clinical Trial. *JAMA Internal Medicine* **2018**, *178* (10), 1350−1357.

(28) Weichenthal, S.; Mallach, G.; Kulka, R.; Black, A.; Wheeler, A.; You, H.; St-Jean, M.; Kwiatkowski, R.; Sharp, D. A randomized double-blind crossover study of indoor air filtration and acute changes in cardiorespiratory health in a First Nations community. *Indoor Air* **2013**, *23* (3), 175−184.

(29) Young, M.; Jansen, K.; Gould, T.; Sack, C.; Hooper, L.; Stewart, J.; Larson, T.; Vedal, S.; Kaufman, J. Diastolic blood pressure effect of traffic-related air pollution: a trial of vehicle filtration. *Eur. Respir. J.* **2018**, *52*, No. PA5069.

(30) Young, M.; Jansen, K.; Gould, T.; Sack, C.; Hooper, L.; Stewert, J.; Larson, T.; Vedal, S.; Kaufman, J. The effect of complex traffic-related mixtures on blood pressure: interaction between particles and gases in a trial of vehicle filtration. *Environmental Epidemiology* **2019**, *3*, 458.

(31) Yu, N.; Shu, S.; Lin, Y.; She, J.; Ip, H. S. S.; Qiu, X.; Zhu, Y. High efficiency cabin air filter in vehicles reduces drivers' roadway particulate matter exposures and associated lipid peroxidation. *PloS One* **2017**, *12* (11), No. e0188498.

(32) Brauner, E. V.; Forchhammer, L.; Møller, P.; Simonsen, J.; Glasius, M.; Wahlin, P.; Raaschou-Nielsen, O.; Loft, S. Exposure to ultrafine particles from ambient air and oxidative stress-induced DNA damage. *Environ. Health Perspect.* **2007**, *115* (8), 1177−1182.

(33) Langrish, J. P.; Mills, N. L.; Chan, J. K. K.; Leseman, D.; Aitken, R. J.; Fokkens, P. H. B.; Cassee, F. R.; Li, J.; Donaldson, K.; Newby, D. E.; Jiang, L. X. Beneficial cardiovascular effects of reducing exposure to particulate air pollution with a simple facemask. *Particle and Fibre Toxicology* **2009**, *6*, 8.

(34) Shi, J. J.; Lin, Z. J.; Chen, R. J.; Wang, C. C.; Yang, C. Y.; Cai, J.; Lin, J. Y.; Xu, X. H.; Ross, J. A.; Zhao, Z. H.; Kan, H. D. Cardiovascular Benefits of Wearing Particulate-Filtering Respirators: A Randomized Crossover Trial. *Environ. Health Perspect.* **2017**, *125* (2), 175−180.

(35) Han, B.; Zhang, N.; Zhao, R.; Zhang, L.; Xu, J.; Yang, W.; Bai, Z.; Vedal, S. A randomized, double-blind, crossover intervention study of traffic-related air pollution and airway inflammation in healthy adults. *Environmental Epidemiology* **2019**, 3 (5), No. e066.

(36) Laumbach, R. J.; Kipen, H. M.; Ko, S.; Kelly-McNeil, K.; Cepeda, C.; Pettit, A.; Ohman-Strickland, P.; Zhang, L.; Zhang, J.; Gong, J.; Veleeparambil, M.; Gow, A. J., A controlled trial of acute effects of human exposure to traffic particles on pulmonary oxidative stress and heart rate variability. *Particle and Fibre Toxicology* **2014**, *11*, DOI: 10.1186/s12989-014-0045-5.

(37) Han, B.; Zhao, R.; Zhang, N.; Xu, J.; Zhang, L.; Yang, W.; Geng, C.; Wang, X.; Bai, Z.; Vedal, S. Acute cardiovascular effects of traffic-related air pollution (TRAP) exposure in healthy adults: A randomized, blinded, crossover intervention study. *Environ. Pollut.* **2021**, *288*, 117583.

