THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

The relationship between personal exposure and ambient PM2.5 and black carbon in Beijing

OPEN ACCESS

The relationship between personal exposure and ambient PM$_{2.5}$ and black carbon in Beijing

Chun Lin [a,b], Dayu Hu [c], Xu Jia [c], Jiahui Chen [c], Furong Deng [c], Xinbiao Guo [c], Mathew R. Heal [b], Hilary Cowie [a], Paul Wilkinson [d], Mark R. Miller [e], Miranda Loh [a,*]

[a] Institute of Occupational Medicine, Research Avenue North, Riccarton, Edinburgh EH14 4AP, UK
[b] School of Chemistry, University of Edinburgh, David Brewster Road, Edinburgh EH9 3FJ, UK
[c] Department of Occupational & Environmental Health Sciences, School of Public Health, Peking University Health Science Center, 38 Xueyuan Road, Beijing 100191, China
[d] London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT, UK
[e] Centre for Cardiovascular Science, Queen's Medical Research Institute, University of Edinburgh, 47 Little France Crescent, Edinburgh EH16 4TJ, UK

HIGHLIGHTS

- Real-time personal PM$_{2.5}$ and BC exposures measured for >90 Beijing college students
- Sensor-based portable particle monitors and GPS were used for personal monitoring.
- Statistics and graphs presented by gender, season, time-of-day and microenvironment
- Personal concentrations were generally lower than ambient concentrations.
- BC personal-ambient difference varied more across microenvironments than PM$_{2.5}$.

GRAPHICAL ABSTRACT
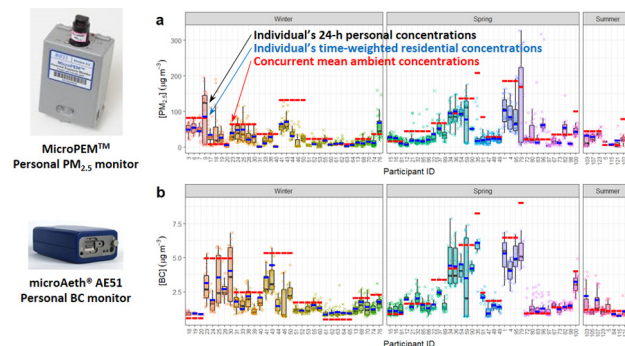
ABSTRACT

This study is part of the "Air Polluion Impacts on Cardiopulmonary disease in Beijing: an integrated study of Exposure Science, Toxicologenomics & Environmental Epidemiology (APIC-ESTEE)" project under the UK-China joint research programme "Atmospheric Pollution and Human Health in a Chinese Megacity (APHH-China)". The aim is to capture the spatio-temporal variability in people's exposure to fine particles (PM$_{2.5}$) and black carbon (BC) air pollution in Beijing, China. A total of 120 students were recruited for a panel study from ten universities in Haidian District in northwestern Beijing from December 2017 to June 2018. Real-time personal concentrations of PM$_{2.5}$ and BC were measured over a 24-h period with two research-grade portable personal exposure monitors. Personal microenvironments (MEs) were determined by applying an algorithm to the handheld GPS unit data. On average, the participants spent the most time indoors (79% in Residence and 16% in Workplace), and much less time travelling by Walking, Cycling, Bus and Metro. Similar patterns were observed across participant gender and body-mass index classifications. The participants were exposed to 33.8 ± 27.8 µg m^{-3} PM$_{2.5}$ and to 1.9 ± 1.2 µg m^{-3} BC over the 24-h monitoring period, on average 24.3 µg m^{-3} (42%) and 0.8 µg m^{-3} (28%) lower, respectively, than the concurrent fixed-site ambient measurements. Relative differences between personal and ambient BC concentrations showed greater variability across the MEs, highlighting

* Corresponding author.
  E-mail address: miranda.loh@iom-world.org (M. Loh).

significant contributions from Dining and travelling by Bus, which involve potential combustion of fuels. This study demonstrates the potential value of personal exposure monitoring in investigating air pollution related health effects, and in evaluating the effectiveness of pollution control and intervention measures.

1. Introduction

Outdoor and indoor air pollution have been identified as the most important environmental risk factors for adverse human health outcomes across the world (Loomis et al., 2013; World Health Organization, 2006; World Health Organization Regional Office for Europe, 2013). The issue of air pollution is especially of concern in developing countries due to their rapid and large-scale urbanisation, leading to extreme levels of pollution impacting large populations. Beijing, the capital city of China, exemplifies this pattern. Its population has nearly doubled to 21.7 million since 2000 (National Bureau of Statistics, 2018), and, accordingly, energy consumption and motor vehicle use have increased dramatically. The fast growth in pollutant emission sources, together with adverse dispersion conditions, particularly in winter, has led to a dramatic deterioration in air quality, often resulting in severe haze episodes that have attracted worldwide attention (An et al., 2019).

It is estimated that 1.15 million people die prematurely each year in China because of ambient air pollution (World Health Organization, 2018). Stroke, ischemic heart disease, lung cancer and chronic obstructive pulmonary disease (COPD) are the top causes of the premature deaths (Institute for Health Metrics and Evaluation (IHME), 2018), and have all been associated with long-term exposure to airborne particulate matter (PM), especially fine PM with an aerodynamic diameter <2.5 μm ($PM_{2.5}$).

The particles within $PM_{2.5}$ derive from a wide range of sources, including directly-emitted "primary" particles, such as resuspended dust, seasalt, and industrial and combustion-related particles, as well as from formation of new secondary inorganic and organic particulate matter from reactions of gaseous sulphur dioxide, nitric oxides, ammonia and volatile organic compounds. One important constituent of $PM_{2.5}$ is black carbon (BC), since it acts as a good tracer for combustion-related air pollution and because of its stronger association with certain adverse health effects than $PM_{2.5}$ (Bell et al., 2009; Janssen et al., 2011; Patel et al., 2009; Schaap and Denier van der Gon, 2007; Spira-Cohen et al., 2011). The greater damage to health is attributed to its large surface capacity to carry significant levels of potentially toxic substances (e.g., heavy metals and persistent organic pollutants), high ability to induce inflammation, penetrating into deeper parts of the lungs (Braniš et al., 2010; Weichenthal, 2012) and deposition in secondary organs (Semmler et al., 2004). BC is relatively straightforward to measure through light absorption techniques and is often examined in investigations of the health impacts of urban air pollution (Chiu et al., 2013; Fang et al., 2012; Hart et al., 2018; Luben et al., 2017; Zhao et al., 2014).

While most of the health effects of exposure to air pollution are widely accepted, the exposure-response associations were established mainly in North America and Europe, and may not be applicable to China because of differences in sources, unique pollution climatology, personal activity patterns that determined their exposure pathways and population vulnerability. To add to the local knowledge and determine effective mitigations to reduce the health risks for the large population in Beijing, researchers in the UK and China have joined forces since 2016 under the "Atmospheric Pollution & Human Health in a Chinese Megacity (APHH-China)" research programme, aiming to identify the concentrations and sources of air pollution in Beijing, and how people are exposed (Shi et al., 2019). Within the programme, the "Air Pollution Impacts on Cardiopulmonary disease in Beijing: an integrated study of Exposure Science, Toxicogenomics & Environmental Epidemiology

(APIC-ESTEE)" project specifically looks into detailed assessments of people's exposure to air pollution for long- and short-term epidemiological analyses.

Most epidemiology studies use point measurements from fixed-site ambient (outdoor) monitoring stations to represent the average pollution level for the whole neighbourhood or community, or modelled higher spatial resolution values for home locations derived from these measurements. However, conventional statutory monitoring stations are bulky and expensive to operate, which greatly limits their spatial coverage in large cities like Beijing. Although various atmospheric modelling approaches have been developed to fill the gaps where no direct measurements are available, they are often inadequate in fully capturing the local variability in concentrations, particularly at sites near traffic (Lin et al., 2017a). Furthermore, the accuracy of the modelled concentration remains uncertain, without appropriate verification through some measurements (Holliday et al., 2014; Meng et al., 2005; Sarnat et al., 2007). In addition, people on average spend 76% of their time in indoor environments (Lei et al., 2016), where air quality could be very different from the ambient levels (Chen and Zhao, 2011; Cortez-Lugo et al., 2008; Huang et al., 2015; Shi et al., 2015). Personal monitoring could provide the most accurate information on individuals' exposure, although it is often more costly (if large numbers of participants are required) and takes considerably more effort to perform and integrate data. Of the small number of personal monitoring studies in China, most of them collected time-integrated samples to determine the total exposure over a certain period of time (Chen et al., 2017; Fan et al., 2018; Shang et al., 2019), which do not show the temporal variability in individuals' exposure and thus could not associate exposure to short-term peak concentrations with acute health outcomes. Other researchers only focused on certain types of pathways, such as commuting, or conducted their studies through prescribed activities (Lei et al., 2017; Shen and Gao, 2019), which lacked a comprehensive understanding of people's exposure in real life. Only very few studies in China, and beyond, have utilised the power of the emerging sensor-based portable air quality monitors to gauge personal exposures (Lei et al., 2016). In these studies, the researchers relied on the manufacturers' calibration of the instruments, whereas there is evidence that careful field calibration was needed (Lin et al., 2017).

Characterisation of the variability of individual's exposure to air pollution can help identify conditions leading to detrimental impacts on health. Therefore, this study aimed to address the following research questions:

- Can lower-cost sensor-based portable personal exposure monitors, GPS trackers, and modern data science tools, be used as a low burden approach to measure individual's real-time exposures to $PM_{2.5}$ and BC in their daily lives?
- What are the contributors to the variability of individual's $PM_{2.5}$ and BC exposures, and can this data provide insight into behaviour changes to reduce personal exposure to air pollution, and interventions to reduce air pollution in general?
- What is the relationship between the "true" personal exposure and the average ambient concentration measured at the nearest fixed-site statutory monitoring station, which is conventionally used to represent community exposure in epidemiological studies?

This study investigates these questions by capturing the spatio-temporal variability in individual's exposures to $PM_{2.5}$ and BC air

pollution in Beijing in higher-education students asked to carry two research-grade low-intrusive real-time personal monitors and GPS trackers. Post-exposure data processing allows a better insight into the activity patterns and how they affect the participants' exposures to these air pollutants. This data will be used for linking with the health metrics obtained later in the APIC-ESTEE project, but also has the potential to be used to shape future studies and advice on exposure reduction and public health protection.

2. Materials and methods

2.1. Study design, study area and population

An overview of the study design is shown in the schematic of research framework in Fig. 1. The study was carried out in Haidian District in north-western Beijing, where most higher education institutes are located. A total of 120 students were recruited for the personal exposure monitoring study, from ten universities around the North 4th Ring Road (Fig. 2), if they met the following inclusion criteria:

- Aged 18–49 yrs.;
- Body mass index (BMI) within 18.5–24.0 ("normal") or > 28.5 kg m^{-2} ("overweight");
- Non-smoking for at least one year prior to the recruitment;
- Absence of metabolic syndrome conditions, e.g., normal blood pressure, lipid values and fasting glucose concentrations;
- High level of cardiorespiratory fitness;
- Able to comply with the study procedure.

The sample size was chosen to yield estimates with a (95% confidence interval) margin of error of around ± 5 μg m^{-3} of the true population value of PM$_{2.5}$ for the main population means.

This study was approved by the Institutional Review Boards of Peking University Health Science Center (PKU-HSC) (IRB00001052-16066), and an informed consent form was signed by each participant before enrolment. The study and reporting conform to the Strengthening the Reporting of OBservational studies in Epidemiology (STROBE) guidelines.

To investigate the potential differences in activities and exposure to air pollution, approximately the same numbers of male and female, and normal-weight and overweight volunteers were recruited.

Personal monitoring of air pollution was performed over three seasons, namely, Winter: 14 December 2017–16 January 2018, Spring: 15 March–18 April 2018, and Summer: 8 May–12 June 2018. Each participant was continuously monitored for their exposures to PM$_{2.5}$ and BC for 24 h during their daily lives on a weekday in a single season. The participant's location was recorded using a handheld GPS tracker, and categorised via post-processing into a set of microenvironments (MEs).

