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Characteristics of school children's personal exposure to ultrafine particles in Heshan, Pearl River Delta, China – A pilot study

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ABSTRACT

Background: There is a significant lack of scientific knowledge on population exposure to ultrafine particles (UFP) in China to date. This paper quantifies and characterises school children's personal UFP exposure and exposure intensity against their indoor and outdoor activities during a school day (home, school and commuting) in the city of Heshan within the Pearl River Delta (PRD) region, southern China.

Methods: Time-series of UFP number concentrations and average size were measured over 24 h for 24 children (9–13 years old), using personal monitors over two weeks in April 2016. Time-activity diaries and a questionnaire on the general home environment and potential sources of particles at home were also collected for each participating child. The analysis included concurrently measured size distributions of ambient UFP at a nearby fixed reference site (Heshan Supersite).

Results: Hourly average UFP concentrations exhibited three peaks in the morning, midday and evening. Time spent indoors at home was found to have the highest average exposure (1.26×10^4 cm^{-3} during sleeping) and exposure intensity (2.41). While there is always infiltration of outdoor particles indoors (from nearby traffic and general urban background sources), indoor exposure at home was significantly higher than outdoor exposure. Based on the collected questionnaire data, this was considered to be driven predominantly by adults smoking and the use of mosquito repellent incense during the night. Outdoor activities at school were associated with the lowest average exposure (6.87×10^2 cm^{-3}) and exposure intensity (0.52).

Conclusion: Despite the small sample size, this study characterised, for the first time, children's personal UFP exposure in a city downwind of major pollution sources of the PRD region in China. Particularly, the results highlighted the impact of smoking at home on children's exposure. While the study could not apportion the specific contributions of second hand-smoking and mosquito coil burning, considering the prevalence of smokers among the parents who smoke at home, smoking is a very significant factor. Exposure to second-hand smoke is avoidable, and these findings point out to the crucial role of government authorities and public health educators in engaging with the community on the role of air quality on health, and the severity of the impact of second-hand smoke on children's health.

Abbreviations: NT, Nano Tracers; PNC, ultrafine particles number concentration; PRD region, Pearl River Delta region; UFP, ultrafine particles; PS, particles sizes; SI, Supporting Information

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1. Introduction

China has become known for its serious air pollution problem as a result of its rapid growth in economic activity, industry, urbanisation, population and transportation activity. Environmental pollution in general, and air pollution specifically, is not only a local issue but also a global challenge due to the complex dynamics of pollution dispersion and transport over short and long distances. Air pollution has been a major public health challenge in China and neighbouring countries (Guan et al., 2016), with high concentrations of particulate matter, black carbon, nitrogen oxides and ozone frequently observed in most megacities. Air pollution in China was reported to be mainly associated with residential and commercial energy use as well as vehicular and transport emissions and was ranked first in affecting global premature mortality attributable to ambient air pollution in 2010 (Lelieveld et al., 2015).

It is well established that among air pollutants, ambient fine particulate matter ($PM_{2.5}$, mass concentration of particles with an aerodynamic diameters less than or equal to 2.5 μm) is one of the leading environmental risk factors in the global burden of disease (GBD 2015 Risk Factors Collaborators, 2016). However, the number concentration of ultrafine particles (UFP, particles ≤ 100 nm) is an important metric for health impact assessment, as UFP are more likely to enter and deposit in the deep regions of the lung (Löndahl et al., 2014); hence be transported into the bloodstream and potentially cause or aggravate health problems such as respiratory and cardiovascular diseases. UFP containing metals also have the potential of directly translocating to the brain along the olfactory nerves, without entering the lung, thereby exerting neurotoxicity (Sunyer, 2008). Previous studies have shown that children attending schools with higher UFP or their component exposure had a smaller improvement in cognitive development (Sunyer et al., 2015). Children are particularly vulnerable to both respiratory effects (e.g. acute respiratory infections and asthma) and extra-pulmonary effects (e.g. impaired cognitive development) of particle pollution, due to their greater ventilation per kilogram body weight, dynamic developmental physiology as well as patterns and degree of their exposure (UNICEF, 2016). While there has been growing interest in assessing the health impacts of airborne particulate matter on children (Clifford et al., 2018; Rizza et al., 2018; Evans et al., 2014; Sunyer et al., 2015; Li et al., 2016), there is still a lack of scientific knowledge about UFP exposure, especially in indoor microenvironments (Heinzerling et al., 2016).

Clifford et al. (2018) found positive associations between systemic inflammation in children aged 8 to 11 years, and exposure to low levels of ambient UFP (median values between $3 \times 10^3\,cm^{-3}$ and $1.4 \times 10^4\,cm^{-3}$) in Brisbane, Australia, where air quality is generally good. Considering such emerging evidence, personal exposure assessment to UFP becomes necessary to fully understand and mitigate the health impact of particulate matter and to complement the findings of previous studies that used ambient concentration as a surrogate for personal exposure.

