Linking activity-travel analysis and exposure assessment: benefits and challenges

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Abstract

This study investigates the relationship between the activity spaces and exposure to air pollutants, using personal activity and monitoring data. The activity space embeds the locations in which daily activities are performed and reflects various spatial and temporal processes that influence exposure to air pollutants: household scheduling of activity routines, the transport system, the time-space organisation of services, and the quality of the environment.

Nitrogen dioxide (NO₂) is the pollutant investigated in this study. Data were collected over five months, during winter and summer 2004, using passive samplers worn by subjects and deployed in seven micro-environments.

The individual spatial and temporal travel patterns were characterised and more accurate exposure profiles were determined based on activity-travel analysis.

Modelling results show that family members with similar activity spaces, engaged in activities in various indoors and outdoors locations, may have different exposure profiles due to different time allocation, different level of contact with pollutants, intensity of activity, and different anthropogenic characteristics. This is useful for identifying individuals potentially at greater risk, not only because of the concentrations of pollutants, but also due to the exposure durations and individual susceptibility to adverse effects.

Keywords: activity space, mobility, air pollution, personal exposure.

1 Introduction: concepts and definitions

Health professionals, policy makers, and the public are increasingly concerned about exposure to air pollutants, especially in urban areas. Many recent
epidemiological studies have generated specific interest in transport-generated pollution [28], [43], [44]. The health effects of air pollution depend on the concentration experienced by individuals conducting activities in different places, so that measurements need to be mobile, rather than from stationary monitoring sites located outdoors [9], [36].

To examine the association between activity patterns and exposure, we selected a ubiquitous pollutant of the urban atmosphere – nitrogen dioxide (NO₂) - that arises mainly as a by-product of combustion processes (particularly traffic related). NO₂ is associated with both chronic and acute health effects on lung function, especially in high risk populations, such as children, elderly, and asthmatics [18], [41], [44].

As exposure is not a unidimensional concept, both temporal dimension and weight/intensity of activities were included. The research addresses the need for an integrated, multi-domain approach in examining pollution and health risk issues [10].

1.1 Personal sampling

Nitrogen dioxide can be reliably measured in the ambient atmosphere with passive samplers [1], [18], [25]. Passive samplers have been increasingly used for the study of air pollutants since they are: simple in structure and use, light-weight, unobtrusive, relatively cheap and do not require power. Most importantly, they are able to capture the spatial and temporal variations of air pollution [2], [4], [15], [30].

As Heal et al. [18] highlight, “studies based on fixed outdoor monitoring sites to estimate personal exposure to air pollution are often weakened” due to uncertainties in spatial variation of pollutant concentration and preponderance of indoor time in human daily routine, where specific indoor sources are present [27], [32]. Because the relationship between pollutants and health outcomes relies on the quantified personal exposure of individuals, personal monitoring has the capability to overcome some of these limitations and to delve into the pollution – health risks issues/association.

The main disadvantage of passive samplers however is that a time integrated concentration is determined, thus it does not capture the instantaneous pollutant concentrations, losing the ability to identify particular peak pollution episodes.

Many researchers assessed the accuracy of passive samplers [1], [17], [25], [47], highlighted technical difficulties associated with atmospheric conditions and chemical interference [11], [16], [25], [26], [32], and identified ways of minimising these influences by appropriate modifications of the samplers [8], [12], [13] and calibration under various conditions [1], [25].

1.2 Concentration and exposure

This study draws on previous CSIRO’s work on personal exposure and incorporates a new dimension into personal exposure – activity patterns and space. While the majority of passive sampling studies evaluated pollutant
concentrations in different locations, outdoors and indoors, focusing on temporal variation [15], [35], [37], few collected and investigated the activity diary of the respondents and their exposure [5], [18], [29].

We particularly consider the combination of integrative sampling and real-time data from monitoring stations with activity patterns as the method by which “the richest information on personal exposure can potentially be obtained” (Williams [45]:172) because this can account for the interaction between individual and pollutant exactly where and when it occurs.

The exposure of the individual in the microenvironment \(i\) in the time period \(P\) is calculated as:

\[
E_{ip} = \frac{t_{ip}}{T_P} (C_{i1P} + C_{i2P})
\]

where \(t_{ip} / T_P\) represents the fraction of time spent in microenvironment \(i\) during the time period \(P\), and \(C_{i1P}, C_{i2P}\) are the NO\(_2\) concentrations in the duplicate samplers for microenvironment \(i\) and time period \(P\).

By adopting the view that activity-related factors may result in susceptibility (McCurdy [34]), this study examined the total exposure accounting for the intensity of activity (\(w_{ip}\) is the weight/intensity for various activities).

