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Exposure to pollutants – contribution of daily activities

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Abstract

Despite well-documented association between the presence of particulate matter (PM) and health outcomes, detailed measurement of indoor concentration and its effects has been rare due to the high cost of data collection and the limited number of policy interventions that can be devised. In this research, both indoor and outdoor environments were assessed, along with their relative contribution to exposure. The analysis confirms a substantial intra-individual variability and the importance of a detailed analysis of exposure, given that different concentrations may be found even in the same building. This means that population-based exposures using concentrations from outdoors environmental monitoring stations are not reflective of individual exposures.

1. Introduction

Urban air pollution is a major focus of public health concern and regulatory activity (World Health Organization WHO, 2002; Khreis *et al*., 2017). There is substantive empirical evidence illustrating the health impacts of ambient air pollution and its relations with respiratory and cardiovascular effects, ranging from minor respiratory symptoms to increased hospital admissions and mortality. Worldwide mortality due to air pollution is higher than the road accidents toll (Künzli *et al*., 2000; Kjellstrom *et al*., 2002; Scoggins *et al*., 2004; Singh *et al*., 2006). Annually, in Europe, more than 200,000 deaths (Brunekreef and Holgate, 2002), in US 20,000–50,000 deaths (Mokdad *et al*., 2004), in Australia more than 3,000 (Doctors for the Environment Australia, DEA, 2017, https://www.dea.org.au/time-to-end-the-debate-and-get-on-with-it/), and in New Zealand 900 preventable deaths are attributable to air pollution (Beer, 2004; Robinson, 2005). In addition, the deleterious effects of ambient air pollution impose high health costs associated with morbidity (Brook *et al*., 2004).

Transport continues to be a significant contributor to traffic pollution (Khreis *et al*., 2017) despite the improvements to emission reduction technologies in recent decades, mainly because they are exceeded by the increased travel demand (Delucchi, 2000; Jerrett *et al*., 2005). The impact of exposure to air pollutants is higher in urban areas due to both high exposure concentration and greater population densities. Even in areas where concentration levels are considered relatively low, the implications for public health are important, as health impacts vary across population groups and are higher in susceptible individuals/groups with pre-existing respiratory conditions, the elderly and children (Brunekreef and Holgate, 2002; Katsouyanni, 2003; Scoggins *et al*., 2004; CDCP, 2011).

In response to this, appropriate guidelines and effective interventions require knowledge of the burden of illness and premature deaths attributable to specific pollutants (Brook *et al*., 2004; Dora, 1999; Künzli *et al*., 2000; WHO, 2003). Cohen *et al*. (2017) found that "*Ambient* $PM_{2.5}$

was the fifth-ranking mortality risk factor in 2015" worldwide. Long-term research programs have been initiated that concentrate on the health effects of air pollutants identifying the association between population distribution and exposure to pollutants (Brunekreef and Holgate, 2002; Beelen *et al*., 2007, 2014; Khreis *et al*., 2017).

However, due to the disciplinary and fragmented treatment of the issue, the links between air pollution and health end-points are weak and subject to numerous controversies. Several limitations concern the aggregated analysis of population exposure relying on fixed monitoring stations, neglecting or simplifying the spatial (and temporal) variability of the pollutants and the movement of individuals performing daily activities. Other factors are the lack of detailed analysis of the structure/composition of the pollutant, the concentration and the effect of different pollutants acting together (Brook *et al*., 2004; Pope, 2000).

This research addresses the exposure to PM at the individual level, following people in their daily movements between locations, accounting for their activities and measuring their personal exposure. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) were applied to identify the structure of PM. Accounting for the spatial and temporal variability of PM combined with personal monitoring of exposure considering daily activities and a detailed analysis of pollutant composition, can contribute to more accurate exposure assessments and to the identification of potential locations and groups with higher health risks, thus having both academic and pollution-control policy implications.

2. Exposure elements

Exposure is a function of the concentration of pollutants and the duration of exposure, therefore high concentrations and longer times spent into a specific microenvironment are influential in exposure assessments (Cepeda *et al*., 2016). Also, the health impact depends on the exposure and the inhaled dose (ventilation parameter m^3/h), depending on the activity intensity (Cepeda *et al*., 2016; Che *et al*., 2016).

2.1. Spatial and temporal dimensions

The continuous spatial and temporal variability of air pollution is due to variability in location of sources and volume of emissions, which follow the patterns of human activities. In addition, the dispersion of pollutants (dependent on meteorological conditions and topography) and the chemical processes lead to geographical heterogeneity of pollutant concentration within a day (and between days and seasons) across a city area (Gulliver and Briggs, 2005; Jerrett *et al*., 2005a; Dirks *et al*., 2016).