People spend most of their time indoors or at home, where the main sources of UFP, $PM_{2.5}$ and air pollution in general include cooking, cleaning activities, indoor combustion (e.g. candles, fireplaces, indoor heating devices, mosquito repellents), use of printers, cigarette smoking, and air pollution infiltration into the building. Ambient and household air pollution, smoking and exposure to environmental tobacco smoke and second-hand smoking are some of the leading environmental risk factors in the global burden of disease assessment (https://www.who.int/phe/health_topics/outdoorair/databases/en/). Second-hand smoke is especially relevant in China, which has one of the highest proportion of children aged younger than 15 years being exposed to second-hand smoking at home (Mbulo et al., 2016), particularly children of low socio-economic status (Yao et al., 2012).

Personal monitoring is the best method for assessing an individual's indoor and outdoor exposure and capturing fine-resolution variations in the concentrations. Personal exposure is highly variable and driven by various built and natural environmental, demographic and socio-economic factors. Several studies have been conducted on characterising school children's exposure to UFP number concentrations (PNC) in both developed and developing countries (Buonanno et al., 2012; Mazaheri et al., 2014; Mazaheri et al., 2016; Wangchuk et al., 2015). However, there is no published literature on children's personal UFP exposure in China to date.

This paper characterises school children's personal UFP exposure in Heshan, a county-level city affiliated with the city of Jiangmen. Heshan is a small manufacturing city located in the Pearl River Delta (PRD) region of Guangdong Province in China. Analysis includes assessment of quantified UFP personal exposure against children's daily activities and general school and non-school environments, namely home and commuting.

2. Materials and methods

2.1. Study area

PRD is the most densely urbanised region in the world in both size and population, and is the most economically dynamic region of China (World Bank Group, 2015). PRD has two industrial clusters, which are the major air pollution sources in the region: the Guangzhou-Foshan area and the Dongguan-Shenzhen area. Heshan is located downwind of these industrial clusters, approximately 80 km from Guangzhou and 50 km from Foshan. There are no major local industrial sources of emissions within the city of Heshan itself, and it is mainly affected by long-distance transport of air pollution and local traffic emissions. For this reason, the Chinese government established the Guangdong Atmospheric Supersite, China's first regional atmospheric supersite, in Heshan in 2011 to monitor and assess regional air pollution and photochemistry.

Motorcycles are the main mode of transportation in Heshan (Heshan Archives Bureau and Heshan Yearbook Editorial Department, 2017, in Chinese). Guangdong province is one of the pilot provinces for applying the National V standard, a central government strategy for improving environment quality, which requires sulphur content in fuel to be $<$ 10 ppm. Heshan has applied the standard for gasoline and diesel since April 2016 (during our study period). As Heshan serves as a transportation hub for the PRD region, significant numbers of cars and cargo trucks from other cities or provinces, which may not comply with the standard, pass through the city every day. These factors add to the complexity of air pollution situation in Heshan.

2.2. Study design

This study was conducted as part of a larger panel study, which aimed to assess the relationships between exposure to particulate matter and lung function, oxidative damage to DNA, endothelial function, and blood pressure in children. The panel study included three observation periods in 2016; consisting of the regional haze period in January, clean period in April and complex air pollution period in October, which were selected based on the typical characteristics of air pollution in the PRD region (Zhong et al., 2013). At the beginning of the panel study, questionnaires were distributed to 400 schoolchildren in grades 2 to 5 in a selected primary school to obtain data on personal information, daily activities, indoor environment, health status and medical history. Among the 256 schoolchildren who returned the questionnaires, we randomly recruited 60 healthy subjects (30 boys, 30 girls) with no personal or family history of clinically diagnosed chronic respiratory diseases. Each observation period was designed to last for two weeks including 10 weekday observations per child. Our earlier panel study has provided proof of concept of the method (Lin et al., 2011, 2015). Personal exposure monitoring was not originally included in the study and was undertaken as part of the authors' collaborations