2.2. Personal monitoring

Up to five participants were monitored simultaneously at any time. Each personal monitoring session started at 08:00 on a Monday, Tuesday, Wednesday or Thursday, when the participant attended the laboratory to be equipped with personal monitors contained in a small messenger bag, and ended at 08:00 the following day when the participant returned to the laboratory.

PM$_{2.5}$ was measured using a MicroPEM personal exposure monitor (RTI International, USA), which is based on optical scattering (nephelometry). BC was measured using a microAeth AE51 personal exposure monitor (AethLabs, USA), which is based on optical absorption. A 610A PRO GNSS handheld GPS unit (IceGPS, China) was used for location tracking. The PM$_{2.5}$ and BC monitors sampled through conductive tubing attached to the bag strap, to allow sampling at the breathing zone (Fig. 3). The participants were instructed to carry the bag as much as possible throughout their regular activities, but were asked to refrain from very strenuous exercises in order to protect the equipment from mechanical shock. Compared with most epidemiological studies that may use only fixed-site ambient measurements, or exposure studies focusing on one aspect of people's activities such as transit, or collecting time-averaged personal pollutant samples, the 24-h continuous personal exposure measurement using portable real-time monitors
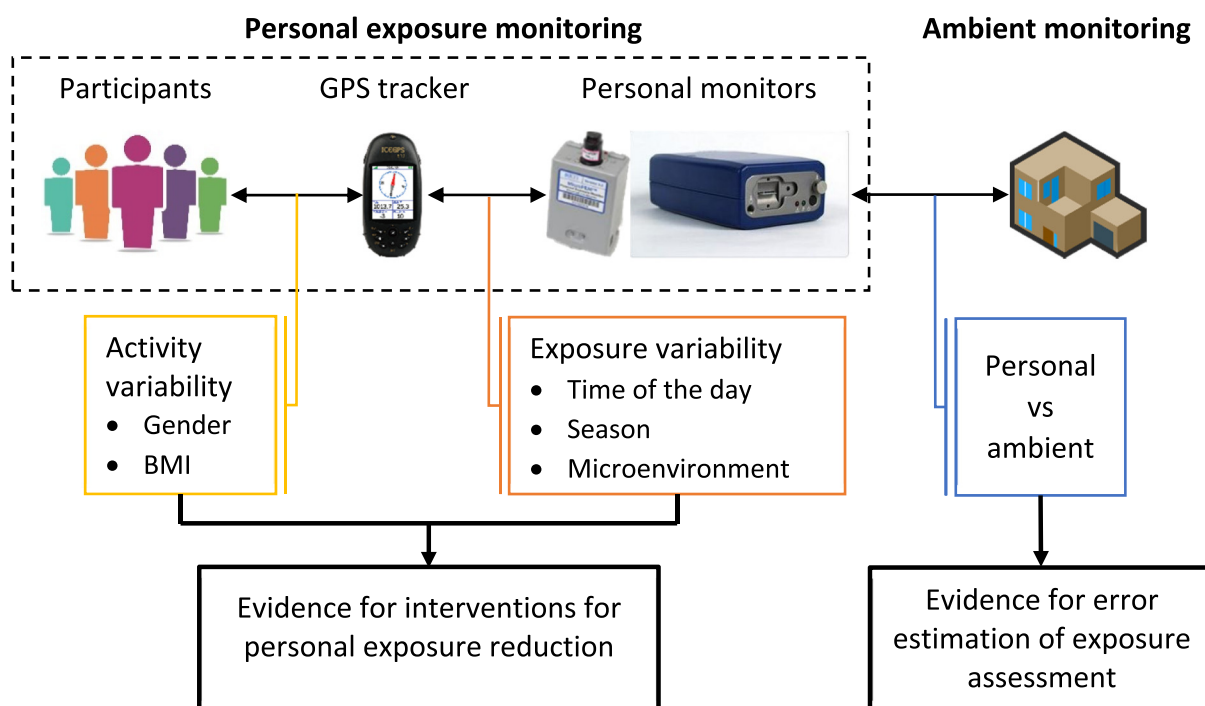

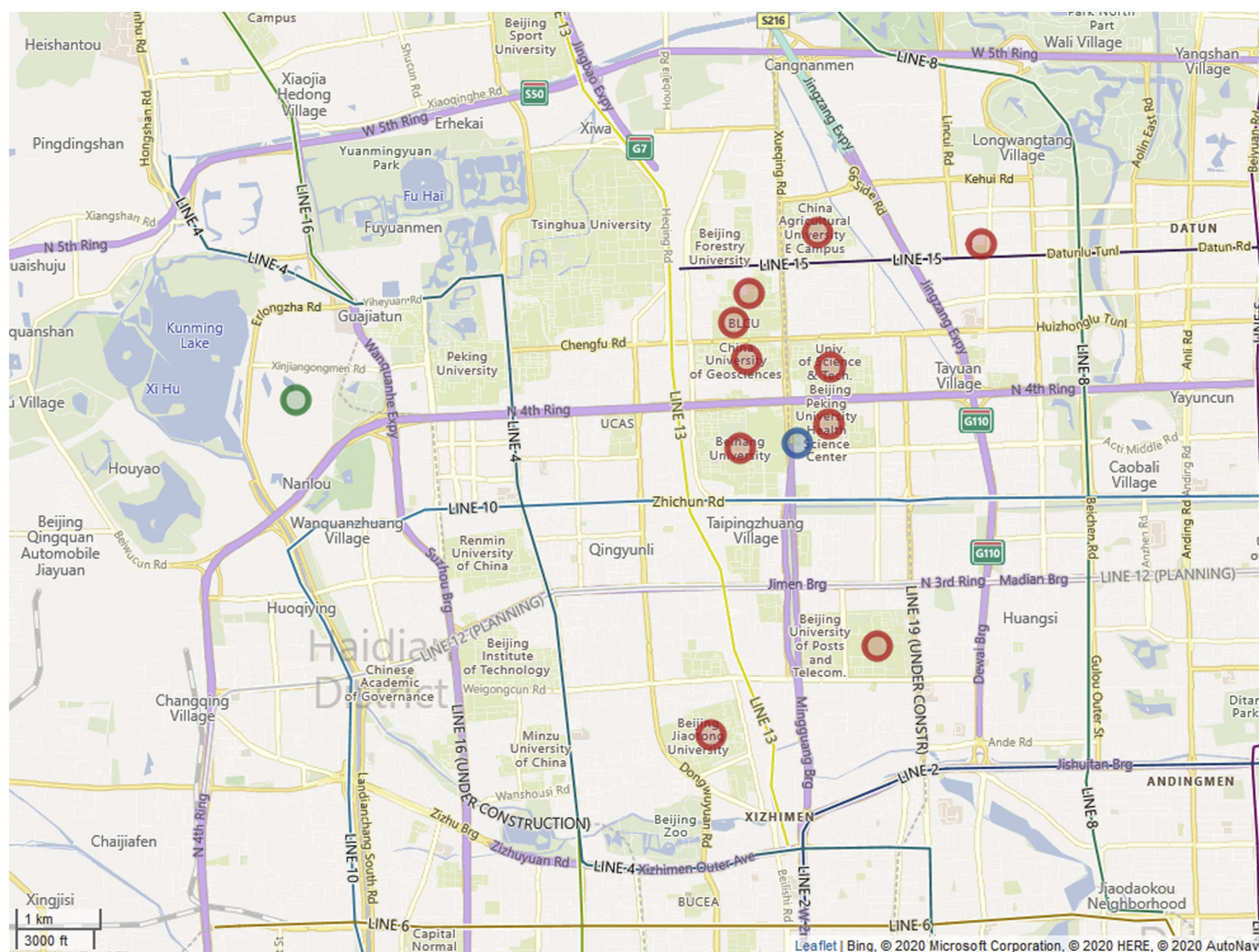**Fig. 1.** Schematic of the research framework.

Fig. 2. Map of the study area in north-western Beijing. The red circles mark the universities, from which the participants were recruited. The green circle indicates the state-operated ambient PM$_{2.5}$ reference analyser at the state-operated Haidian Wanliu Monitoring Station. The blue circle represents the BC reference analyser on the roof of Peking University School of Public Health. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

allowed the participants to carry on with their normal daily lives. We believe that this approach provides a more comprehensive, realistic and detailed understanding of their activity patterns and how their exposures to PM$_{2.5}$ and BC varied in relation to activity. The more granular information could be helpful for assessing associations with health responses.

The MicroPEMs were operated in the continuous mode at a flowrate of 0.5 L min^{-1}, taking PM$_{2.5}$ readings every 10 s. They also collected particles onto a 25 mm Teflon filter, which permitted post-deployment gravimetric quantification of cumulative PM$_{2.5}$. The microAeth units measured BC concentration by determining the absorption of an 880 nm wavelength laser beam by the particulate deposit on the filter every 1 min at a flowrate of 150 mL min^{-1}. The filter discs and strips in each MicroPEM and microAeth monitor were replaced before each personal monitoring session to avoid overloading by particles and consequent impact on flowrate and optical determination. The GPS trackers logged the participant's location every 1 min, and were programmed to enter energy saving mode to pause logging when satellite signals were lost for an extended period of time (such as when staying in a building), and resume logging when connections were re-established.

Lung function, heart rate variability and blood pressure were recorded during the same period, and a blood and urine sample was collected from each participant before and after the personal monitoring period. The methodological details and results for the health-related part of the wider study are being reported separately elsewhere.

2.3. Personal monitoring data integration and QA/QC

Raw data from the MicroPEMs were converted to PM$_{2.5}$ mass concentrations (corrected for relative humidity) and exported using the proprietary MicroPEM Docking Station software. Occasionally, a MicroPEM sampled at an unexpected flowrate due to the internal filter being overloaded by very high concentrations of PM$_{2.5}$ or a malfunctioning pump. Since this would lead to calculation of an erroneous PM$_{2.5}$ concentration, any concentration associated with a flowrate outside the manufacturer's specified operational range of 0.45–0.55 L min^{-1} was discarded.

Raw BC measurements from the microAeths were first uploaded to the AethLabs' Dashboard for optical noise attenuation (ONA) smoothing, for which the ONA threshold (ΔATN) was set to 0.01. This is an adaptive time-averaging algorithm to reduce the occurrence of negative values due to high-frequency sampling and low BC concentrations (Hagler et al., 2011). The smoothed measurements were then corrected for underestimation from the filter loading effect (Apte et al., 2011).

To ensure inter-comparability of measurements from individual monitors, the MicroPEM PM$_{2.5}$ measurements from each personal

Fig. 3. Illustration of personal monitoring kit worn by a researcher. All battery-operated personal monitors and a GPS tracker were contained in the small messenger bag, and measured personal pollution levels through conductive tubing.

exposure session were calibrated using the mass change of the monitor's internal filter during that session. Retrieved filter samples were stored in a laboratory freezer at −20 °C when not in use. Prior to weighing, filters were conditioned for 24 h in the same controlled environment (25 °C, ~45% relative humidity) as the high precision microbalance used for weighing (AG285, Mettler Toledo, USA). The filter-based mass of particles collected were compared with the cumulative sequence of $PM_{2.5}$ concentrations derived from the monitor optical scattering. Occasionally a MicroPEM unit returned a negative value when $PM_{2.5}$ concentrations were very low (<3 μg m^{-3}). Therefore, for the filter-based calibration correction, reported concentrations of less than −3 μg m^{-3} were discarded, and those within [−3,0) μg m^{-3} were set to 0. The whole time-series was discarded if the relative difference between the post- and pre-processed mean concentrations was >50%. This excluded 11 (12%) of the participants.