(38) Lochhead, J. J.; McCaffrey, G.; Quigley, C. E.; Finch, J.; DeMarco, K. M.; Nametz, N.; Davis, T. P. Oxidative Stress Increases Blood−Brain Barrier Permeability and Induces Alterations in Occludin during Hypoxia−Reoxygenation. *Journal of Cerebral Blood Flow & Metabolism* **2010**, *30* (9), 1625−1636.

(39) Heusinkveld, H. J.; Wahle, T.; Campbell, A.; Westerink, R. H. S.; Tran, L.; Johnston, H.; Stone, V.; Cassee, F. R.; Schins, R. P. F. Neurodegenerative and neurological disorders by small inhaled particles. *NeuroToxicology* **2016**, *56*, 94−106.

(40) Oberdörster, G.; Sharp, Z.; Atudorei, V.; Elder, A.; Gelein, R.; Kreyling, W.; Cox, C. Translocation of inhaled ultrafine particles to the brain. *Inhalation toxicology* **2004**, *16* (6−7), 437−445.

(41) Hopkins, L. E.; Patchin, E. S.; Chiu, P.-L.; Brandenberger, C.; Smiley-Jewell, S.; Pinkerton, K. E. Nose-to-brain transport of aerosolised quantum dots following acute exposure. *Nanotoxicology* **2014**, *8* (8), 885−893.

(42) Ghelfi, E.; Rhoden, C. R.; Wellenius, G. A.; Lawrence, J.; Gonzalez-Flecha, B. Cardiac oxidative stress and electrophysiological changes in rats exposed to concentrated ambient particles are mediated by TRP-dependent pulmonary reflexes. *Toxicol. Sci.* **2008**, *102* (2), 328−336.

(43) Rhoden, C. R.; Wellenius, G. A.; Ghelfi, E.; Lawrence, J.; González-Flecha, B. PM-induced cardiac oxidative stress and dysfunction are mediated by autonomic stimulation. *Biochimica et Biophysica Acta (BBA)-General Subjects* **2005**, *1725* (3), 305−313.

(44) Gao, X.; Coull, B.; Lin, X.; Vokonas, P.; Spiro, A.; Hou, L.; Schwartz, J.; Baccarelli, A. A. Short-term air pollution, cognitive performance and nonsteroidal anti-inflammatory drug use in the Veterans Affairs Normative Aging Study. *Nature Aging* **2021**, *1* (5), 430−437.

(45) van Berlo, D.; Albrecht, C.; Knaapen, A. M.; Cassee, F. R.; Gerlofs-Nijland, M. E.; Kooter, I. M.; Palomero-Gallagher, N.; Bidmon, H.-J.; van Schooten, F.-J.; Krutmann, J.; Schins, R. P. F. Comparative evaluation of the effects of short-term inhalation exposure to diesel engine exhaust on rat lung and brain. *Arch. Toxicol.* **2010**, *84* (7), 553−562.

(46) Costa, L. G.; Cole, T. B.; Coburn, J.; Chang, Y.-C.; Dao, K.; Roqué, P. J. Neurotoxicity of traffic-related air pollution. *NeuroToxicology* **2017**, *59*, 133−139.

(47) Szyszkowicz, M. Air pollution and emergency department visits for depression in Edmonton, Canada. *International Journal of Occupational Medicine and Environmental Health* **2007**, *20* (3), 241.

(48) Li, J.; Huang, L.; Han, B.; van der Kuijp, T. J.; Xia, Y.; Chen, K. Exposure and perception of PM2.5 pollution on the mental stress of pregnant women. *Environ. Int.* **2021**, *156*, 106686.

(49) Zivin, J. G.; Neidell, M. The impact of pollution on worker productivity. *American Economic Review* **2012**, *102* (7), 3652−73.

(50) Chang, T.; Graff Zivin, J.; Gross, T.; Neidell, M. Particulate pollution and the productivity of pear packers. *American Economic Journal: Economic Policy* **2016**, *8* (3), 141−69.

(51) Archsmith, J.; Heyes, A.; Saberian, S. Air Quality and Error Quantity: Pollution and Performance in a High-Skilled, Quality-Focused Occupation. *Journal of the Association of Environmental and Resource Economists* **2018**, *5* (4), 827−863.