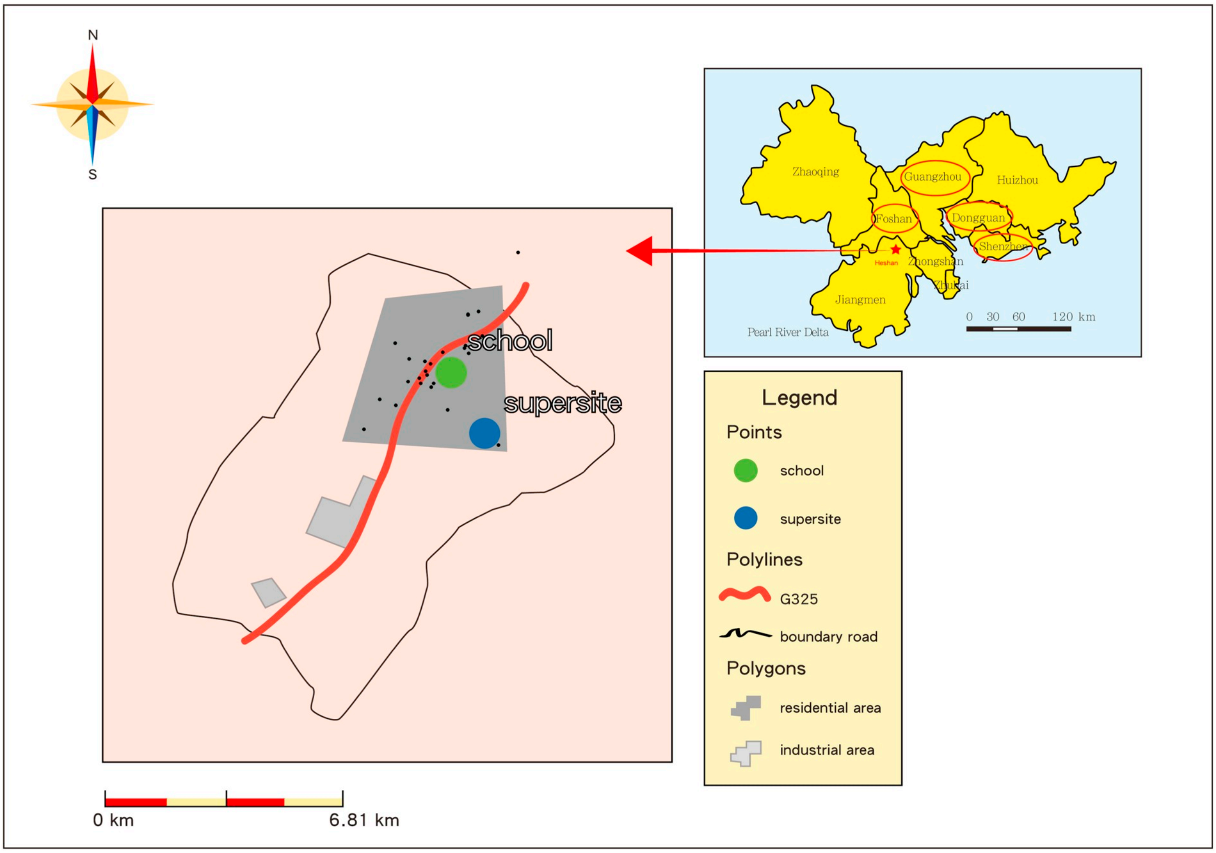

Fig. 1. Map of the Pearl River Delta (PRD) showing the study area and surrounding air pollution sources (G325 indicates a national highway numbered 325; the boundary road on the map represents a primary road in Taoyuan Town, Heshan; black dots indicate a residential districts of the participating children).

through Australia-China Centre for Air Quality Science and Management only during the clean period observation in April 2016 due to restrictions in availability of UFP personal monitors.

There are eight primary schools in Heshan, and selection of the participating school was based on the distance to the Heshan Supersite. One school was selected for this study, which is located within the main residential area of Heshan and is the closest school to the Heshan Supersite (1.2 km). All the classrooms in the school were naturally ventilated, used blackboard and chalk for teaching, and had no heaters or printers operating. School hours were from 08:00 to 17:00, with a lunch break from 11:00 to 13:30.

All the 9 to 13 years old healthy children were invited to participate in this study, regardless of their socioeconomic conditions. Children with personal or family history of clinically diagnosed chronic respiratory disease or chronic inflammation were excluded. 24 children (13 boys and 11 girls) participated following their parents'/guardians' written consent and completing the study questionnaire (Ethics clearance: 2015[010], approved by the Institution Review Board of School of Public Health, Sun Yat-sen University). All participating children's homes were within 5 km of the school. Fig. 1 shows the location of the school, the Heshan Supersite and the surrounding industrial area.

The size distribution of ambient UFP within the 14–700 nm size range were obtained from the Heshan Supersite for the duration of the study. These measurements were conducted every five minutes using a scanning mobility particle sizer (SMPS 3936, TSI, USA).