To calibrate the microAeth BC measurements, the five microAeths were set up to sample alongside a reference BC analyser (Aethalometer AE33, Magee Scientific, USA) on the roof of the School of Public Health at Peking University Health Science Centre (PKU-SPH) for three consecutive 24-h sessions during 24–27 August 2018. Simple linear regressions were then derived from the co-located measurements for each microAeth, to correct the personal exposure measurements. Personal exposure monitors were set up in the same way for the co-located sampling as for the personal monitoring sessions to ensure the applicability of the calibration regressions.

The 1-min GPS tracking data was initially geotagged as follows according to its inferred speed of movement (<0.5 km h^{-1}: sedentary; 0.5–5.8 km h^{-1}: walking; 5.8–18.0 km h^{-1}: cycling; >18.0 km h^{-1}: in a vehicle) as well as according to building and road data on OpenStreetMap. The tagging of Metro was delineated as the period between entering a metro station and leaving a subsequent metro station. This preliminary identification was cross-checked and corrected with a custom-built R Shiny app, which visualised the GPS tracking on OpenStreetMap. The verified geotags were then categorised into eight MEs grouped under Indoors (Residence, Workplace, Dining and Shop) and Outdoors (Walking, Cycling and travelling by Bus and Metro), before synchronising with the pollution measurements to compare exposure levels between MEs.

Sometimes the GPS tracker did not activate as expected after an interrupted reception of satellite signals, resulting in untracked movement between locations. These gaps were labelled as "non-determinable (ND)" and excluded from ME exposure analysis (20.3%), but still retained for personal exposure analysis, because they comprised part of the individual's exposure.

2.4. Ambient $PM_{2.5}$ and BC measurements

The nearest state-operated Haidian Wanliu automatic Urban Environment Evaluation Monitoring Station was chosen as the fixed-site station for comparison. Situated in the same district with the participating universities, ambient air quality measurements at Haidian Wanliu are most likely to be used as a proxy for personal exposures for this area in conventional epidemiological study designs. Hourly ambient $PM_{2.5}$ concentrations from Haidian Wanliu were downloaded from China's Air Quality Historical Data repository (Wang, 2018). As this site does not measure ambient BC concentrations, ambient BC measurements at 1-min intervals were obtained from the aforementioned reference BC analyser on the roof of PKU-SPH.

Ambient and personal pollution measurements were all averaged to hourly values and merged together by timestamp. The hourly concentrations were also geotagged with the prevailing MEs identified for each hour from the personal exposure monitoring.

2.5. Data analysis

Statistics and graphical analysis were performed to show variations by gender, season and time-of-day. The contribution of each ME to total exposure was quantified for each pollutant separately. Pearson correlation was used to assess the association between ambient and personal concentrations for each pollutant. Additionally, a relative personal increment/decrement was calculated for each pollutant ($C_{personal} − C_{ambient})/C_{ambient}$, and compared between pollutants.

All data processing and reporting were performed in R version 3.6.1, with custom code using packages of tidyverse, readxl, openair, caret, broom, shiny, leaflet, leaflet.extras, plotly, qwraps2, ggpubr and rmarkdown.

3. Results

Of the 120 students originally recruited for the study, 94 completed the personal monitoring phase of the study. Incomplete personal pollution recordings (e.g., from monitoring equipment malfunction) were excluded, resulting in 79 (84.0%) and 83 (88.3%) time-series of personal exposure measurements for $PM_{2.5}$ and BC, respectively (Table 1).

Fig. 4 summarises the proportion of time, on average, spent by participants in different MEs stratified by gender and by weight classification. On average, the participants spent most of the time (at least 18.9 h, 79.0%) in Indoor environments, with the most time in Residence (14.8 h, 61.9%) and Workplace (3.9 h, 16.3%), and substantially less time travelling, mainly Walking (26.8 min), followed by Cycling (8.4 min), taking a Bus (4.0 min) and taking the Metro (2.5 min) (time presented as average across all participants in the study). Due to interrupted satellite signals, 4.3 h (18.1%) of each participant's time could not be

Table 1
Demographic of study participants (age = 23 ± 2 yr).

	PM$_{2.5}$				BC			
	Male (N = 48)	Female (N = 31)	Normal-weight (N = 44)	Overweight (N = 35)	Male (N = 47)	Female (N = 30)	Normal-weight (N = 44)	Overweight (N = 33)
Number of participants, n (% participants per season)								
Winter	24 (50.0)	12 (38.7)	21 (47.7)	15 (42.9)	22 (46.8)	11 (36.7)	18 (40.9)	15 (45.5)
Spring	18 (37.5)	17 (54.8)	20 (45.5)	15 (42.9)	18 (38.3)	17 (56.7)	20 (45.5)	15 (45.5)
Summer	6 (12.5)	2 (6.5)	3 (6.8)	5 (14.3)	7 (14.9)	2 (6.7)	6 (13.6)	3 (9.1)
Bodily statistics, mean ± SD								
Height (m)	1.73 ± 0.06	1.63 ± 0.05	1.68 ± 0.08	1.70 ± 0.06	1.73 ± 0.06	1.63 ± 0.05	1.68 ± 0.09	1.69 ± 0.06
Weight (kg)	76.4 ± 11.7	60.1 ± 11.3	59.8 ± 8.8	82.9 ± 6.7	75.4 ± 11.8	60.3 ± 11.4	59.8 ± 8.5	82.5 ± 6.8
BMI (kg m^{-2})	25.7 ± 4.0	22.7 ± 3.9	21.1 ± 1.9	28.8 ± 1.6	25.4 ± 4.1	22.8 ± 4.0	21.0 ± 1.9	28.8 ± 1.6
Pollutant concentration, mean ± SD								
Ambient (µg m^{-3})	55.5 ± 45.8	62.4 ± 56.4	46.2 ± 42.4	73.4 ± 55.1	2.3 ± 1.8	3.0 ± 2.3	2.2 ± 1.9	3.2 ± 2.1
Personal (µg m^{-3})	30.3 ± 23.9	39.3 ± 32.8	32.6 ± 28.3	35.4 ± 27.6	1.7 ± 0.9	2.3 ± 1.5	1.7 ± 1.1	2.3 ± 1.3

attributed to an ME determined by GPS tracking. Time spent in different MEs did not show any substantial differences between male and female, and normal-weight and overweight participants.

3.1. Overview of personal PM$_{2.5}$ and BC concentrations

Fig. 5 summarises the range of hourly personal PM$_{2.5}$ and BC concentrations experienced by each participant. Personal hourly-averaged PM$_{2.5}$ concentrations ranged from 0.2 to 643.4 µg m^{-3} (across all person-hours in the dataset) and the equivalent personal BC concentrations varied between 0.6 and 86.5 µg m^{-3}, revealing variability between participants monitored during the same monitoring period (e.g., Participants 41–50 for both PM$_{2.5}$ and BC), as well as within an individual participant's exposure period (e.g., Participants 9, 59, 79 for

PM$_{2.5}$ and Participants 25, 30, 59 for BC). These variabilities reflected the impact on personal exposure by different MEs, which was not captured by the ambient concentrations. However, personal PM$_{2.5}$ and BC concentrations were generally correlated with the prevailing levels of concurrent ambient PM$_{2.5}$ and BC concentrations, i.e., when ambient levels were higher (lower), then personal values were higher (lower), although the personal PM$_{2.5}$ and BC concentrations were generally lower than their concurrent ambient values.

On average, the participants were exposed to 33.8 ± 27.8 µg m^{-3} PM$_{2.5}$ and to 1.9 ± 1.2 µg m^{-3} BC over their 24-h monitoring period. Compared with the ambient concentrations of PM$_{2.5}$ (58.2 ± 50.0 µg m^{-3}) and BC (2.7 ± 2.1 µg m^{-3}) for the same periods, the mean personal exposures were therefore 24.3 µg m^{-3} (41.8%) and 0.8 µg m^{-3} (28.1%) lower for the two pollutants, respectively.
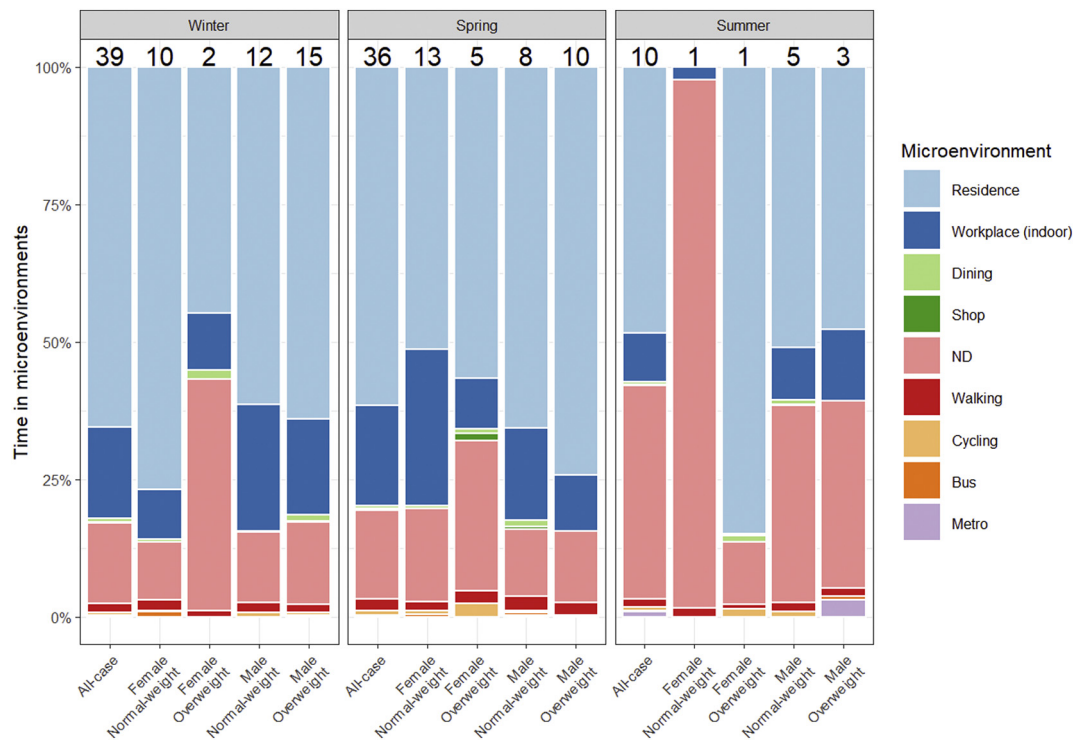