The total exposure is therefore:

\[
E_P = \sum_i E_{ip}w_{ip}
\]

1.3 Health effects of NO\(_2\)

Exposure to high levels of NO\(_2\) is associated with increases in respiratory effects or potentiation of other agents such as: pollutants or allergens [3], [7], [41], [44]. Yet the health effects of NO\(_2\) at low concentrations are uncertain [6], [14], [20], [21], [33], [39], [42] and there is no evidence to establish a threshold for either short or long term exposure [44]. In Australia, associations between NO\(_2\) ambient levels and hospital admissions for respiratory and cardiac conditions have been observed [38].

Dosage at tissue level is very important, but it is usually beyond the scope of health studies, so that exposure estimates become even more critical. Exposure-response relations are expected to be steeper (greater responses from exposure to lower levels of pollution) in those more sensitive to such responses. This emphasises the need for activity-based exposure. For example, as children spend more time outdoors and are more active, they may be more susceptible to pollutant induced injury, increased risk of respiratory illness, bacterial and viral infections.

1.4 Activity spaces and factors affecting them

Activity-travel analysis investigates the complexity of daily life (the spatial and temporal variability of activities), with impact on exposure to pollutants. There is a spatial common “denominator” appearing in this association: human activities
are spread geographically and the contact with pollutants provides exposure for the individual receptor.

The activity space illustrates the “repertoire” of daily activities. In this research we use the confidence ellipse, representing the part of the urban area $A$ visited by an individual in a certain time period, calculated by the covariance matrix of all ordered activity locations [40]:

$$A = 6\pi \sqrt{\text{det}(S)}$$

where $S = \begin{pmatrix} S_{xx} & S_{xy} \\ S_{yx} & S_{yy} \end{pmatrix}$ and

$$S_{xy} = S_{yx} = \frac{1}{n-2} \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})$$

The centre of gravity of activities is the centre of the ellipse. The activity spaces have been compared across subjects and across consecutive periods of the analysis, then analysed in their relationship with exposure. The rationale was that people living and working in the same area are expected to be exposed to the same level of pollutants. However, if the activity routine is different, the exposure profiles may vary. McCurdy [34] suggested there are lifestyle and activity factors (such as exercising near pollution sources, using gas for cooking and heating) that result in susceptibility regardless of the intrinsic conditions. This aspect of activity-related exposure is highlighted in this study.

2 Empirical setting

The longitudinal study was conducted in Melbourne, over approximately 5 months in 2004, winter to summer. The exposure to NO$_2$ of three female individuals (mother, grandmother, and younger daughter) living in a non-smoking house, with natural gas heating and cooking, located 500 m from a main road, was determined using passive samplers. Duplicate NO$_2$ passive samplers were worn on a badge for 10 weeks during winter and 8 weeks during spring-summer 2004. A second set of passive samplers was deployed in seven micro-environments (indoors and outdoors) where subjects reported spending considerable time every day. Due to the relatively low pollution levels, it was not possible to obtain daily measurements; therefore we measured cumulative exposure over blocks of about two-three weeks. The NO$_2$ samplers were analysed by CSIRO Atmospheric Research and concentrations were calculated according to Fick’s Law of diffusion. Unexposed field and laboratory blanks were also used during each study period as a further quality control check [17], [23]. Consistent with Lebret et al. [30] and Gonzales et al. [15], this research found very small replicate errors from the duplicate tubes (5-8%).

In addition, fixed sites’ time series concentrations of NO$_2$ were provided by the Air Quality monitoring network of EPA Victoria, Melbourne as hourly data. This has been used for validation and to highlight peak concentrations that may cause biological damage. A detailed activity diary kept for each individual
served to build exposure profiles accounting not only for the time spent in various locations, but also for the type and intensity of the performed activity.

# Findings

## 3.1 Activity space over time

Table 1: shows the subjects’ activity spaces over the five periods of the study. The investigation of the similarity of consecutive periods shows a remarkable degree of stability. All activity spaces are built around home. On a weekday, the activity spaces are similar across the three family members. The size of the confidence ellipse of their activity spaces is about 30 km² during weekdays and more than double during weekends. This shows that the daily universe of activities is contracted to Aspendale, the suburb where the subjects live. Summer activity spaces are much larger than winter activity spaces, confirmed by the larger amount of time spent out-of-home (Table 2).