2.3. Instruments

This study used three Philips Aerasense NanoTracers (NT) to measure time-series of UFP number concentrations and average particle size at a personal level every 10 s in real-time. NT personal monitors measure particles in the 10–300 nm size range for concentrations up to $1 \times 10^6\ cm^{-3}$. The NTs were calibrated by the manufacturer prior to the measurements and were also tested against TSI model 3787 condensation particle counter ensure consistency between the NTs readings at the International Laboratory for Air Quality and Health, Queensland University of Technology, Australia. Details on the NT specification and limitations of the NT is outside the scope of this study and have been previously discussed by Marra et al. (2010) and Mazaheri et al. (2014).

2.4. Data collection

Data collection for this study consisted of a take-home questionnaire on the general home environment, including potential sources of particles at home (smoking at home, burning candles, mosquito repellent incense); types of ventilation and stovetop (electric or gas); measured personal UFP number concentrations and average size over a 24-hour period; a complete activity diary during the personal exposure monitoring; and GPS data for the child's movement during the 24-hour period.

The collected GPS data were used to check the accuracy of the time-activity diaries in relation to being indoors and outdoors.

Time-series of personal UFP exposure were measured by each participating child carrying an NT for 24 h. Data analysis was performed on the 24-hour time-series of UFP number concentrations at the personal level and the daily activity diaries that were collected from the participating children. An activity diary was completed by the children to record each microenvironment/activity that they spent time in and its duration. This included information about the time spent at school, home, and commuting, and their mode of transport. In addition, the participating children were asked to specify the time that they spent indoors and outdoors along with the time spent eating and sleeping at home. The children were instructed to wear the NT and keep it in close proximity at all times; e.g. when asleep or at home. The NT was to be charged during the time spent in the classroom and at home.

2.5. Quantification of children's personal UFP exposure

Analysis of the completed activity diaries confirmed that the participating children's time on the monitoring day was mainly split between home, school, and commuting microenvironments. The home microenvironment was further split into home-indoors, home-eating-cooking, home-sleeping and home-outdoors. Although eating, cooking and sleeping took place indoors at home, the home-indoors microenvironment excluded these activities, and these were analysed as separate microenvironments. Schooling hours were broken into school-indoors and school-outdoors. Other-indoors and other-outdoors were defined as activities or microenvironments other than these three identified categories or was unknown.

Personal UFP exposure during any given activity or microenvironment, k, was defined as:

$$\text{Personal UFP exposure}_k\,(\text{cm}^{-3}\text{s}) = \sum_{M(i)=k} \overline{PNC}_i\ \Delta t_i \tag{1}$$

where $\overline{PNC}_i$ is the average UFP number concentration for activity period i in microenvironment $M(i) = k$, having duration Δt_i. Exposure intensity was defined as the proportion of daily exposure received in a given microenvironment as a fraction of the proportion of the day spent in that microenvironment:

$$\text{Personal UFP exposure intensity}_k = \frac{\frac{\sum_{M(i)=k} \overline{PNC}_i\ \Delta t_i}{\Delta t_{24}\overline{PNC}_{24}}}{\frac{\sum_{M(i)=k}\Delta t_i}{\Delta t_{24}}} = \frac{\sum_{M(i)=k} \overline{PNC}_i\ \Delta t_i}{\overline{PNC}_{24}\ \Delta t_k} \tag{2}$$

where Δt_k is the time spent in microenvironment k and $\overline{PNC}_{24}$ is the daily average PNC encountered by the child. Personal exposure intensity gives a dimensionless value and is a better indication of how relatively polluted a microenvironment is for a given child.

3. Results

(11 female and 13 male students participated in this study).

No issues were reported during the data collection, and a small amount of missing data was due to the NT not being charged or an incomplete activity diary. Exposure intensity analysis was performed when at least 23 h of data was available.

3.1. Diurnal variation of ambient particles

Fig. 2 presents diurnal variations in the measured ambient particle number size distributions at the Heshan Supersite during the study period (18–29 April 2016). Generally, the results show that UFP with particle sizes of < 50 nm and 50–100 nm typically had the highest concentrations around midday, probably as a result of new particle formation due to photochemical activity, which we have previously observed in the PRD region (Yue et al., 2016). High concentrations of particles of size 100–200 nm were observed around noon driven by new particle formation events, and/or during the evening likely caused by the continuous growth of UFP. The particle number concentrations in Heshan were dominated by the ranges 50–100 nm and 100–200 nm, with daily average number concentrations of $1.9\times 10^3 \pm 1.1\times 10^3$ cm^{-3} and $2.0\times 10^3 \pm 1.0\times 10^3$ cm^{-3}, respectively. Throughout the day the number concentration of particles < 50 nm ($0.7\times 10^3 \pm 0.4\times 10^3$ cm^{-3}) and 200–300 nm ($0.6\times 10^3 \pm 0.2\times 10^3$ cm^{-3}) were about three times lower than the above ranges.