Fig. 4. Average time spent in different microenvironments stratified by gender and BMI classification. The number on the top of each column indicates the number of participants in the corresponding category.
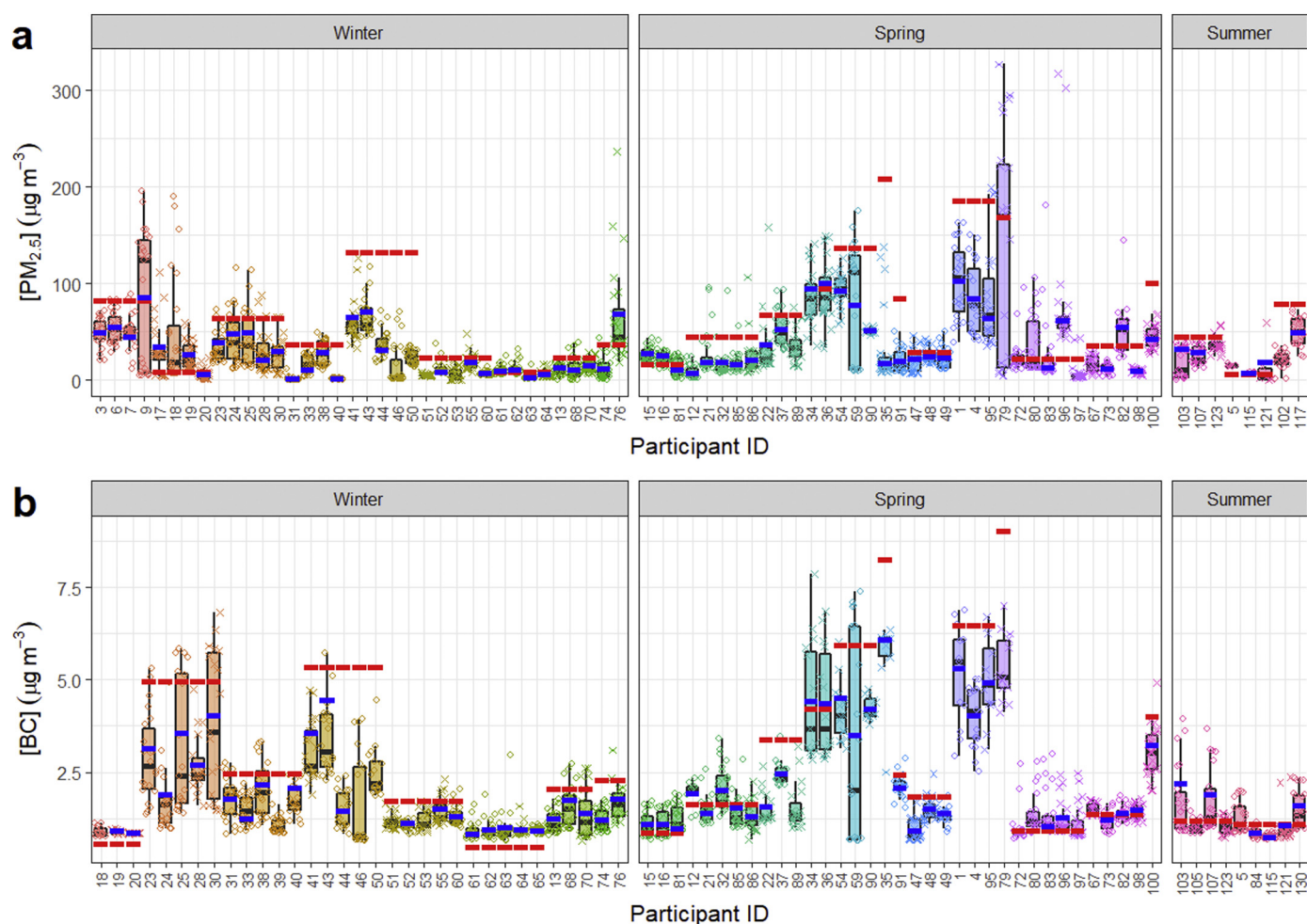
Fig. 5. Boxplots of measured a) PM$_{2.5}$ and b) BC concentrations (hourly averages) for each participant's 24-h personal exposure period. Each box with whiskers shows the median, the interquartile range (IQR) and the smallest and the largest values within 1.5 × IQR from the lower and the upper quartiles. Jitters (circles: male, crosses: female) represent the hourly averaged personal concentrations. Boxes and jitters are colour-coded by monitoring period. The red dashed lines show the mean ambient concentrations of the respective pollutant for the nearest fixed-site monitoring station for the corresponding monitoring periods (thus the length of the dashed line indicates which participants were monitored in parallel in the same period). The blue dashes show the time-weighted residential mean concentrations of the respective pollutant for each participant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As many modelling epidemiological studies used concentrations of pollutants at residential addresses to represent exposure to air pollution, the measured PM$_{2.5}$ and BC concentrations geotagged as "residential" in this study were also extracted to calculate the time-weighted residential exposure concentrations for the participants. On average, the participants were exposed to 33.9 ± 27.1 μg m^{-3} PM$_{2.5}$ and 2.1 ± 1.3 μg m^{-3} BC in their residences. These values are similar to and highly correlated with the participants' 24-h mean exposure concentrations ($r = 0.980$ and $r = 0.990$ for PM$_{2.5}$ and BC, respectively). These correlations are higher than those between the 24-h personal and ambient concentrations ($r = 0.678$ for PM$_{2.5}$ and $r = 0.880$ for BC), largely because the personal-residential (indoor) concentrations are part of the 24-h personal concentrations.

3.2. Temporal and seasonal variation in personal PM$_{2.5}$ and BC concentrations

Boxplots summarising the diurnal profile in personal PM$_{2.5}$ and BC concentrations for each measurement period are presented in Fig. 6. The personal PM$_{2.5}$ and BC concentrations show distinctive diurnal patterns, which also varied over the three seasons of the study.

In the winter, personal PM$_{2.5}$ concentration increased steadily through the morning rush hours, before reaching the first peak of the day at 10:00 (27.7 ± 32.1 μg m^{-3}). Concentrations briefly declined at noon (17.6 ± 17.0 μg m^{-3}), before increasing again with the afternoon rush hours to a maximum around 19:00 (39.7 ± 45.6 μg m^{-3}). The PM$_{2.5}$ concentration then gradually decreased in late evenings to the daily low (18.3 ± 18.3 μg m^{-3}) before dawn.

Personal BC concentration in the winter showed a similar diurnal pattern, with a morning peak at 09:00 (1.7 ± 0.8 μg m^{-3}), and a later evening peak at 21:00 (2.1 ± 1.4 μg m^{-3}). The daily minima in personal BC concentration coincided in time with those for PM$_{2.5}$ concentration at 12:00 (1.3 ± 0.5 μg m^{-3}) and 06:00 (1.2 ± 0.5 μg m^{-3}) (Fig. 6).

The daily patterns in personal PM$_{2.5}$ and BC concentrations in the spring were generally similar to those in the winter, albeit with slightly different timings for the maxima and minima. However, the much higher peak personal concentrations of both pollutants in the morning (70.5 ± 74.5 μg m^{-3} PM$_{2.5}$ at 08:00, and 2.5 ± 1.4 μg m^{-3} BC at 09:00) dwarf the fluctuations in the rest of the 24-h period, and thus make the diurnal patterns less pronounced. Also, hourly aggregated concentrations of both pollutants appeared to vary more within each hour in the spring than in the winter.

In contrast, Fig. 6 shows that diurnal variation of personal PM$_{2.5}$ and BC concentrations was rather different in the summer than in the winter and spring. Although maxima and minima occurred at roughly the same time of the day, personal concentrations of both pollutants was lower in
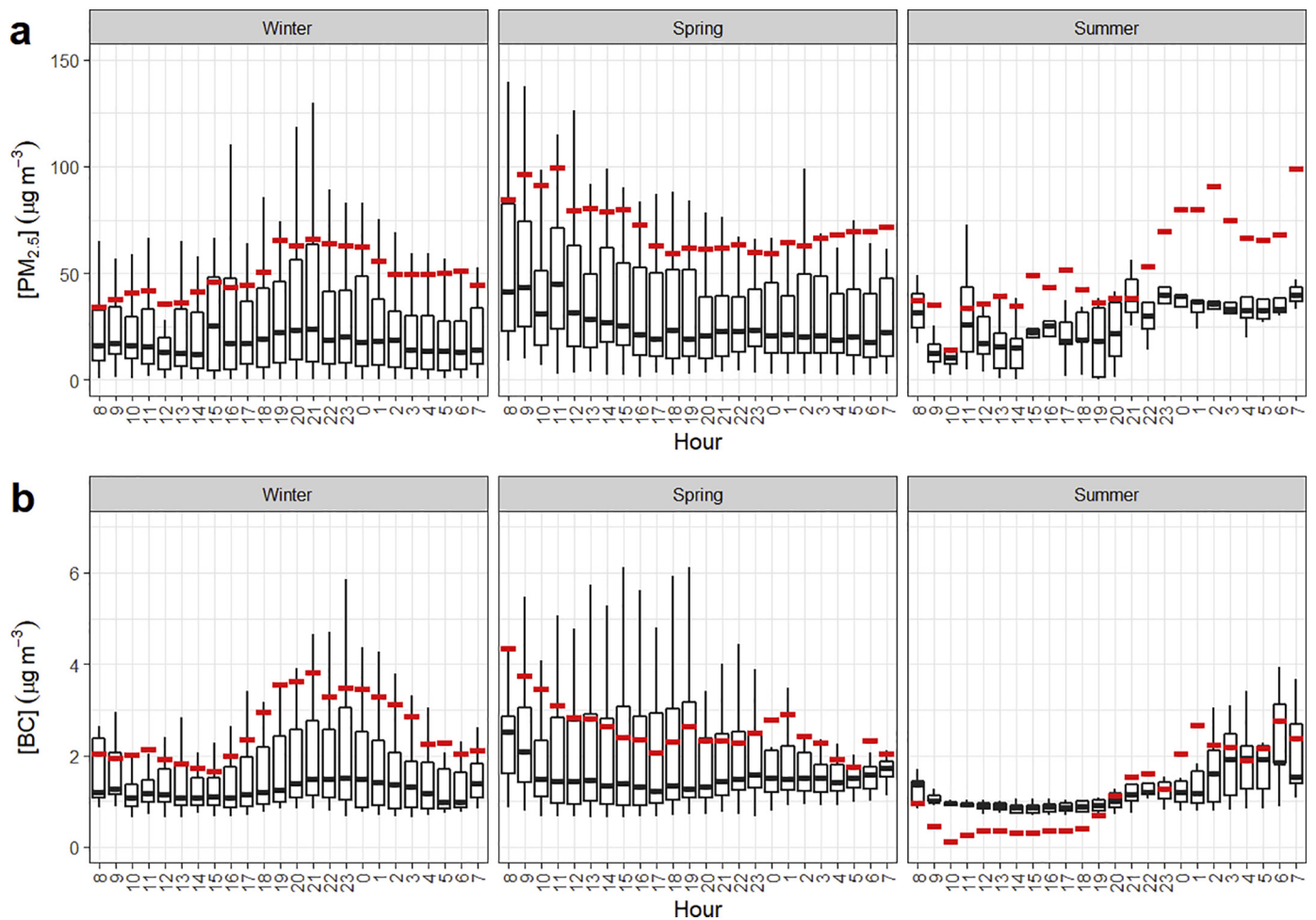
Fig. 6. Boxplots of measured a) PM$_{2.5}$ and b) BC personal concentrations averaged for each hour during each study period. Each box with whiskers represents the median, the inter-quartile range (IQR), and the extreme values within 1.5 × IQR from the upper and the lower quartiles of all personal measurements within that hour. The red dashes show the mean ambient concentrations of the respective pollutant for the corresponding hours. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the daytime, and elevated after midnight, despite the relatively large variability in the hourly-averaged personal PM$_{2.5}$ concentrations.

In all three seasons, the hourly mean personal PM$_{2.5}$ and BC concentrations correlated well with the concurrent hourly mean ambient concentrations of these two pollutants (albeit with personal measurements usually substantially lower than those from the ambient monitoring station) (Table 2). However, the difference between the personal and ambient concentrations fluctuated throughout the day, with larger differences between late evening and early morning hours (Fig. 6).

The differences between mean personal and ambient PM$_{2.5}$ and BC concentrations, indicating the potential error when using ambient concentration to quantify personal exposure, also showed clear seasonal and diurnal variability.

Across the three seasons, the difference between personal and ambient PM$_{2.5}$ concentrations was greater in the spring ($-28.2\ \mu g\ m^{-3}$) than in the summer and winter (-24.4 and $-22.4\ \mu g\ m^{-3}$, respectively) (Fig. 6 and Table 2). The personal-ambient differences in BC concentrations exhibited a different and much greater seasonal variability, with the greatest differential in the winter ($-0.9\ \mu g\ m^{-3}$), followed by in the spring and in the summer (-0.5 and $0.1\ \mu g\ m^{-3}$, respectively).

With respect to diurnal patterns in the differences between personal and ambient concentrations of PM$_{2.5}$ and BC, lower differences tended to occur during the morning and evening rush hours, as well as the noon sub-rush hours (Fig. 6). The greater differences were usually observed between late evening and early morning hours, and in the middle of the morning and the afternoon.