<table>
<thead>
<tr>
<th>Period</th>
<th>Adult 1 (Full time job)</th>
<th>Adult 2 (Pensioner)</th>
<th>Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (winter)</td>
<td>49.95</td>
<td>23.36</td>
<td>35.30</td>
</tr>
<tr>
<td>2 (winter)</td>
<td>36.08</td>
<td>21.09</td>
<td>28.12</td>
</tr>
<tr>
<td>3 (summer)</td>
<td>42.83</td>
<td>22.67</td>
<td>29.54</td>
</tr>
<tr>
<td>4 (summer)</td>
<td>64.03</td>
<td>39.72</td>
<td>44.15</td>
</tr>
<tr>
<td>5 (summer)</td>
<td>68.63</td>
<td>36.96</td>
<td>42.37</td>
</tr>
<tr>
<td>Total weekday winter</td>
<td>22.13</td>
<td>20.01</td>
<td>21.16</td>
</tr>
<tr>
<td>Total weekday summer</td>
<td>55.26 (43.48*)</td>
<td>35.71</td>
<td>41.85</td>
</tr>
<tr>
<td>Total weekend winter</td>
<td>38.26</td>
<td>24.47</td>
<td>30.53</td>
</tr>
<tr>
<td>Total weekend summer</td>
<td>94.84 (69.70*)</td>
<td>45.60</td>
<td>49.94</td>
</tr>
</tbody>
</table>

* Excluding time away from home (outside Melbourne).

Table 2 presents seasonal averages for time spent during weekdays by adult 1. It also shows the ambient and passive sampling (PS) measurements of NO₂. Considerable variation can be noticed in the duration of activities, with more travel and time spent out-of-home during summer periods, compared to winter. The same pattern was also observed for the other two subjects, although not as prominent.

Common sense would suggest that all three family members experience the same environmental conditions and same exposure. However, the girl and the two adult females are at different life cycle stages, which influence their daily routine. The mother is a researcher, the younger daughter is a six year old primary school student, and grandmother is a pensioner, spending most time at home. Even at home, while one adult is engaged in domestic activities inside,
another may be gardening, and the child may be playing or doing her homework; or in indoor sport activities one adult may spectate while the others compete, etc.

An average daily personal exposure profile for a weekday is provided in Figure 1: and it confirms that individual exposure differs among the three family members and it is much higher (about 30%) for adult 2, compared to adult 1. With respect to time, the personal exposure for all three subjects decreased from June-July to November-December in accordance with the reduced outdoor and indoor concentrations of NO₂.

Over an average weekday, the lowest exposure is recorded for adult 1, who spends more than a third of the weekday time in a clean indoor environment, her office (6.5-7.5 ppbv). The highest exposure appears to be for the grandmother, especially during winter. Gas heaters and cooking are the strong contributors [36] and added more than 10 ppbv (18 µg/m³) – consistent with [5] and [37].

Table 2: NO₂ ambient, microenvironment concentrations, and average time spent on activities for individual 1.

<table>
<thead>
<tr>
<th>Type activity</th>
<th>Season</th>
<th>Ambient NO₂ (ppbv)</th>
<th>NO₂ from PS (ppbv)</th>
<th>Mean activity time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>Sleep</td>
<td>Winter</td>
<td>7.77</td>
<td>5.16</td>
<td>10.76</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>6.86</td>
<td>5.06</td>
<td>5.64</td>
</tr>
<tr>
<td>Domestic activities, recreation</td>
<td>Winter</td>
<td>12.42</td>
<td>7.66</td>
<td>10.26</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>9.86</td>
<td>6.40</td>
<td>7.60</td>
</tr>
<tr>
<td>Meal preparation, consumption</td>
<td>Winter</td>
<td>15.16</td>
<td>7.23</td>
<td>18.16</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>7.98</td>
<td>7.33</td>
<td>22.09</td>
</tr>
<tr>
<td>Work at home</td>
<td>Winter</td>
<td>12.23</td>
<td>7.08</td>
<td>15.27</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>7.66</td>
<td>5.91</td>
<td>10.24</td>
</tr>
<tr>
<td>Physical activities at home</td>
<td>Winter</td>
<td>11.34</td>
<td>7.36</td>
<td>13.30</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>9.60</td>
<td>6.38</td>
<td>17.89</td>
</tr>
<tr>
<td>Work at office</td>
<td>Winter</td>
<td>11.48</td>
<td>5.69</td>
<td>7.37</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>7.45</td>
<td>5.04</td>
<td>5.86</td>
</tr>
<tr>
<td>Other indoor activities</td>
<td>Winter</td>
<td>16.85</td>
<td>11.05</td>
<td>13.51</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>7.16</td>
<td>5.22</td>
<td>12.61</td>
</tr>
<tr>
<td>Travel</td>
<td>Winter</td>
<td>14.87</td>
<td>9.22</td>
<td>21.96</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>8.92</td>
<td>7.19</td>
<td>19.44</td>
</tr>
<tr>
<td>Outdoor activities</td>
<td>Winter</td>
<td>12.22</td>
<td>7.11</td>
<td>25.18</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>7.95</td>
<td>4.93</td>
<td>15.73</td>
</tr>
</tbody>
</table>

High concentrations have been observed for outdoor activities (gardening, walking, etc.), consistent with identified pollution episodes during the study.
period. Travel, per se, did not contribute significantly to the exposure, as very little car use occurred (about 2% of time): the three subjects mostly walk, cycle, or ride public transport.