3.2. Daily time-activity patterns and home characteristics

Participating children spent 95% of their day indoors. Natural ventilation (open/close windows) and gas cooktops were used in the homes. The common indoor sources of particles at home were identified as smoking (85% of the children had a smoker parent or lived with a smoker) and use of mosquito repellent incense (used at night in 69% of the homes). Printing at home was reported by two children (8%) during the early afternoon. 25% of children either walked or rode a bicycle to commute between home and school, 21% were driven on a motorbike, 17% were driven in a private car, and 13% caught a bus. A summary of the collected time-activity and questionnaire data and percentages of the average times spent for each of the identified activities at each microenvironment over all the participating children are provided in the Supporting Information (SI) document (Tables S1 and S2).

3.3. Variation in UFP size and number concentrations

Hourly averages of the UFP number concentrations (PNC) were derived from the measured time-series for each child. Fig. 3 presents time-series of hourly averaged PNCs over all the participating children (solid blue line) as well as the individual participants' averages (light grey lines).

As expected, a large variation in hourly PNC was observed both for each child and among children. Generally, three peaks were observed in the overall average daily PNC cycle; morning, midday and evening. The morning peak corresponds to home-indoor activities and morning eating time, and the midday peak, which is less pronounced than the

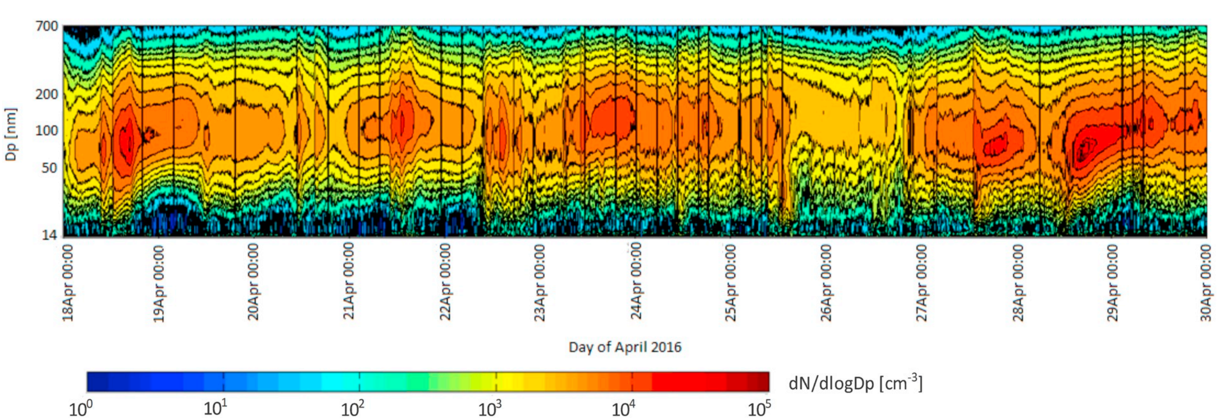

Fig. 2. Time-series of the particle number size distributions during the study period. The black vertical lines show when the instrument's silica desiccant was replaced.

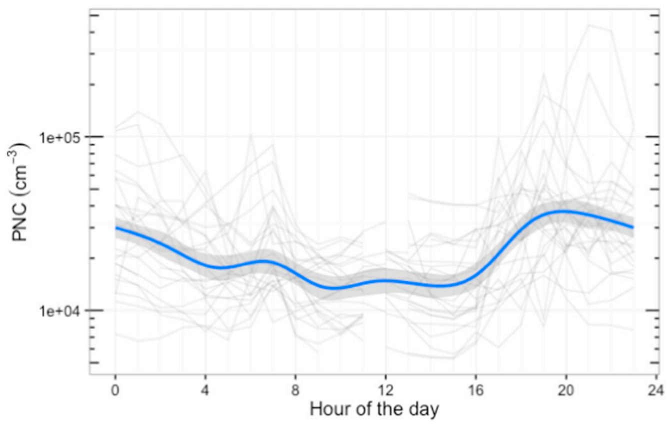

Fig. 3. Diurnal variations of the measured hourly averaged PNC (cm^{-3}) over all participating children. The shaded area represents 95% confidence intervals. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

morning peak, corresponds to the lunch break at school. The evening peak is most pronounced, where PNC starts to rise at around 16:00, coinciding with commuting times from school to home and then the time spent at home, and peaks around 19:00 after cooking and eating (typically 17:30–19:00).