3.3. Personal exposure to PM$_{2.5}$ and BC by ME

Table 3 summarises the average concentrations of PM$_{2.5}$ and BC in each ME by season. On average, over all participants and seasons, the participants were exposed to their highest concentrations of PM$_{2.5}$ when Cycling ($109.8\ \pm\ 62.4\ \mu g\ m^{-3}$), in the Shop ($79.6\ \pm\ 103.4\ \mu g\ m^{-3}$) and travelling by Bus ($63.9\ \pm\ 22.1\ \mu g\ m^{-3}$), and to their lowest concentrations of PM$_{2.5}$ when in the Metro ($11.0\ \pm\ 11.7\ \mu g\ m^{-3}$), Residence ($33.8\ \pm\ 34.5\ \mu g\ m^{-3}$) and Workplace ($38.9\ \pm\ 47.7\ \mu g\ m^{-3}$).

The highest personal concentrations of BC occurred when on the Bus ($4.7\ \mu g\ m^{-3}$), Cycling ($3.9\ \pm\ 2.1\ \mu g\ m^{-3}$), and in the Shop ($3.2\ \pm\ 2.7\ \mu g\ m^{-3}$), and the lowest concentrations when Dining, in Workplace and Residence ($1.4\ \pm\ 0.8$, $1.7\ \pm\ 0.9$ and $1.9\ \pm\ 1.4\ \mu g\ m^{-3}$, respectively).

Table 3 shows that there was some seasonality in both the personal PM$_{2.5}$ and BC concentrations in each ME. The highest personal concentrations of both pollutants were observed in the spring. Personal BC concentrations in all MEs in the winter were consistently higher than those in the summer, but there was little consistency in personal PM$_{2.5}$ concentrations.

Table 2
Mean hourly-averaged personal and ambient PM$_{2.5}$ and BC concentrations, the personal minus ambient concentration differences and the correlations between hour-of-the-day personal and ambient concentrations, each stratified by season.

Season	[PM$_{2.5}$]$_{pers}$ (µg m^{-3})	[PM$_{2.5}$]$_{ambi}$ (µg m^{-3})	[PM$_{2.5}$]$_{diff}$ (µg m^{-3})	$r_{PM2.5}$	[BC]$_{pers}$ (µg m^{-3})	[BC]$_{ambi}$ (µg m^{-3})	[BC]$_{diff}$ (µg m^{-3})	r_{BC}
Winter	27.0	49.4	−22.4	0.632	1.6	2.6	−0.9	0.922
Spring	43.7	71.9	−28.2	0.879	2.1	2.6	−0.5	0.880
Summer	28.8	53.2	−24.4	0.779	1.3	1.2	0.1	0.895

Fig. 7a shows the relative difference between personal and ambient PM$_{2.5}$ concentrations for each ME. This illustrates that personal PM$_{2.5}$ concentrations were generally lower across all MEs than the concurrent ambient levels at the nearby Haidian Wanliu Urban Environmental Monitoring Station, except for a number of observations in the Shop and when travelling by Metro, Walking and Bus. There was no significant difference in PM$_{2.5}$ average relative difference values across all MEs, although Indoor environments (Workplace, Residence and Dining) tended to attenuate personal PM$_{2.5}$ concentrations more. However, there was considerable variability in PM$_{2.5}$ relative differences in some MEs; for example, some participants were exposed to PM$_{2.5}$ concentrations up to 3.5 times higher than the ambient levels when they were in the Shop (Fig. 7a).

The relative difference between personal and ambient BC concentrations for each ME is shown in Fig. 7b. The relative differences between personal and ambient BC showed considerably greater variability across the MEs than was the case for PM$_{2.5}$ (Fig. 7a). The largest attenuation and enhancement in personal BC concentration were observed in the Workplace and the Metro, respectively. While reductions in personal BC concentrations were statistically insignificant in most MEs, personal BC concentrations were clearly elevated when the participants were Dining and travelling by Metro. On average, BC concentration in the Metro was twice as high as the ambient level, and the difference could be up to 3.5 times (Fig. 7b).

Most of the participants' personal exposure (defined as the product of personal concentration and time spent in an ME) was from Residence and Workplace (96.2% combined), whereas the other Indoor MEs (Dining and Shop) contributed only 1.1% and all Outdoor MEs (Walking, Cycling, Bus and Metro) merely 2.7% (Table 4). Contributions to personal PM$_{2.5}$ exposure by MEs also varied by season. Personal exposure to PM$_{2.5}$ in Residence was much higher in the summer (92.8%) than in the winter and the spring (77.5 and 71.3%, respectively). In contrast, personal exposure to PM$_{2.5}$ at the Workplaces was much lower in the summer (6.8%) than in the other seasons (23.5 and 20.4% for the spring and the winter, respectively) (Table 4).

The participants travelled mostly by Walking (a total of ~13 h across the whole study), which also represented the greatest contribution to personal exposure to outdoor PM$_{2.5}$ (1.3%). While the participants spent roughly the same amount of time Cycling and travelling by Bus and Metro (~4 h), Cycling contributed the second most personal

exposure to outdoor PM$_{2.5}$ (0.8%), 8 times higher than travelling by Metro (0.1%), with travelling by Bus in between (0.5%).

Similar to the observations for personal PM$_{2.5}$ exposure, Residence and Workplace together contributed the greatest personal exposure to BC (96.5%). Among the remainder of the MEs, the participants were exposed to BC while Walking (1.1%), followed by Cycling and Dining (0.7 and 0.6%, respectively). BC exposures when travelling by Bus and Metro and in Shop were likewise lower (contributing 0.4, 0.3, and 0.4% of daily exposure, respectively).

Personal BC exposure by MEs also showed a degree of seasonality. Personal exposures to BC in Residence were similar in the winter and the spring (accounting for 74.6 and 75.9% of daily exposure, respectively), but substantially higher in the summer (85.2%), whereas the contribution from Workplace to personal BC exposure decreased on moving through the winter, spring and summer seasons (23.3, 19.1, and 12.1%, respectively) (Table 4).

4. Discussion

This study characterised the spatio-temporal and personal variabilities in individuals' 24-h exposures to PM$_{2.5}$ and BC via a panel study of >90 university students from ten universities in north-western Beijing. Real-time personal exposure measurements were collected using portable monitors in winter, spring and summer, and compared with concurrent fixed-site ambient measurements in Beijing, to reveal main exposure pathways for the study population. Filter-based correction and co-located field calibration of individual personal monitors ensure the intercomparability of the personal and ambient measurements. This is one of the first detailed datasets of real-time personal exposure assessment of this kind in Beijing.

4.1. Activity patterns and personal exposure levels

Post-monitoring processing of the participants' GPS data successfully attributed people's exposure to eight identified MEs over 80% of the time, without the need for a conventional time-activity diary. The student participants spent the majority of the time in indoor environments, largely in their Residence or their Workplace, an observation that was independent of gender or weight classification. Comparatively, a handbook for exposure factors in China suggests a median of 83% of time spent in indoor MEs (Duan et al., 2015). This differs from previous

Table 3
Personal PM$_{2.5}$ and BC concentrations (mean ± SD, µg m^{-3}) by ME and by season. NA indicates that the total time spent in the respective ME and season was <30 min, or there was no personal pollution data.

| Season	Residence	Workplace	Dining	Shop	Walking	Cycling	Bus	Metro
PM$_{2.5}$								
Winter	27.3 ± 31.5	29.6 ± 22.9	5.0 ± 2.0	15.1 ± NA	30.3 ± 29.0	97.4 ± 26.2	56.0 ± 34.7	17.2
Spring	41.6 ± 37.8	51.9 ± 63.4	69.2 ± 66.4	111.9 ± 123.0	60.6 ± 54.9	122.2 ± 101.9	71.9 ± 3.2	24.3
Summer	31.0 ± 19.2	10.8 ± 12.9	7.1 ± NA	NA	NA	NA	NA	1.2 ± 1.4
All-season	33.8 ± 34.5	38.9 ± 47.7	45.4 ± 60.0	79.6 ± 103.4	53.6 ± 50.8	109.8 ± 62.4	63.9 ± 22.1	11.0 ± 11.7
BC								
Winter	1.7 ± 1.2	1.6 ± 0.7	1.0 ± 0.2	1.0	1.1	4.0 ± 1.3	4.7	2.7
Spring	2.3 ± 1.6	1.9 ± 1.1	2.0 ± 0.9	4.4 ± 2.7	2.8 ± 2.1	5.4 ± 1.4	NA	3.0
Summer	1.4 ± 0.8	1.1 ± 0.3	0.8 ± 0.2	NA	NA	1.0	NA	1.4 ± 0.6
All-season	1.9 ± 1.4	1.7 ± 0.9	1.4 ± 0.8	3.2 ± 2.7	2.6 ± 2.1	3.9 ± 2.1	4.7	2.2 ± 0.9
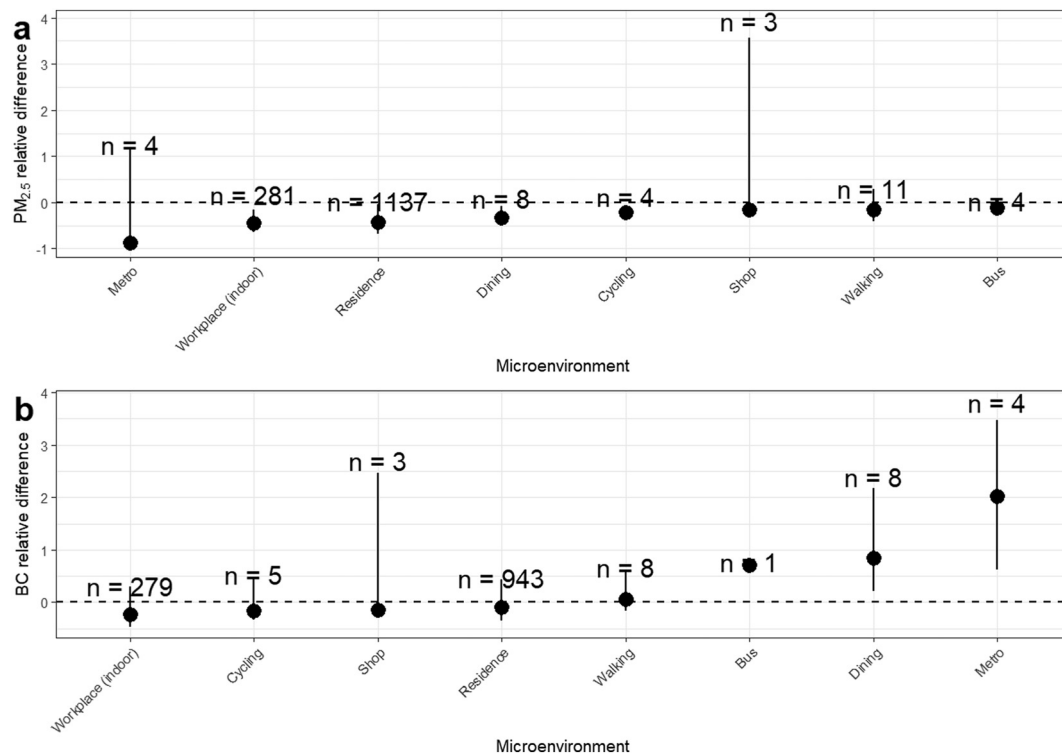
Fig. 7. Relative difference between a) PM$_{2.5}$ and b) BC personal and ambient concentrations by ME. The points and whiskers are the medians and interquartile ranges of hourly relative differentials in personal PM$_{2.5}$ and BC exposure in the corresponding MEs. n shows the number of hourly relative differentials in each ME for all participants.

studies in other parts of the world involving participants with more di-versified professions (Dons et al., 2011), but is typical for university stu-dents in China, who stay in on-campus accommodation during term time. The students were mostly attending lectures and conducting re-search during the study period, so there were fewer periods of other ac-tivities in the remaining time. It was also because campuses of Chinese universities usually provide most amenities, eliminating the need to leave the campus frequently. The real-life measurements made in this study provide reasonable estimates of the exposure patterns of the stu-dent population in Beijing. However, to represent personal exposure for the broader population in Beijing, additional studies are needed that in-clude a greater variety of people of different ages with more diverse daily tasks, such as caterers, delivery drivers and building workers.