Past scholarly work on exposure has been limited and considered city-wide averages for pollutant concentrations obtained from a small number of fixed monitoring stations (Brook *et al*., 2004). Some other studies were even more aggregated in their analysis of pollution and therefore failed to predict pollutant concentrations and consider important local variations (Lyons *et al*., 2003). This approach is generally applied at the population level; guidelines and standards referring to exposure consider only concentrations in populated areas, without a precise assessment of exposure (e.g. DEE, 2014 – p.63 mentioned reduction of 10% in major urban areas in their *Exposure Reduction Framework* for the period 2015 – 2025).

Another limitation is the fact that individuals move through numerous microenvironments[1] (Moeller, 2005) (locations with homogeneous pollutant concentration where individuals perform certain activities) every day and they spend more than 80% of their time indoors (Olaru *et al.*, 2005). Therefore, the aggregate values at the city level cannot represent the true exposure for an individual; rather they are a simplification adopted most often for practical reasons.

Dispersion models and GIS spatial regression models are currently being applied in atmospheric research. They have shown that detailed models are necessary to characterise more accurately the emission-to-exposure relationship. As an example, Greco *et al.* (2007) estimated both primary and secondary $PM_{2.5}$ mobile source intake fractions (iFs) in USA. The iF represents the fraction of a pollutant or its precursor emitted from a source inhaled by a specified population during a given time. Source-receptor models and regressions were developed to assess the air pollution risk level. The authors concluded that long-range dispersion models with coarse geographic resolution are appropriate for risk assessment of secondary $PM_{2.5}$ or primary $PM_{2.5}$ emitted from mobile sources in rural areas, but that more resolved dispersion models are warranted for primary $PM_{2.5}$ in urban areas due to the substantial contribution of near-source population. This suggests that distance from sources (e.g., road) affects the PM concentration considerably (Wang *et al.*, 2006). Similarly, Montagne *et al.* (2013) found consistent significant association between concentrations and personal exposure to soot, but not for $PM_{2.5}$. On the other hand, Brauer *et al.* (2012) used a combination of methods and data sources to obtain PM 2.5 estimates in Perth, WA:

- a 3-dimensional global atmospheric chemistry transport model, TM5;
- a SAT (satellite-derived $PM_{2.5}$) – through which satellite observations of Aerosol Optical Depth (AOD), are used to calculate ground-level concentrations of fine particulate matter ($PM_{2.5}$);
- PM global database available measurements.

The results of the models concurred with each other and showed that Perth region displays a 2005 annual average of $PM_{2.5}$ surface monitoring of 5-10 $\mu g/m^3$ concentrations, very close to the threshold of 8 $\mu g/m^3$, which is the Australian standard.

Steinle *et al.* (2013) questioned whether developments of study design are keeping up with the developments in monitoring technology and considered that a way forward would be tracking the actual movements of a person in space and time while, at the same time, collecting information on environments and other characteristics (housing type, transport mode, residential area), so that more determinants of exposure can be incorporated. This line of research is adopted here, combining personal monitoring with activity analysis to produce a more accurate assessment of exposure to PM.

2.2. Dose-response relationship

A growing body of epidemiological[2] and clinical evidence has shown that elevated concentrations of PM are associated with increased hospital admissions and emergency department visits for respiratory conditions (Kjellstrom *et al.*, 2002) and cardiovascular diseases (Peters *et al.*, 2001; Magari *et al.* 2001; Pope *et al.*, 2004; Brook *et al.*, 2004; Maitre *et al.*, 2006). The impacts are both short and long-term (Cepeda *et al.*, 2002), the literature

[1] Indoors and outdoors

[2] Despite the fact that it is not inherently designed for studying biological mechanisms, epidemiological research can evaluate consistency between health end-points and potential pathways of disease (Pope III *et al.*, 2004).

being broadly split into acute and chronic exposure studies. Publications referring to long-term effects are fewer (Brook *et al*., 2004; WHO, 2005; Khreis *et al*., 2017) and subject to intense scrutiny given their relevance for public health. More recently, Kioumourtzoglou *et al*. (2016) were the first to note associations between long-term exposure to fine particles ($PM_{2.5}$) and time to hospitalisation for common neurodegenerative diseases (dementia, Alzheimer's and Parkinson's). The study followed an elderly population across the northeastern USA.

With respect to changes in mortality, numerous studies estimated that a 10 $\mu g/m^3$ increase in *annual* $PM_{2.5}$ changes cardiopulmonary mortality typically by 6-9% and lung cancer mortality by 8-14% (Künzli *et al*., 2000; Pope, 2000; Robinson, 2005) and that 10 $\mu g/m^3$ increase in *daily* PM_{10} leads to a 0.21 (0.5-1.5% in Pope, 2000) and 0.31% daily total and cardiopulmonary mortality (Brook *et al*., 2004). Notably, the list of adverse health effects also includes symptoms that can interfere with daily routine or diminished quality of life, but their cost is more difficult to estimate.

2.3. Differentiated effects of exposure

The consequences of exposure vary across the population and are stronger for more susceptible population groups, such as children, elderly (CDCP, 2011). Socio-economic characteristics and circumstances also influence the relation between pollutants and health:

- Lower socio-economic status is associated with greater exposure to air pollutants (people living closer to roads and polluting industrial facilities, or with greater occupational exposure);
- Also, lower socio-economic status groups may have poorer health in general and have less access to health care than other populations, creating an exacerbation of any health response and making them more vulnerable
- The intensity of activities plays a significant role in exposure .