Mean PNC at home ($3.5 \times 10^4 \pm 1.4 \times 10^2\,cm^{-3}$; median: $3.0 \times 10^4\,cm^{-3}$) was higher than at school ($1.7 \times 10^4 \pm 6.6 \times 10^1\,cm^{-3}$; median: $3.0 \times 10^4\,cm^{-3}$) and during commuting ($2.9 \times 10^4 \pm 5.5 \times 10^2\,cm^{-3}$; medina: $2.0 \times 10^4\,cm^{-3}$). Mean concentrations during eating and sleeping hours (typically 21:00–06:30) were $3.6 \times 10^4 \pm 5.8 \times 10^2\,cm^{-3}$ (median: $2.4 \times 10^4\,cm^{-3}$) and $3.3 \times 10^4 \pm 1.8 \times 10^2\,cm^{-3}$ (median: $2.9 \times 10^4\,cm^{-3}$), respectively. The lowest concentrations were during home-outdoors followed by time spent at school over all the participating children. The highest concentrations were recorded at indoor microenvironments outside school hours, namely other-indoors and home-indoors. Comparison of the hourly averaged PNC that were concurrently measured for ambient concentrations using SMPS at the supersite and through personal monitoring using NTs showed a generally similar trend in PNC variation between 21:00 and 01:00, as well as during day-time and schooling hours. Ambient PNC stayed relatively constant between 01:00 and 08:00, when children were at home (mostly sleeping hours), whereas the personal PNC had a generally decreasing trend. Increased personal PNC during 17:00 to 19:00 is attributable to home and indoor activities such as home-eating-cooking and indoor sources (e.g. gas cooking, environmental tobacco smoke). Over 24 h, hourly average personal PNC were lower than ambient PNC by $5.18 \times 10^4\,cm^{-3}$ (65%) (Fig. S1). These results highlight that fix site measurements were not representative of personal exposure, which are strongly driven by indoor sources and lifestyle factors.

The measured UFP sizes (PS) using the NTs were generally consistent with the ambient particle size distributions measured at the Heshan Supersite (Fig. 2). The average PS during time spent at home was 104 nm, ranging from 70 nm to 106 nm, which was in the lower range of corresponding ambient particle sizes. PS during school hours and commuting ranged from 51 nm to 75 nm and was in the same range of ambient particles sizes during corresponding hours. Diurnal variations in the hourly average PS and summary statistics of the average PNC and PS for each activity or microenvironment over all participants are available in the SI document (Figs. S1 and S2 and Table S3). We consider investigation of the relationship between PNC and PS outside the scope of this paper because data on sources (traffic counts, hours of operation of industry etc.) were not available.

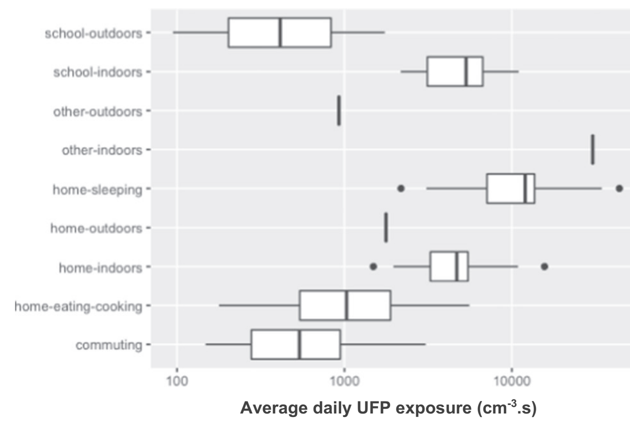

Fig. 4. Box plot of children's average personal UFP exposure (cm^{-3}).

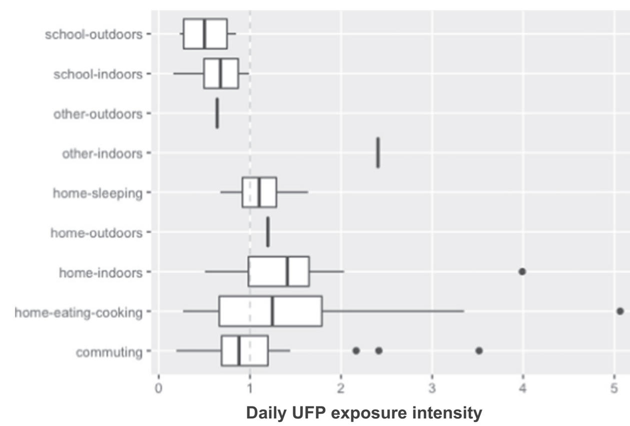

Fig. 5. Box plot of children's average personal UFP exposure intensity.

3.4. Children's personal UFP exposure and exposure intensity

The calculated personal UFP exposure and exposure intensity for each of the identified activities and microenvironments are presented in Figs. 4 and 5. The discussion does not include time spent at home-outdoors, other-indoors and other-outdoors, as only one of the participating children included these microenvironments in their time-activity diary. Summary statistics of the average exposure and exposure intensity or each activity or microenvironment over all participants are available in the SI document (Table S4).