The personal PM$_{2.5}$ daily mean concentration measured in this study, 33.8 ± 27.8 µg m^{-3}, exceeds the WHO's guideline for 24-h mean PM$_{2.5}$ concentration of 25 µg m^{-3} (World Health Organization, 2006). It is also higher than previously reported personal PM$_{2.5}$ mea-surements in Europe (with the range of study averages of 5.2 to 19.4 µg m^{-3}) (Johannesson et al., 2011; Lanki et al., 2007; Montagne et al., 2014) and North America (with the range of study averages of 13.0 to 22.0 µg m^{-3}) (Kim et al., 2005; Williams et al., 2000). This was due to the generally higher PM$_{2.5}$ pollution in Beijing, but nonetheless meets the Chinese Grade-II standard for 24-h mean PM$_{2.5}$ concentration of 75 µg m^{-3} (Ministry of Ecology and Environment of the People's Republic of China, 2012), and is in line with observations in other major Chinese cities (2.9–126.8 µg m^{-3}) (Baccarelli et al., 2014; Chen et al., 2018; Du et al., 2010; Lei et al., 2016; Liu et al., 2019). The WHO has not set a guideline concentration for BC at present, but the personal concentration measured in this study (1.9 ± 1.2 µg m^{-3}) was compara-ble with the exposure levels observed in vehicles in another Chinese megacity, Shanghai (Lei et al., 2016), and on jogging trails in Macau (3.5 ± 2.3 µg m^{-3}) (Liu et al., 2019). Both of these published studies re-ported a large spatial variability in BC in relation to distance to major roads. This current study also found substantial variability in personal

BC concentration between participants monitored on the same day and within some individual participants, whereas such variability was less dramatic for personal PM$_{2.5}$ concentrations, particularly between si-multaneously monitored participants.

4.2. Personal exposure vs ambient concentration

Over the three seasons, personal PM$_{2.5}$ and BC exposures correlated well with ambient concentrations, showing the importance of outdoor sources to participants' exposure to air pollution, even though partici-pants were indoors most of the time. The highest personal and ambient concentrations being observed in the spring of 2018 was unusual for Beijing, where PM concentrations are typically highest in winter, as the result of extra emissions from large-scale heating and adverse dis-persion conditions due to temperature inversion. The significantly lower PM concentrations in winter in the present study were probably due to various strict emission controls the local government applied to-wards the end of 2017, in order to meet the air quality objectives of a 5-year reduction of 25% in PM$_{2.5}$ concentration by 2017 set in the "Action Plan on Prevention and Control of Air Pollution". These emission con-trols are undoubtedly effective in reducing ambient air pollution. None-theless, it should not be overlooked that the determinants of ventilation of the indoor MEs, such as the building structure, door and window opening patterns, and the availability and use of air conditioners and air purifiers will make a difference to indoor pollution levels.

On average, the personal PM$_{2.5}$ and BC concentrations measured in this study were 41.8% and 28.1% lower than their respective fixed-site ambient concentrations. This contrasts with findings from previous studies comparing personal exposure and ambient concentrations in other Chinese megacities (Fan et al., 2018; Lei et al., 2016). This is mostly because of the different activity patterns between the study popula-tions. Our participants spent most of the time in indoor environments, whereas the concentrations in the published studies were also experi-enced more in road travelling and cooking. The personal-ambient

Table 4
Time-weighted personal $PM_{2.5}$ and BC exposure contributed by each ME (%) in each season. NA indicates the total time spent in respective ME across the season was <30 min, or there was no personal pollution data.

Season	Residence	Workplace	Dining	Shop	Walking	Cycling	Bus	Metro
$PM_{2.5}$								
Winter	77.5	20.4	0.0	0.1	0.4	0.9	0.5	0.1
Spring	71.3	23.5	1.1	0.7	2.0	0.8	0.5	0.1
Summer	92.8	6.8	0.3	NA	NA	NA	NA	0.1
All-season	74.7	21.5	0.7	0.4	1.3	0.8	0.5	0.1
BC								
Winter	74.6	23.3	0.2	0.1	0.6	0.6	0.4	0.2
Spring	75.9	19.1	0.9	0.7	1.8	0.8	0.5	0.2
Summer	85.2	12.1	0.8	NA	NA	0.5	NA	1.4
All-season	76.0	20.5	0.6	0.4	1.1	0.7	0.4	0.3

differences will also reflect the locations of both the ambient monitoring station and the participants. In any event, these findings highlighted the great variability in personal exposures to $PM_{2.5}$ and BC, which is unlikely to be represented in fixed-site point measurements used in conventional approaches.

Personal $PM_{2.5}$ and BC concentrations measured in this study exhibited relatively clear diurnal patterns, namely, the dual peaks in the morning and the evening, as previous studies in other Chinese megacities have also observed (Liu et al., 2019; Qiu et al., 2019). However, in contrast to the higher morning peaks reported in the other studies, our participants were exposed to higher concentrations of these pollutants in the evenings (Fig. 6). This appears to be correlated with the higher evening ambient concentrations of both pollutants observed in the winter and the summer. Greater personal-ambient differences were found between late evening and early morning hours, when our participants returned to their Residence, and thus had a greater degree of separation from outdoor sources. This was reflected in the differences and correlations between personal and ambient BC concentrations examined by season. Despite the broadly similar personal-ambient correlations over the three seasons ($r \approx 0.9$), the difference between the personal and ambient BC concentrations was higher in the winter than in the summer, indicating that our participants were exposed to more outdoor air as the weather turned warmer in the year (Table 2).

4.3. Microenvironment contributions to personal exposure

Exposure analysis by ME revealed that Cycling, Shop and Bus were the most polluted MEs for both $PM_{2.5}$ and BC. PM concentrations are expected to be higher in these MEs due to traffic emissions (for Cycling and Bus), indoor sources (for Shop, including food courts within a shopping centre), and particle resuspension enhanced by larger volumes of people movement. On the other hand, Residence and Workplace were consistently among the three cleanest MEs in our study. This relative pattern of personal $PM_{2.5}$ and BC concentrations in different MEs was consistent with that reported in a previous transport-related survey in Xi'an, China, albeit the personal $PM_{2.5}$ concentration recorded during Cycling in our study was much higher (up to ~9 times higher than the WHO guideline value) (Qiu et al., 2019; World Health Organization, 2006). However, $PM_{2.5}$ personal concentrations measured during Cycling (more closely reflecting the $PM_{2.5}$ concentrations on roads and cycle paths) were lower than the fixed-site ambient measurements ~5 km away. This suggested that the high concentration, to which the cyclists were exposed might be attributed to higher $PM_{2.5}$ concentrations in the broader urban environment, not only from traffic sources.

This study did not find statistically significant differences between relative differentials in personal $PM_{2.5}$ concentrations across the eight MEs. This is partly due to the very small amounts of time spent in some of the MEs and the large within-ME variability for some MEs, and partly because there were $PM_{2.5}$ sources in all MEs. The relative differentials between personal and ambient concentrations were more variable across the MEs for BC than for $PM_{2.5}$. Despite the small sample size, the significantly elevated personal BC concentrations when Dining and on the Bus highlighted the emissions of BC from potential uses of biomass and coal fuels in cooking and from combustion of fossil fuels in bus engines. The observation in this study that travelling by Metro appears to significantly increase measured personal BC concentration may be a measurement artefact, considering that the metros in Beijing are electrically powered. The microAeth AE51 used in this study estimates BC concentration by determining the light absorption by the dark spot on the filter strip. However, previous studies have reported potential interference from iron oxides in PM (e.g., from wheel and rail wear) in Aethalometer measurements (Cai et al., 2013, 2014).

4.4. Implications of the findings

This study found substantial variability in both within- and between-person exposures to BC, among the study population of higher-education students in Beijing, which was larger than the variability in $PM_{2.5}$ exposures. This suggests that BC could be a more discriminating indicator for health responses to traffic-related pollution in urban environments, and that people's exposure to BC is less likely to be fully represented by point ambient measurements at a distant fixed-site monitor. This highlights the value of more detailed personal exposure assessment in air pollution epidemiology. For example, when attributing health outcomes observed in individuals to their exposures, the undifferentiated point measurements may reduce the correlation between the two, and thus hinder the identification of associations between PM and health parameters. Studies have found stronger associations between cardiorespiratory emergency department visits and exposure to traffic pollution using more spatiotemporally resolved air pollution and exposure data, compared with point measurements from a centrally located monitoring station (Batterman et al., 2014).

Ambient $PM_{2.5}$ and BC concentrations appeared to be the most important drivers of personal exposures for the study population, although personal exposure monitoring shows that using the average ambient concentrations as a surrogate of true personal exposures may lead to an overestimate of ~70% and ~40% for $PM_{2.5}$ and BC, respectively. The uncertainty could be larger in a broader population with a more diverse lifestyle. However, the important role of outdoor pollution in personal exposure calls for more informed ventilation strategies and indoor air treatment for exposure reduction and health protection, during the time when greater reductions in ambient PM are attained. For example, it is common practice in China to open the windows for ventilation first thing in the morning, however, the peak pollution levels over extended morning rush hours suggest that it may be better to do so later in the morning, or resort to a dedicated outdoor air system for the more vulnerable.

Real-time personal monitoring highlighted the potential risks to residents of Beijing from air pollution during commuting. This has

encouraged the local residents to adopt personal protective measures, such as wearing suitable facemasks and closing the window when in vehicles to reduce their exposure to air pollution (Cherrie et al., 2018; Kolluru et al., 2019). While the effectiveness of these personal-level interventions needs further research in both typical and high pollution scenarios, the greater influence of this study could be to educate individuals on behaviour changes beneficial for a greener society and environment, including via influence on businesses. After all, everyone has social responsibility to help achieve the 17 Sustainable Development Goals in the United Nations 2030 Agenda for Sustainable Development.

4.5. Limitations of the study

This study demonstrated the feasibility of quantifying individuals' true personal exposures to $PM_{2.5}$ and BC in Beijing using field-calibrated portable monitors and GPS trackers. The participants were monitored through their daily normal life, and there was no significant additional burden to participants (from, for example, keeping a manual time-activity diary). The approach adopted in this study improved the data integrity by automating data collection and was better able to reflect all pathways contributing to individuals' exposure. On the other hand, there were some technical challenges, such as participants' MEs not being fully determined with the GPS data, which affected the attribution of some exposure to the MEs, and limited the exposure assignment to hourly averages in this study. This was due to the variable delays in reactivating the GPS trackers when leaving a building. A better solution may be to use smartphone-based location services, which utilises GPS satellites as well as connectivity to cellular and WiFi networks to allow more responsive and accurate tracking of bearers (Dewulf et al., 2016). For indoor MEs where detailed location tracking is challenging, more insight into the pathways of exposure may be obtained by identifying people's activities, such as cooking and cleaning, via recording and identifying sounds or video footage alongside personal pollution levels and locations (Milà et al., 2018; von Schneidemesser et al., 2019) or source apportionment via size-resolved particle sampling and simultaneous measurement of multiple pollutants (Vu et al., 2015). Other limitations of this study include that each participant could only be monitored once due to the large study population and the time and effort required for follow-up. Repeated measurements from the same individual across seasons would be advantageous in establishing the variability of individual's activity patterns and exposure pathways, and allow for better association with health outcomes. Lastly, this study did not measure inhaled dose, which can differ with race, gender, age, body weight and intensity of physical activity.

Despite these limitations, the comparison of personal and ambient pollutant concentrations in this study has highlighted the higher increment in personal BC exposure in MEs that use biomass and fossil fuels. This information should be considered when devising informed pollution control policies and intervention measures to reduce people's exposure in these MEs. For example, cleaner energy should be promoted for cooking and heating, as well as for motor vehicles; better ventilation should be installed at metro stations; separation between motor vehicles and cyclists and pedestrians should be increased to allow further attenuation of traffic-related pollution. The spatiotemporally resolved personal-ambient comparison can also provide insight for evaluating the effectiveness of such mitigations. For example, measurements in this study revealed that the ambient concentrations peaked slightly later in the day than the personal concentrations. Also, the highest BC personal exposure occurred slightly later in the day than that of $PM_{2.5}$. Given that 45% of Beijing's local air pollution is generated by mobile sources (vehicles) (UN Environment, 2019), particularly diesel-engine vehicles, which are a major source of BC, these differences in peak times may reflect the positive effects on air quality of the policy that restricts certain heavy goods vehicles from passing through the city (within the 6th ring road, including our study area) at rush hours.