This combination of increased susceptibility and exposure suggests that SES indicators may be useful for characterising populations that could be subject to disproportionate environmental air pollution (Apelberg *et al*., 2005; Brown, 1995; Neufeld *et al*. 2001; Faber and Krieg, 2002; Finkelstein *et al*., 2005; Morello-Frosch *et al*., 2002; Sexton *et al*., 1993). Several studies addressed relationships among socio-economic factors, air pollution, and health (e.g., Jerrett *et al*., 2004, 2005b; Martinis *et al*., 2004; O'Neill *et al*., 2004; Perlin *et al*., 2001; Wojtyniak *et al*., 2001; Speidel 2000; Zanobetti and Schwartz, 2000). Most studies (but not all – e.g. Zanobetti and Schwartz, 2000, pointed out only gender differences and modest SES related to effects of PM on mortality) have shown a social gradient in traffic-related air pollution exposure with respect to SES (Gunier *et al*., 2003; Kingham *et al*., 2007), greater exposure to indoor air pollutants and even occupational exposure to air pollutants for those in lower income brackets (e.g., Rotko *et al*., 2000).

2.4. Exposure profiles

A personal profile is a set of data consisting of contextual and spatio-temporal information and ambient concentration, collected by a person over a specific period of time, designed to capture certain individual characteristics (in term of exposure, behavioural patterns, and activities).

Gerharz *et al*. (2009) obtained detailed dynamics of $PM_{2.5}$ personal exposure by combining the outdoors estimated spatial distribution, indoor modelling techniques and GPS (Global Positioning System) individual tracking. Initiated in Munster, Germany, during winter, their pilot project used GPS tracking and 24-hrs diaries to measure exposure for one working day and one weekend day. The 14 profiles showed an average daily exposure between 21 to 198 $\mu g/m^3$, with a high daily variability, mainly due to behavioural aspects. The indoor measurements in three microenvironments showed the influence of: building and ventilation type/intensity; human movement and activity (lighting candles, smoking, cooking, visiting busy places - such as pubs or restaurants); time spent outdoor and outdoors trends. An interesting finding was the increased $PM_{2.5}$ concentration during night, while the outdoor $PM_{2.5}$ concentration diminished. The high standard deviation of all profiles substantiated the variability of the individual exposure and showed that the use of the daily mean exposure can easily flatten the shape of exposure. This limitation could be overcome by using mobile recording of PM concentrations with a high temporal resolution.

Broich *et al.* (2012) followed the movement of a heterogeneous group of 16 persons over a 24-hrs period. Each person kept a diary and carried a measurement kit including a spectrometer for counting the particle numbers and measure the particle mass, a GPS device for recording the geographical location and a video camera for capturing daily activities. All personal profiles recorded a higher exposure than the outdoor PM_{10} measured at fixed sites. The PM_{10} averaged 24-hrs exposure of all profiles ranged from 27 to 322 $\mu g/m^3$, with large differences in PM exposure across individuals. Overall, the highest concentrations of PM_{10} and $PM_{2.5}$ were recorded while riding a bus, while the lower concentrations of $PM_{2.5}$ were measured on train. On average, bicycle riders had a lower PM_{10} exposure than car riders, but higher $PM_{2.5}$ exposure. PM concentrations while travelling by car varied considerably.

The higher exposure for pedestrians and cyclists compared to car drivers was previously described by Gulliver and Briggs (2004), who explained the increased exposure due to the longer journey times on foot compared to car. Unless the achieved reduction in traffic volumes is sufficient to provide compensatory reductions in ambient pollution levels, at least on certain routes, this aspect has to be considered when recommending increasing physical activity levels along roads with heavy traffic (Good *et al*., 2016). Yet, for the global average urban background $PM_{2.5}$ concentration ($22\mu g/m^3$) benefits of physical activity outweigh risks from air pollution even under extreme levels of active travel, as shown by Tainio *et al.* (2016).

2.5. Input-Output ratios

Since both indoors and outdoors environments contribute to exposure, it is expected that the concentrations and the reciprocal effect are accounted for in exposure assessments. In Australia, substantial research has been undertaken in monitoring criteria pollutants and their indoor-outdoor distribution effects. Guo *et al.* (2010) monitored in Brisbane, Queensland, both the particle number and mass concentrations of $PM_{2.5}$ in a school. They concluded that indoor PM, both counts and mass concentrations, were significantly affected by human activities (smoking, lawn mowing), as well as outdoor PM, the latter being a direct result of vehicular emissions.

Lawson *et al.* (2011) looked at the indoor air quality of 27 dwellings in Melbourne, Australia in order to analyse the effect of major road proximity (Near Road vs Far Road) on indoor air quality. Indoor and outdoor PM_{10} and $PM_{2.5}$ (among other air pollutants) were measured and the indoor mean concentration was significantly higher at 'Near Road' dwellings compared to 'Far Road' dwellings.