Overall, the highest exposure and exposure intensity were found to occur during times spent indoors and at home. Natural ventilation was used in all the indoor microenvironments, which made the infiltration of outdoor particles indoors a natural process. Vehicular traffic was the immediate source of UFP in this study. NT's particle size detection range of 10–300 nm overlaps with traffic related particulate matter emissions, which are mostly in the UFP range (Morawska et al., 2008). Therefore, traffic related UFP emissions were considered to directly influence the measured concentrations and in turn exposures.

UFP exposure was derived from the PNC and the duration of exposure (Eq. (1)). On average, participating children spent 9 h of the day sleeping, which could explain the highest exposure occurring during sleeping hours ($1.26 \times 10^4 \pm 1.95 \times 10^3\,cm^{-3}$). Time-activity data showed that, apart from air pollution infiltration, sources of UFP during sleeping hours were driven by smoking at home (reported in 20 of the participating households) and the use of mosquito repellent incense during the night (in 15 of the participating households). We could not separate the contributions of smoking from those of mosquito coil burning, however, judging by the higher prevalence of smoking than mosquito coil burning, the impact of smoking is very significant. The

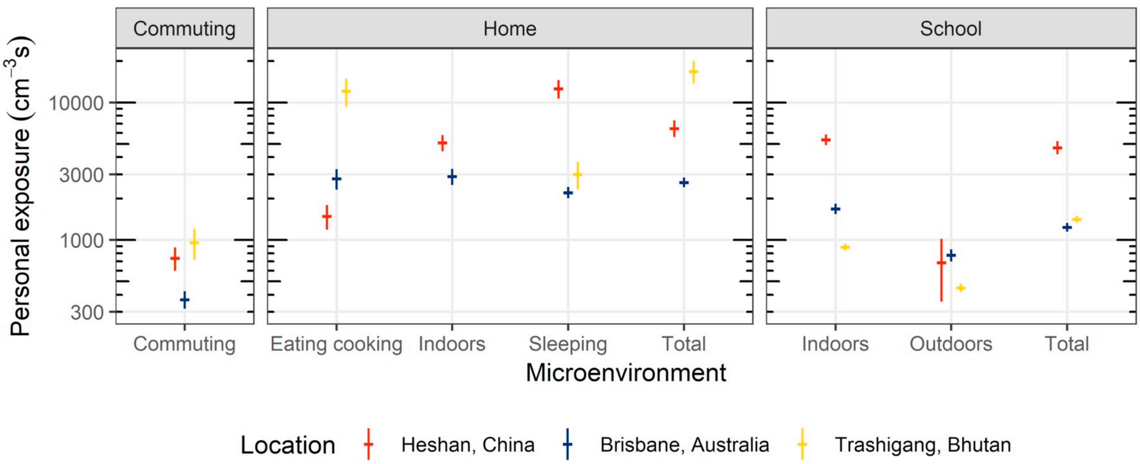

Fig. 6. Comparison of children's average personal UFP exposure in three different study areas.

coil burning is conducted as prevention against mosquito borne diseases, and it would be a separate discussion whether this is the best preventive measure, considering that it is associated with prolonged exposures to UFP particles. The lowest exposure occurred during outdoor activities at school ($6.87 \times 10^2 \pm 3.31 \times 10^2\,cm^{-3}$) and while commuting ($7.40 \times 10^2 \pm 1.44 \times 10^2\,cm^{-3}$), comprising 1% and 3% of the children's day respectively.

The highest exposure intensity occurred during home-indoors (14% of the day) and home-eating-cooking (4% of the day) times at home, and the lowest exposure intensity occurred during school-outdoors (1% of the day). The contribution of home-eating-cooking was highest even though it comprised only a small portion of the day, which highlights the impact of using gas cooktops (82% of monitored households) on indoor exposure and indoor air quality in general. Opening/closing windows was the most commonly used ventilation method at home (96% of the households). Since home-indoors excludes other indoor categories of home-eating-cooking and home-sleeping, high home-indoors exposure and exposure intensity indicate the significant impact of indoor sources or activities when children were home, (such as being exposed to cigarette smoking) above UFP infiltration from outside.