5. Conclusions

This study demonstrated the feasibility of capturing the variability in personal exposures to $PM_{2.5}$ and BC pollution in Beijing, using lower-cost portable devices and modern data science tools. In the study of >90 university students, personal measurements of $PM_{2.5}$ and BC were found to be generally lower than concurrent ambient measurements from fixed sites in the broader neighbourhood. Greater personal-ambient differences in BC concentrations across MEs confirmed BC as a good indicator for traffic-related pollution in the urban environment, and also identified cooking as a notable source of exposure to combustion-derived PM during shopping in retail outlets with dining areas. Overall, the use of personal monitoring of $PM_{2.5}$ and BC concentrations captured the high variation between participants monitored over the same period, and within some individual participants. This detailed exposure characterisation is likely to be valuable when assessing the effect of air pollution exposure on health outcomes, and could also offer valuable insight into the effectiveness of interventions to reduce air pollution.

CRediT authorship contribution statement

Chun Lin: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Dayu Hu:** Conceptualization, Methodology, Investigation, Data curation. **Xu Jia:** Investigation, Data curation. **Jiahui Chen:** Investigation, Data curation. **Furong Deng:** Conceptualization, Supervision, Resources, Writing - review & editing, Project administration, Funding acquisition. **Xinbiao Guo:** Conceptualization, Supervision, Resources, Writing - review & editing, Project administration, Funding acquisition. **Mathew R. Heal:** Conceptualization, Supervision, Writing - review & editing, Project administration, Funding acquisition. **Hilary Cowie:** Writing - review & editing. **Paul Wilkinson:** Conceptualization, Writing - review & editing, Funding acquisition. **Mark R. Miller:** Conceptualization, Writing - review & editing, Funding acquisition. **Miranda Loh:** Conceptualization, Methodology, Resources, Supervision, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition.

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.

Acknowledgements

References

An, Z., Huang, R.J., Zhang, R., Tie, X., Li, G., Cao, J., Zhou, W., Shi, Z., Han, Y., Gu, Z., Ji, Y., 2019. Severe haze in northern China: a synergy of anthropogenic emissions and atmospheric processes. Proc. Natl. Acad. Sci. U. S. A. 116, 8657–8666. https://doi.org/10.1073/pnas.1900125116.

Apte, J.S., Kirchstetter, T.W., Reich, A.H., Deshpande, S.J., Kaushik, G., Chel, A., Marshall, J.D., Nazaroff, W.W., 2011. Concentrations of fine, ultrafine, and black carbon particles in auto-rickshaws in New Delhi, India. Atmos. Environ. 45, 4470–4480. https://doi.org/10.1016/j.atmosenv.2011.05.028.

Baccarelli, A.A., Zheng, Y., Zhang, X., Chang, D., Liu, L., Wolf, K.R., Zhang, Z., McCracken, J.P., Díaz, A., Bertazzi, P.A., Schwartz, J., Wang, S., Kang, C.M., Koutrakis, P., Hou, L., 2014.

Air pollution exposure and lung function in highly exposed subjects in Beijing, China: A repeated-measure study. Part. Fibre Toxicol. 11, 51. https://doi.org/10.1186/s12989-014-0051-7.

Batterman, S., Ganguly, R., Isakov, V., Burke, J., Arunachalam, S., Snyder, M., Robins, T., Lewis, T., 2014. Dispersion modeling of traffic-related air pollutant exposures and health effects among children with asthma in Detroit, Michigan. Transp. Res. Rec., 105–113 https://doi.org/10.3141/2452-13.

Bell, M.L., Ebisu, K., Peng, R.D., Samet, J.M., Dominici, F., 2009. Hospital admissions and chemical composition of fine particle air pollution. Am. J. Respir. Crit. Care Med. 179, 1115–1120. https://doi.org/10.1164/rccm.200808-1240OC.

Braniš, M., Vyškovská, J., Malý, M., Hovorka, J., 2010. Association of size-resolved number concentrations of particulate matter with cardiovascular and respiratory hospital admissions and mortality in Prague, Czech Republic. Inhal. Toxicol. 22, 21–28. https://doi.org/10.3109/08958378.2010.504758.

Cai, J., Yan, B., Kinney, P.L., Perzanowski, M.S., Jung, K.H., Li, T., Xiu, G., Zhang, D., Olivo, C., Ross, J., Miller, R.L., Chillrud, S.N., 2013. Optimization approaches to ameliorate humidity and vibration related issues using the microAeth black carbon monitor for personal exposure measurement. Aerosol Sci. Technol. 47, 1196–1204. https://doi.org/10.1080/02786826.2013.829551.

Cai, J., Yan, B., Ross, J., Zhang, D., Kinney, P.L., Perzanowski, M.S., Jung, K.H., Miller, R., Chillrud, S.N., 2014. Validation of microAeth as a black carbon monitor for fixed-site measurement and optimization for personal exposure characterization. Aerosol Air Qual. Res. 14, 1–9. https://doi.org/10.4209/aaqr.2013.03.0088.

Chen, X.-C., Jahn, H.J., Engling, G., Ward, T.J., Kraemer, A., Ho, K.-F., Yim, S.H.L., Chan, C.-Y., 2017. Chemical characterization and sources of personal exposure to fine particulate matter (PM2.5) in the megacity of Guangzhou, China. Environ. Pollut. 231, 871–881. https://doi.org/10.1016/j.envpol.2017.08.062.

Chen, X.-C., Ward, T.J., Cao, J.-J., Lee, S.-C., Chow, J.C., Lau, G.N.C., Yim, S.H.L., Ho, K.-F., 2018. Determinants of personal exposure to fine particulate matter (PM2.5) adult subjects in Hong Kong. Sci. Total Environ. 628–629, 1165–1177. https://doi.org/10.1016/j.scitotenv.2018.02.049.

Chen, C., Zhao, B., 2011. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. Atmos. Environ. 45, 275–288. https://doi.org/10.1016/j.atmosenv.2010.09.048.

Cherrie, J.W., Apsley, A., Cowie, H., Steinle, S., Mueller, W., Lin, C., Horwell, C.J., Sleeuwenhoek, A., Loh, M., 2018. Effectiveness of face masks used to protect Beijing residents against particulate air pollution. Occup. Environ. Med. 75, 446–452. https://doi.org/10.1136/oemed-2017-104765.

Chiu, Y.-H.M., Bellinger, D.C., Coull, B.A., Anderson, S., Barber, R., Wright, R.O., Wright, R.J., 2013. Associations between traffic-related black carbon exposure and attention in a prospective birth cohort of urban children. Environ. Health Perspect. 121, 859–864. https://doi.org/10.1289/ehp.1205940.

Cortez-Lugo, M., Moreno-Macias, H., Holguin-Molina, F., Chow, J.C., Watson, J.G., Gutiérrez-Avedoy, V., Mandujano, F., Hernández-Ávila, M., Romieu, I., 2008. Relationship between indoor, outdoor, and personal fine particle concentrations for individuals with COPD and predictors of indoor-outdoor ratio in Mexico city. J. Expo. Sci. Environ. Epidemiol. 18, 109–115. https://doi.org/10.1038/sj.jes.7500557.

Dewulf, B., Neutens, T., Lefebvre, W., Seynaeve, G., Vanpoucke, C., Beckx, C., Van de Weghe, N., 2016. Dynamic assessment of exposure to air pollution using mobile phone data. Int. J. Health Geogr. 15, 14. https://doi.org/10.1186/s12942-016-0042-z.

Dons, E., Int Panis, L., Van Poppel, M., Theunis, J., Willems, H., Torfs, R., Wets, G., 2011. Impact of time–activity patterns on personal exposure to black carbon. Atmos. Environ. 45, 3594–3602. https://doi.org/10.1016/J.ATMOSENV.2011.03.064.

Du, X., Kong, Q., Ge, W., Zhang, S., Fu, L., 2010. Characterization of personal exposure concentration of fine particles for adults and children exposed to high ambient concentrations in Beijing, China. J. Environ. Sci. 22, 1757–1764. https://doi.org/10.1016/S1001-0742(09)60316-8.

Duan, X., Zhao, X., Wang, B., Chen, Y., Cao, S., 2015. Highlights of the Chinese Exposure Factors Handbook (Adults). Elsevier Inc.

Fan, Z., Pun, V.C., Chen, X.-C., Hong, Q., Tian, L., Ho, S.S.-H., Lee, S.-C., Tse, L.A., Ho, K.-F., 2018. Personal exposure to fine particles (PM2.5) and respiratory inflammation of common residents in Hong Kong. Environ. Res. 164, 24–31. https://doi.org/10.1016/j.envres.2018.02.009.

Fang, S.C., Mehta, A.J., Alexeeff, S.E., Gryparis, A., Coull, B.A., Vokonas, P.S., Christiani, D.C., Schwartz, J.D., 2012. Residential black carbon exposure and circulating markers of systemic inflammation in elderly males: the normative aging study. Environ. Health Perspect. 120, 674–680. https://doi.org/10.1289/ehp.1103982.

Hagler, G.S.W., Yelverton, T.L.B., Vedantham, R., Hansen, A.D.A., Turner, J.R., 2011. Post-processing method to reduce noise while preserving high time resolution in aethalometer real-time black carbon data. Aerosol Air Qual. Res. 11, 539–546. https://doi.org/10.4209/aaqr.2011.05.0055.

Hart, J.E., Grady, S.T., Laden, F., Coull, B.A., Koutrakis, P., Schwartz, J.D., Moy, M.L., Garshick, E., 2018. Effects of indoor and ambient black carbon and PM2.5 on pulmonary function among individuals with COPD. Environ. Health Perspect. 126. https://doi.org/10.1289/EHP3668.

Holliday, K.M., Avery, C.L., Poole, C., McGraw, K., Williams, R., Liao, D., Smith, R.L., Whitsel, E.A., 2014. Estimating personal exposures from ambient air pollution measures: using meta-analysis to assess measurement error. Epidemiology 25, 35–43. https://doi.org/10.1097/EDE.0000000000000006.

Huang, L., Pu, Z., Li, M., Sundell, J., 2015. Characterizing the indoor-outdoor relationship of fine particulate matter in non-heating season for urban residences in Beijing. PLoS One 10. https://doi.org/10.1371/journal.pone.0138559.

Institute for Health Metrics and Evaluation (IHME), 2018. China Profile. IHME, University of Washington, Seattle, WA.

Janssen, N.A.H., Hoek, G., Simic-Lawson, M., Fischer, P., van Bree, L., ten Brink, H., Keuken, M., Atkinson, R.W., Anderson, H.R., Brunekreef, B., Cassee, F.R., 2011. Black carbon as

an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2.5. Environ. Health Perspect. 119, 1691–1699. https://doi.org/10.1289/ehp.1003369.

Johannesson, S., Rappaport, S.M., Sallsten, G., 2011. Variability of environmental exposure to fine particles, black smoke, and trace elements among a Swedish population. J. Expo. Sci. Environ. Epidemiol. 21, 506–514. https://doi.org/10.1038/jes.2011.13.

Kim, D., Sass-Kortsak, A., Purdham, J.T., Dales, R.E., Brook, J.R., 2005. Sources of personal exposure to fine particles in Toronto, Ontario, Canada. J. Air Waste Manag. Assoc. 55, 1134–1146. https://doi.org/10.1080/10473289.2005.10464710.

Kolluru, S.S.R., Patra, A.K., Dubey, R.S., 2019. In-vehicle PM2.5 personal concentrations in winter during long distance road travel in India. Sci. Total Environ. 684, 207–220. https://doi.org/10.1016/j.scitotenv.2019.05.347.