Bo *et al.* (2017) also reviewed PM I/O ratios reported in different studies. Variations of PM_{10} and $PM_{2.5}$ were recorded both between and within outdoor and indoor environments. External factors such as ventilation type, meteorological conditions, proximity to the source, and architectural characteristics, have a significant contribution to the outdoor pollution, which in turn influence the level of indoor exposure. The general tendency is a higher outdoor concentration, compared to the indoor, thus a ratio >1. This ratio can be reversed in case of a powerful indoor source(s). Spatial, temporal and seasonal variability of the report I/O have been recorded. One of the most influential factors of the I/O ratio is the human activity/occupant behaviour.

Several studies use correlations to indicate I/O links. Liu *et al*. (2004) showed a wide range of correlations for PM_{10} (R^2 varying between 0.32 and 0.99), with the highest correlation for classrooms, where there are no indoor sources. When comparing activities during the week, Branis *et al*. (2005) found lower correlations (0.707, R^2=0.5) during weekend nights, but higher for workdays and particularly nights (0.884, R^2=0.781).

3. Methods and materials

Data collection was undertaken in two stages: fixed locations (Study 1) and personal monitoring (Study 2). Forty-three individuals (employees of the university) agreed to participate for one or two days of monitoring. Ethics approval was obtained from the university's research ethics committee for both studies. No incentives were offered.

Monitoring was undertaken in two specific departments of the university. They were chosen based on their location with respect to the natural and campus features and included a building where substantial renovation work was undertaken ('treatment' case). According to Hameed *et al*. (2004), renovations should be wisely planned and carried out, in order to minimise degradation of the indoor and outdoor air quality. The first hypothesis was that individuals in the newly built establishment will record a higher exposure during the working hours than their colleagues at other locations.

During the two studies, each individual carried one or two monitoring devices, depending on the availability of equipment and willingness of participants to engage in the data collection. Each participant also completed a questionnaire on general socio-demographics and her/his daily activities and routines. At the end of the monitoring period, the equipment was collected and a short re-construction and validation interview was conducted for daily activities, eliciting feedback on the study. Given the relative complexity of the study, short training sessions were organised prior to monitoring, explaining the objective of the research to the participants and describing the toolkit and the processes. The devices (a GilAir/Gillian 5000 pump and a DustTrak SidePak AM510 pump) and their associated materials (chargers, filters, cawl-cassettes) were presented/demonstrated by the student and each session concluded with Q&A.

After data collection, the data was downloaded, the equipment was reset and recharged in preparation for the following participant. Environmental monitoring was conducted approximately 8 hrs/day, during weekdays, starting around 9 a.m. and ending 5 p.m., the usual business hours for non-academic staff. Additionally, the time spent outside work, in other environments (at home, in their own vehicles or while riding public transport, outdoors, etc.) was captured in the activity diaries and environmental monitoring.

4. Data analysis

Factor Analysis (FA) was applied to summarise the presence of chemical elements, then Multivariate Analysis of Variance (MANOVA) compared the 'aggregated' counts by location (e.g. floor and side of a building) or microenvironments. A regression analysis furthered the exploration, by linking the weighted exposure with sources and activities, location and socio-economic indicators. Descriptive statistics and correlation analysis provided information on the consistency between the integrative measures of exposure (counts of elements and classes), the overall mass loading obtained through gravimetric methods, and the average PM concentration measured by the DustTrak SidePak equipment.

5. Results

5.1. Sample description

The final sample comprised 43 individuals (24 women and 19 men, aged between 20 and 70 with a mean age of 42.9 years. Detailed descriptives are provided in Table 1.

Table 1: Sample statistics

Descriptive Statistics	Study 1 (N=30) Mean (std. deviation) or % (count)	Study 2 (N=15) Mean (std. deviation) or % (count)
Age	43 (11.57)	42.33 (7.99)
Gender (F)	50 (15)	87 (13)
Education (Tertiary level)	90 (27)	67 (10)
# activities/day	6.13 (2.83)	5.54 (1.76)
Exposure to cigarette smoking (proportion)	31 (9)	6.7 (1)
Main type of heating		
• wood	13 (4)	0 (0)
• gas	37 (11)	47 (7)
• electric	43 (13)	40 (6)
Main type of cooking		
• gas	57 (17)	53 (8)
• electric	43 (13)	47 (7)
Number of reported activities per day		
• indoors	2.87 (1.55)	2.53 (1.12)
• travel	1.63 (1.81)	1.80 (1.47)
TOTAL	6.13 (2.83)	5.54 (1.76)
Exposure duration (min)	628 (134)	677 (109)

For study 1, the mass loading indicated an average of 0.087 mg/filter, which corresponds to 52.2 $\mu g/m^3$, and a significant variation (range of 0.15 mg/filter). For study 2, the weight was much higher for the fixed locations (on average 0.179 mg/filter, sd = 0.261, compared to the mobile filters (on average 0.084 mg/filter, sd = 0.032, for an average duration of 176 min).