Commuting exposure intensity was calculated for each of the different modes of transport used by the participating children. Although the children spent generally the same amount of time commuting, regardless of the mode of transport (Tables S1 and S2), the results showed that the intensity was highest for children who were driven by a private car, followed by those who walked, and the intensity was lowest for children who rode a bicycle or caught a bus (Fig. S3). It is noted that children's commuting times were during peak traffic time when roads are at their most congested and the traffic flow is slow. Additionally, the vehicle fleet in Heshan is composed of old, fuel-inefficient cars without air-conditioning. This could explain why the exposure intensity for children driven by car was higher than for other modes of transport. Nevertheless, the breakdown of commuting methods is only indicative because of the very small sample size in this study and the high level of uncertainty in the reported commuting times. Because students do not use all modes of transport, comparison across modes with only a small number of students may be more heavily influenced by individual-level effects than commuter mode effects.

4. Discussion

Out of the three main identified categories of home, school and commuting, the results demonstrated that the times spent at home-indoors and in the classroom (school-indoors) contributed the most to children's total daily UFP exposure in Heshan. This is generally consistent with previous similar studies conducted in Brisbane, Australia (a city located in a developed country) (Mazaheri et al., 2014) and Trashigang District in Bhutan (a rural area in a developing country) (Wangchuk et al., 2015) (Fig. 6 and Table S5). The differences between the three study areas in the calculated personal exposure at home, school and while commuting are directly influenced by the time spent in each microenvironment. There are major differences between the three study settings, including urban characteristics, school schedules, housing environment and socioeconomic status. Brisbane and Heshan have similar sources of ambient UFP (traffic emissions and distant industries) but different urban characteristics (e.g. population and traffic density; vehicular fuel, fleet type and age; socioeconomic status). Biomass burning is the main source of indoor and ambient UFP in rural Bhutan, with significantly lower population and traffic density and socioeconomic status than Brisbane and Heshan. Children's exposure in the three main microenvironments is compared below.

Home: Bhutanese children were exposed to significantly higher UFP during home-eating-cooking than children in the two other cities, due to domestic use of biomass burning, such as for cooking, cattle feed preparation, distilling local liquor, and heating. Due to lack of data, home-outdoor exposures were not compared between the three study areas. Home-indoors exposure was significantly higher in Heshan than in Brisbane, which is attributed to UFP infiltration (outdoor PNC of above $10^4\,cm^{-3}$, as presented in Fig. 2) and adults smoking at home. Home-indoors exposure was not specifically reported in the study conducted in Bhutan. Sleeping exposure was considerably higher in Heshan (infiltration and mosquito repellent) than in Bhutan (burning candles associated with religious ceremonies) and was lowest in Brisbane (infiltration).

School: Students in Heshan spent longer inside classrooms than students in Brisbane and Trashigang District in Bhutan (8.5 h versus about 5 of the 24 h). Comparison of the available data in the three study areas showed that exposure in classrooms was highest in Heshan and lowest in Bhutan. This is explained by the school settings; the school in Heshan was located in a high-density area and close to busy roads and local businesses, whereas the schools in Bhutan were in a rather remote area with no busy roads, residences or businesses in close proximity.

Commuting: Commuting exposure was highest in Bhutan and lowest in Brisbane. Commuting exposure in Heshan and Brisbane was driven by road traffic, and the results reflect the influence of fleet and fuel types and traffic conditions on exposure. Children's commuting exposure in Bhutan and Heshan was in the same order of magnitude and almost twice as high as Brisbane, although the sources of exposure were completely different. Road traffic emissions in the studied Bhutanese villages were negligible and commuting exposure was driven by biomass burning, as the children walked through the village neighbourhood at the time of cooking with woodfire.

The main limitations of this pilot study were the small sample size and short monitoring period in assessing personal UFP exposure. Although this study did not present seasonal variation in UFP personal exposures, it was the first of its kind in China. There is no published literature on children's personal UFP exposure in China to date and the results of this study provide a quantitative insight into children's personal UFP exposure in a small and low socio-economic city located downwind from the intensive industrial PRD in China.

5. Conclusion

This pilot study provided a quantitative assessment of school children's personal exposure to UFP in terms of exposure and exposure intensity during a school day in Heshan county, China. The results showed significant differences between the concurrently measured PNC using fixed-site (Heshan supersite) and personal monitors, which demonstrated that fixed-site monitoring does not provide a realistic estimate for personal exposures. The outcomes point to the significance of home exposure and impact of indoor activities on children's exposure in Heshan, including use of mosquito repellent incense and smoking at home. This work highlights the crucial role of government authorities and public health educators in engaging with the community in relation to the sources of air pollution, and the extent and magnitude of the impact of smoking emissions on air quality, especially within indoor microenvironments.

It should be noted that this study does not assess any likelihood of adverse health impacts associated with UFP exposure. The results can guide future directions in assessing population exposure in China and developing air pollution mitigation strategies, especially in relation to indoor air quality.

Declaration of competing interest

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

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Appendix A. Supplementary data

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