Lanki, T., Ahokas, A., Alm, S., Janssen, N.A.H., Hoek, G., de Hartog, J.J., Brunekreef, B., Pekkanen, J., 2007. Determinants of personal and indoor PM2.5 and absorbance among elderly subjects with coronary heart disease. J. Expo. Sci. Environ. Epidemiol. 17, 124–133. https://doi.org/10.1038/sj.jes.7500470.

Lei, X., Xiu, G., Li, B., Zhang, K., Zhao, M., 2016. Individual exposure of graduate students to PM2.5 and black carbon in Shanghai, China. Environ. Sci. Pollut. Res. 23, 12120–12127. https://doi.org/10.1007/s11356-016-6422-x.

Lei, X.-N., Bian, J.-W., Xiu, G.-L., Hu, X.-F., Gu, X.-S., Bian, Q.-G., 2017. The mobile monitoring of black carbon and its association with roadside data in the Chinese megacity of Shanghai. Environ. Sci. Pollut. Res. 24, 7482–7489. https://doi.org/10.1007/s11356-017-8454-2.

Lin, C., Heal, M.R., Vieno, M., MacKenzie, I.A., Armstrong, B.G., Butland, B.K., Milojevic, A., Chalabi, Z., Atkinson, R.W., Stevenson, D.S., Doherty, R.M., Wilkinson, P., 2017a. Spatiotemporal evaluation of EMEP4UK-WRF v4.3 atmospheric chemistry transport simulations of health-related metrics for NO2, O3, PM10 and PM2.5 for 2001–2010. Geosci. Model Dev. 10, 1767–1787. https://doi.org/10.5194/gmd-10-1767-2017.

Lin, C., Masey, N., Wu, H., Jackson, M., Carruthers, D.J., Reis, S., Doherty, R.M., Beverland, I.J., Heal, M.R., 2017. Practical field calibration of portable monitors for mobile measurements of multiple air pollutants. Atmosphere 8, 231. https://doi.org/10.3390/atmos8120231.

Liu, B., He, M.M., Wu, C., Li, J., Li, Y., Lau, N.T., Yu, J.Z., Lau, A.K.H., Fung, J.C.H., Hoi, K.I., Mok, K.M., Chan, C.K., Li, Y.J., 2019. Potential exposure to fine particulate matter (PM2.5) and black carbon on jogging trails in Macau. Atmos. Environ. 198, 23–33. https://doi.org/10.1016/j.atmosenv.2018.10.024.

Loomis, D., Grosse, Y., Lauby-Secretan, B., Ghissassi, F.E., Bouvard, V., Benbrahim-Tallaa, L., Guha, N., Baan, R., Mattock, H., Straif, K., 2013. The carcinogenicity of outdoor air pollution. Lancet Oncol. 14, 1262–1263. https://doi.org/10.1016/S1470-2045(13)70487-X.

Luben, T.J., Nichols, J.L., Dutton, S.J., Kirrane, E., Owens, E.O., Datko-Williams, L., Madden, M., Sacks, J.D., 2017. A systematic review of cardiovascular emergency department visits, hospital admissions and mortality associated with ambient black carbon. Environ. Int. 107, 154–162. https://doi.org/10.1016/j.envint.2017.07.005.

Meng, Q.Y., Turpin, B.J., Polidori, A., Lee, J.H., Weisel, C., Morandi, M., Colome, S., Stock, T., Winer, A., Zhang, J., 2005. PM2.5 of ambient origin: estimates and exposure errors relevant to PM epidemiology. Environ. Sci. Technol. 39, 5105–5112. https://doi.org/10.1021/es048226f.

Milà, C., Salmon, M., Sanchez, M., Ambrós, A., Bhogadi, S., Sreekanth, V., Nieuwenhuijsen, M., Kinra, S., Marshall, J.D., Tonne, C., 2018. When, where, and what? Characterizing personal PM2.5 exposure in Periurban India by integrating GPS, wearable camera, and ambient and personal monitoring data. Environ. Sci. Technol. 52, 13481–13490. https://doi.org/10.1021/acs.est.8b03075.

Ministry of Ecology and Environment of the People's Republic of China, 2012. Ambient Air Quality Standards (GB3095–2012). China Environmental Science Press.

Montagne, D., Hoek, G., Nieuwenhuijsen, M., Lanki, T., Siponen, T., Portella, M., Meliefste, K., Brunekreef, B., 2014. Temporal associations of ambient PM2.5 elemental concentrations with indoor and personal concentrations. Atmos. Environ. 86, 203–211. https://doi.org/10.1016/j.atmosenv.2013.12.021.

National Bureau of Statistics, 2018. China Statistical Yearbook. China Statistics Press, Beijing.

Patel, M.M., Chillrud, S.N., Correa, J.C., Feinberg, M., Hazi, Y., Deepti, K.C., Prakash, S., Ross, J.M., Levy, D., Kinney, P.L., 2009. Spatial and temporal variations in traffic-related particulate matter at New York City high schools. Atmos. Environ. 43, 4975–4981. https://doi.org/10.1016/j.atmosenv.2009.07.004.

Qiu, Z., Wang, W., Zheng, J., Lv, H., 2019. Exposure assessment of cyclists to UFP and PM on urban routes in Xi'an, China. Environ. Pollut. 250, 241–250. https://doi.org/10.1016/j.envpol.2019.03.129.

Sarnat, J.A., Wilson, W.E., Strand, M., Brook, J., Wyzga, R., Lumley, T., 2007. Panel discussion review: session 1 — exposure assessment and related errors in air pollution epidemiologic studies. J. Expo. Sci. Environ. Epidemiol. 17, S75–S82. https://doi.org/10.1038/sj.jes.7500621.

Schaap, M., Denier van der Gon, H.A.C., 2007. On the variability of black smoke and carbonaceous aerosols in the Netherlands. Atmos. Environ. 41, 5908–5920. https://doi.org/10.1016/j.atmosenv.2007.03.042.

Semmler, M., Seitz, J., Erbe, F., Mayer, P., Heyder, J., Oberdörster, G., Kreyling, W.G., 2004. Long-term clearance kinetics of inhaled ultrafine insoluble iridium particles from the rat lung, including transient translocation into secondary organs. Inhal. Toxicol. 16, 453–459. https://doi.org/10.1080/08958370490439650.

Shang, J., Khuzestani, R.B., Tian, J., Schauer, J.J., Hua, J., Zhang, Y., Cai, T., Fang, D., An, J., Zhang, Y., 2019. Chemical characterization and source apportionment of PM2.5 personal exposure of two cohorts living in urban and suburban Beijing. Environ. Pollut. 246, 225–236. https://doi.org/10.1016/j.envpol.2018.11.076.

Shen, J., Gao, Z., 2019. Commuter exposure to particulate matters in four common transportation modes in Nanjing. Build. Environ. 156, 156–170. https://doi.org/10.1016/j.buildenv.2019.04.018.

Shi, S., Chen, C., Zhao, B., 2015. Air infiltration rate distributions of residences in Beijing. Build. Environ. 92, 528–537. https://doi.org/10.1016/j.buildenv.2015.05.027.

Shi, Z., Vu, T., Kotthaus, S., Harrison, R.M., Grimmond, S., Yue, S., Zhu, T., Lee, J., Han, Y., Demuzere, M., Dunmore, R.E., Ren, L., Liu, D., Wang, Y., Wild, O., Allan, J., Acton, W.J., Barlow, J., Barratt, B., Beddows, D., Bloss, W.J., Calzolai, G., Carruthers, D., Carslaw, D.C., Chan, Q., Chatzidiakou, L., Chen, Y., Crilley, L., Coe, H., Dai, T., Doherty, R., Duan, F., Fu, P., Ge, B., Ge, M., Guan, D., Hamilton, J.F., He, K., Heal, M., Heard, D., Hewitt, C.N., Hollaway, M., Hu, M., Ji, D., Jiang, X., Jones, R., Kalberer, M., Kelly, F.J., Kramer, L., Langford, B., Lin, C., Lewis, A.C., Li, J., Li, W., Liu, H., Liu, J., Loh, M., Lu, K., Lucarelli, F., Mann, G., McFiggans, G., Miller, M.R., Mills, G., Monk, P., Nemitz, E., O'Connor, F., Ouyang, B., Palmer, P.I., Percival, C., Popoola, O., Reeves, C., Rickard, A.R., Shao, L., Shi, G., Spracklen, D., Stevenson, D., Sun, Y., Sun, Z., Tao, S., Tong, S., Wang, Q., Wang, W., Wang, Xinming, Wang, Xuejun, Wang, Z., Wei, L., Whalley, L., Wu, X., Wu, Z., Xie, P., Yang, F., Zhang, Q., Zhang, Yanli, Zhang, Yuanhang, Zheng, M., 2019. Introduction to the special issue "in-depth study of air pollution sources and processes within Beijing and its surrounding region (APHH-Beijing)". Atmos. Chem. Phys. 19, 7519–7546. https://doi.org/10.5194/acp-19-7519-2019.

Spira-Cohen, A., Chen, L.C., Kendall, M., Lall, R., Thurston, G.D., 2011. Personal exposures to traffic-related air pollution and acute respiratory health among bronx schoolchildren with asthma. Environ. Health Perspect. 119, 559–565. https://doi.org/10.1289/ehp.1002653.

UN Environment, 2019. A Review of 20 Years' Air Pollution Control in Beijing. United Nations Environment Programme, Nairobi.

von Schneidemesser, E., Steinmar, K., Weatherhead, E.C., Bonn, B., Gerwig, H., Quedenau, J., 2019. Air pollution at human scales in an urban environment: impact of local environment and vehicles on particle number concentrations. Sci. Total Environ. 688, 691–700. https://doi.org/10.1016/j.scitotenv.2019.06.309.

Vu, Tuan V., Delgado-Saborit, Juana Maria, Harrison, Roy M., 2015. Review: particle pumber size distributions from seven major sources and implications for source apportionment studies. Atmos. Environ. 122, 114–132. https://doi.org/10.1016/j.atmosenv.2015.09.027.

Wang, X., 2018. 北京市空气质量历史数据. 中国空气质量历史数据 | 中国气象历史数据 | 北京市空气质量历史数据. URL. https://quotsoft.net/air/.

Weichenthal, S., 2012. Selected physiological effects of ultrafine particles in acute cardiovascular morbidity. Environ. Res. 115, 26–36. https://doi.org/10.1016/j.envres.2012.03.001.

Williams, R., Suggs, J., Creason, J., Rodes, C., Lawless, P., Kwok, R., Zweidinger, R., Sheldon, L., 2000. The 1998 Baltimore Particulate Matter Epidemiology–Exposure Study: Part 2. Personal exposure assessment associated with an elderly study population. J. Expo. Sci. Environ. Epidemiol. 10, 533–543. https://doi.org/10.1038/sj.jea.7500108.

World Health Organization, 2006. Air Quality Guidelines. Global Update 2005. Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide. WHO Press, Geneva.

World Health Organization, 2018. Mortality and burden of disease from ambient air pollution [WWW document]. Global Health Observatory (GHO) data. URL. https://apps.who.int/gho/data/node.main.BODAMBIENTAIRDTHS?lang=en.

World Health Organization Regional Office for Europe, 2013. Review of Evidence on Health Aspects of Air Pollution – REVIHAAP Project: Technical Report. WHO Regional Office for Europe, Copenhagen.

Zhao, X., Sun, Z., Ruan, Y., Yan, J., Mukherjee, B., Yang, F., Duan, F., Sun, L., Liang, R., Lian, H., Zhang, S., Fang, Q., Gu, D., Brook, J.R., Sun, Q., Brook, R.D., Rajagopalan, S., Fan, Z., 2014. Personal black carbon exposure influences ambulatory blood pressure: air pollution and cardiometabolic disease (AIRCMD-China) study. Hypertension 63, 871–877. https://doi.org/10.1161/HYPERTENSIONAHA.113.02588.