When the renovated building was analysed separately, substantial differences were also noticed across wings (PG vs KW) and floors of the building (range 0.08 to 0.15 mg/filter). The highest mass loading was noticed at the top floor and the wing facing the river (KW), whereas the lowest on the ground floor on the opposite direction to the river, towards the campus (PG).

5.2. Results exposure

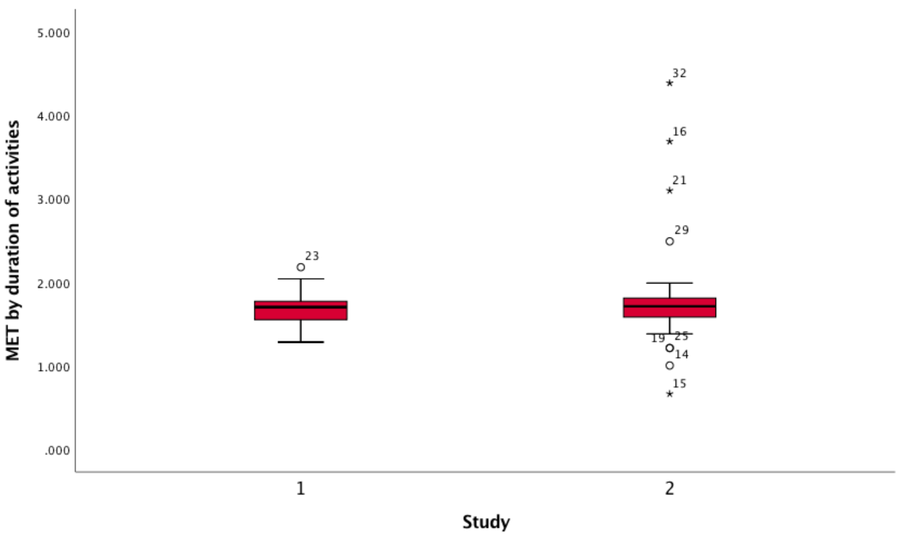
When considering the durations of activities and their contribution to exposure, it was found that 66% of the monitoring time was spent indoors, 29% while travelling (4.5% walking and cycling), the remaining time being time in outdoor activities. By applying the metabolic equivalent task intensities (MET) of activities (Ainsworth *et al*., 2011), along with durations and concentrations, better individual assessments of exposure are expected. Table 2 presents averages for classes of activities, considering their reported nature and intensity.

Table 2: Assumed MET for daily activities

Activity code	Subcode	Activity	MET code	MET score
0		Indoor Home	07011	1.00
1		Indoor working	09040	1.80
2		Travel differentiated by:		
	2.1	Travel by car	16010	2.00
	2.2	Travel by motorcycle	16030	2.50
	2.3	Travel by public transport	17151	2.00
	2.4	Travel by walking	17161	2.50
	2.5	Travel by cycling	01015	7.50
3		Gardening	04246	3.00
4		Other Indoor (store, deposit, laboratory)	11850	8.50
	4.1	Shopping	05060	2.30
5		Outdoor activities (eating out, movies outdoor)	09100; 09115	1.50

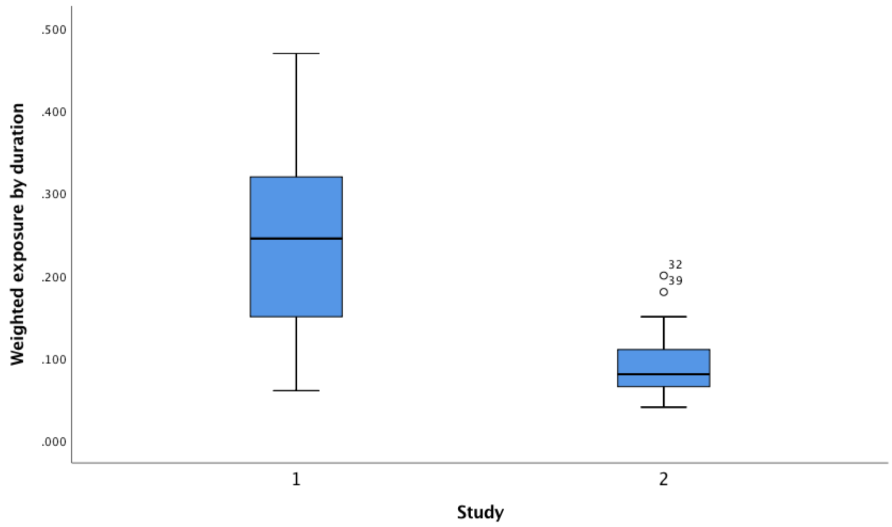
The average MET value during monitoring was 1.79 (st.dev. = 0.61), with similar physical activity levels recorded during both studies. This is expected, because most of the monitoring time occurred during working hours and it was dominated by indoors and outdoors light physical activities. Figure 1 also indicates a number of outliers in study 2, either engaged in active travel or working (physically) in the deposit/laboratory.

Figure 1: Weighted MET by duration



On the other hand, the weighted exposure was higher in study 1 (Figure 2) with an average of 0.255 (st.dev. = 0.136), with a maximum of 0.47 mg. In study 2, the average exposure was much lower, 0.092 (st.dev. = 0.037). A few participants had average METs over 3 (all of them being from study 1) which contributed to the differentiated results. Still, the intensity of the physical activity and exposure to PM did not covary, which means that duration and metabolic expenditures should be considered separately in the exposure assessment.

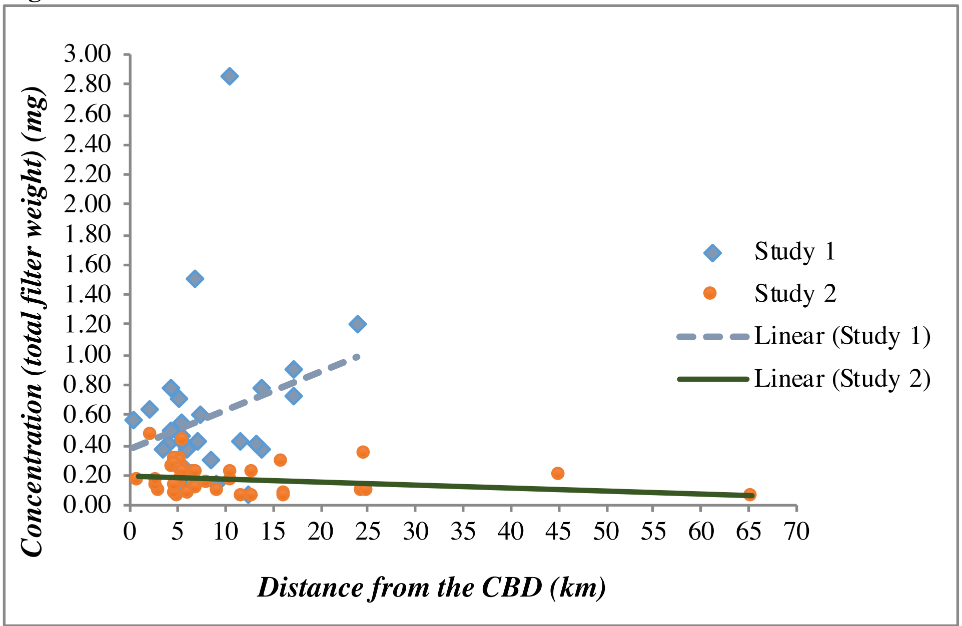
Figure 2: Weighted exposure by duration



5.3. Associations exposure-location

Figure 3 shows a weak aggregate relationships between overall exposure concentration and distance from the CBD. Whereas for study 1, the scatterplot suggests a positive link, this is non-existent for Study 2, again stressing that location alone is a poor explanatory variable of exposure and instead the nature and duration of activities have a more prominent role in exposure assessment. The substantial heteroscedasticity for data from study 1 is explained by the fact that most respondents live in the central and middle suburbs of Perth, within 17 km from the city centre.

Figure 3: Concentration vs distance from the CBD



5.4. Compositional analysis

This research used Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) techniques, to reveal elemental and chemical composition of the PM (Liu *et al*., 2014). The frequency of elements found on every filter were classified by size (coarse and fine particles) and by height of the peak (major and minor). Overall, the most frequent

elements were Oxygen (O), together with Si, Ca, Chlorine (Cl), Na, Fe, Al and Sulphur (S). Given the coating process, high frequency for C is not included in the results. The presence of metals and O suggests the presence of oxides. The high frequency of Si, Ca, Na and Cl may be indicative of the penetration of sand and salt from the river estuary.
Notably, Si, Ca, Na, Fe, O, and Cl were present in each of the four categories, whereas Bismuth (Bi) and Bromine (Br) appear sporadically and only as minor peaks for coarse particles; likewise, Nickel (Ni), Selenium (Se), and Vanadium (V) are present only as minor peaks for fine particles. These counts were factor analysed (highest loadings for major coarse 0.868 and major fine 0.832 particles) and a factor score then used to compare the prevalence of the elements by location in the renovated building.

The results indicate that most elements have a constant and even presence on both wings. O, Si, and Cl are the dominant elements. The next prevailing elements are Na, Ca, and Fe, indicating the presence of marine salt in the KW wing and sand and metal oxides, especially in the PG wing (highlighted in bold).

Table 3: Elements by building wings

Element	PG wing	KW wing
O	119.4	120
Si	**62.75**	51.10
Cl	38.00	**63.70**
Na	40.12	**57.10**
Ca	**57.75**	48.50
Fe	**39.62**	34.30
Al	**34.13**	24.40
S	25.25	24.40
Mg	18.00	**21.70**
K	20.62	16.70
Ti	13.50	10.10
Cu	**18.53**	7.80
Mn	3.00	**4.50**
Zn	3.00	2.80
P	3.12	1.40
Cr	**3.64**	0.90
Br	**4.35**	0.10
Ni	0.87	0.10
Bi	**4.38**	0.10

Al and Cu have a stronger representation on PG wing, whereas Mg and Mn on the KW side. Although the traces of the last four elements in the table (Cr, Br, Ni and Bi) are reduced, their presence is relevant, given documented health effects associated with them (Chen *et al.*, 2017; Gonzáles *et al.*, 2017).

When investigating frequencies by the levels of the building (Table 4), the distribution is quite even, with Na, Cl, Si, and Ca present on every level and a higher count for Fe, Al, S, K, and Cu on the 1st and 2nd levels (all differences significant at 0.05 level).

As part of the validation, correlations between elements, mass loadings, and average DustTrak measurements were calculated and they show consistency: the element counts showed a correlation of 0.57 with the gravimetric measurements, and 0.79 with the DustTrak aggregates (see an example of DustTrak profile in the Appendix).

Table 4: Elements by building floors

Element	Ground Floor	1st Floor	2nd Floor
O	119.67	120.00	119.67
Si	50.33	**64.67**	53.67
Cl	53.83	50.50	52.5
Na	53.33	**53.83**	41.5
Ca	**60.00**	51.00	46.83
Fe	27.67	**41.50**	40.83
Al	23.83	**33.67**	28.67
S	20.83	**28.17**	22.33
Mg	20.50	17.83	21.83
K	17.83	**23.00**	14.50
Ti	13.83	11.83	9.17
Cu	12.16	**15.33**	9.67
Mn	4.67	4.67	2.17
Zn	3.50	2.83	2.33
P	1.83	**3.00**	1.67
Cr	**3.00**	2.17	1.17
Br	2.50	**3.33**	0.17
Ni	0.17	**1.00**	0.17
Bi	**3.83**	2.00	0.00

5.5. Regression results

To account for all exposure influences, a regression model estimated at the individual level tested the relation between exposure (derived from concentration, which depends on location and sources, as well as the types of activities undertaken at the point of contact with PM) and activity duration and intensity. Gender was included as covariate.

Predictor	Unstandardised Coefficients		Standardised Coefficients	t	Significance Level (p)
	B	Std. Error	Beta		
(Constant)	-0.003	0.012		-0.235	0.814
MET	0.014	0.003	0.235	4.028	0.000
Travel by motorised mode	0.032	0.010	0.204	3.111	0.002
Time spent indoors	1.2E-04	1.9E-05	0.436	6.499	0.000
Gender Female	0.018	0.009	0.117	2.040	0.042

R^2-adj=0.379, see = 0.022

The strongest predictor of exposure was the time spent indoors, followed by intensity of activity (MET). On average, female participants had a higher weighted exposure than males by 0.018 mg (everything else kept constant). Also, travelling by car or motorcycle has resulted in an increase of weighted exposure by 0.032 mg, everything else being constant. These results clearly indicate that especially in environments with low concentrations of criteria pollutants (below occupational levels), a combined analysis of activities and exposure reveals the role of intensity of activity (measured in METs) and duration spent in the microenvironment.

6. Conclusions

The analysis of fixed locations further confirms that even in a limited geographical area (much smaller than the area normally "allocated" to an urban fixed monitoring station) and with similar types of activity conducted (office work and research) there are differences of PM concentration (depending on the indoor sources, the deposition processes, air exchange rates, etc.) and exposure.

In the building with substantial renovation work, the presence of marine salt, oxides, and compounds from construction materials and paints is clear, but to various degrees, depending on the location (the side of the building/orientation and the flooring materials).
This significant spatial variation, even within the same building, highlights the need for more spatially refined exposure assessments - currently lacking, primarily due to prohibitive costs, especially for the collection of indoor measurements of air pollutants (Banerjee and Annesi-Maesano, 2012).

The chemical analysis presented in this paper is a key contribution of this work, as the size of the PM does not provide any information on the nature/characteristics of particles (e.g., morphology, composition). Whereas metals may have severe respiratory and neuro-behavioural effects, other particulate matter may be genotoxic or have distinct cytotoxic effects, thus knowing its nature is key for designing strategies for reducing PM emissions.

The use of time diaries allowed for better understanding of the source of exposure. For example, outdoor sources are due to sea spray, sand, dust, and road traffic/combustion, whereas the main indoor sources were domestic activities such as cooking, heating, cleaning/dusting, or work in a workshop/lab where grinding and fumes were present.
The information may assist changing practices in organisations (e.g., air conditioning/ventilation systems, cleaning appliances and products) and in the households (vacuuming, mowing, cooking), especially for population segments with higher susceptibility. This is in addition to the continuously improving standards, to the generation reduction mechanisms and to the additional filters, traps, catalysts that may be installed in various microenvironments.

In addition to highlighting the spatial and temporal variability of exposure during the day, this research showed the high influence of the time spent indoors (working environments, residential microenvironments) and travel in the total exposure. Whereas the contribution to the value of total personal exposure of activities indoors may be explained by the high percentage of time spent indoors and not necessarily by higher indoor concentration, during travel, the concentrations may be an order of magnitude higher than the background average level, although for shorter durations (Lim *et al*., 2012). As shown in this research, the overall exposure due to travel represented 29%, compared to 60% from indoors activities.

Despite a relatively small sample size, which prevented testing more complex multivariate models, this study provided evidence that exposure has strong spatial, temporal, and behavioural components, which cannot be aggregated in "one number", usually provided by an outdoors monitoring station. The unequal distribution of elements even in the same building, as well as the variability in the intensity of activities conducted in various locations, draws attention to potential hot spots and unequal environmental conditions, with deleterious effects for those with higher susceptibility to PM pollution.

7. References

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Appendix

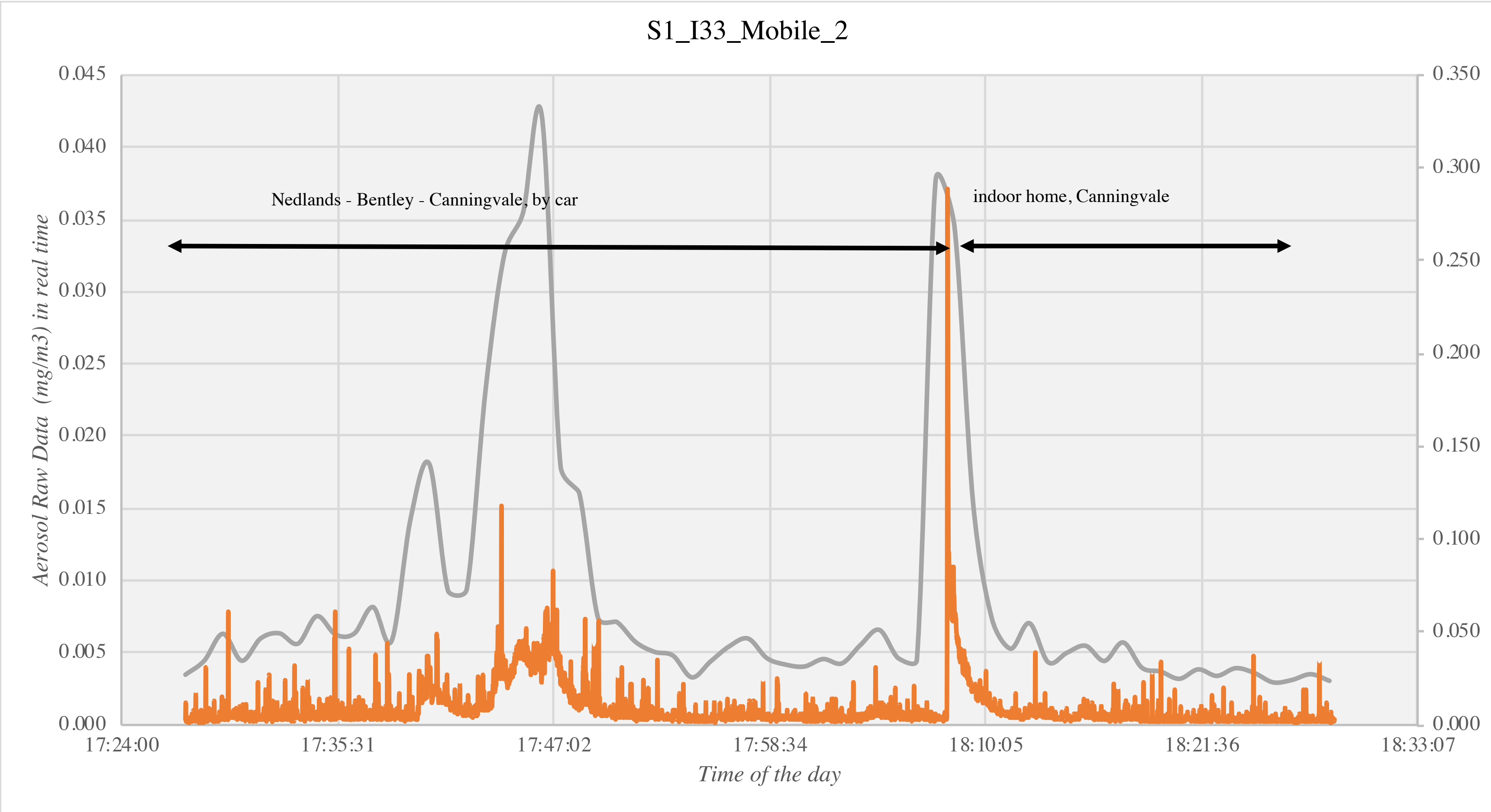

Figure A1: Example temporal profile PM from DustTrak