In terms of concentration, the NO₂ averages for fixed car samples were very small, comparable with the indoor office concentrations (5.7 ppbv). However, Beer et al. [21] investigated concentrations during different phases of car operation and the levels in a moving car were 7-8 times higher than for a stationary vehicle.

The NO₂ concentrations for the other indoor activities have been monitored together. With the exception of one visit to the ice-skating ring (with well-documented elevated concentrations [46]), the activities included mainly swimming, shopping, social visits.

When including the activity intensity/level of contact with the pollutant, via respiratory parameters (we used as weights the metabolic equivalents of work, METS [34]:255) we noticed even larger differences in exposures. During weekdays, the exposure for adult 2 increased to more than 40% compared with adult 1. Similarly, the exposure for the child increased as a result of numerous physical-intensive activities conducted.

The considerable variability in exposure profiles suggests potential different health effects for the three subjects. Although the magnitude of concentrations does not pose health risks in this case (average exposure of only 19.8 μg/m³, compared to 46 μg/m³ in Hong Kong [5], > 43 μg/m³ in Prague [24], or 125 μg/m³ in Mexico city [31]), the methodology may be used to identify population

Figure 1: Cumulative exposure profiles for all subjects.
groups at risk in situations/locations where the exposure profiles would be sufficiently different on a clinical dose-response basis.

### 3.2 Spatial mapping

Figure 2: presents activity spaces for adult 1, on weekdays and weekends, in winter and summer, along with the concentrations of NO$_2$. The mapping of activity spaces has shown the following different tendencies/patterns:

- The centre of gravity of activities weighted either by frequency of activities or by duration of activities is very close to home;
- For weekdays, distinguished by their strong commuting imprint, the activity space is significantly smaller than for the weekend, due to life and activity circumstances; the activity spaces for weekdays is a narrow ellipse, whereas during weekends individuals visit locations more spatially spread.

Figure 2: Activity spaces and NO$_2$ concentrations from microenvironment measurements.

Without making any inference at the population level, the results show that activity spaces are stable and similar, but NO$_2$ varies within the activity spaces. Even within the house, the kitchen, the living area, and the bedrooms had different NO$_2$ concentrations. This indicates that the assumption of homogeneity of pollutant concentration (usually the outdoor concentration from fixed
monitoring sites), prevalent in most aggregated studies of population exposure, needs to be relaxed and that the activity-based methodology combined with personal samplers is able to capture the spatial, temporal, and behavioural variation of exposure.

4 Validation

Comparison of NO₂ passive samplers’ concentrations with average ambient concentrations provided by EPA Victoria for two monitoring sites close to subjects’ home has been performed for validation purposes. Concentrations of ambient NO₂ showed typical peaks associated with traffic: noticeable high values in the afternoon-evening peak, slightly higher on winter compared to spring-summer. Although the air quality standards were not exceeded, two pollution episodes during the study period, with peak concentrations over 40 ppbv, were reflected in the personal monitoring data.

Consistent results were seen for indoor-outdoor correlations for work at office (explained by the absence of significant NO₂ sources and air conditioning in the office [32], [37]) and for outdoor physical activities (statistically significant at 0.001), but not for other microenvironments. The home indoor levels of NO₂ were general higher than the outdoor, explained by the main indoor sources: gas heating (winter) and gas cooking.

5 Summary

This research bridges a gap between activity-travel analysis in transport and health studies, illustrating how exposure assessment may be enhanced with personal sampling measurements and activity data analysis. The methodology contributes to more accurate measures of exposure to airborne pollutants. The method is based on measured exposure and not on subjective reporting of the severity of exposure, thus it eliminates the potential bias of individual perception of pollution [19].

Activity spaces and personal exposure to NO₂ for two females and one child, over 18 weeks in winter and summer 2004, were examined. The activity space concept, used in transport modelling, was applied to assess whether activity spaces are indicative of the magnitude and variability of exposure. Activity spaces varied between weekdays and weekends and were larger in summer. On weekdays the activity spaces for the three subjects were virtually the same. Considerable spatial variation in pollution was found within the activity spaces, including different concentrations in different parts of the house (highest in the kitchen, lowest in the bedrooms/bathrooms). The highest personal exposure occurred in winter. Inter-personal variability appeared due to different activity routines and personal characteristics. The aggregate exposure assessment, relying on average ambient concentration, has been underestimated by 20-30%. When activity intensity was included, the variability of exposure increased. Further investigation of these aspects, maybe coupled with biological markers monitoring, would bring more insights in the exposure to pollutants – health
impacts. The analysis demonstrates the large effect of indoor activities on personal exposure and the large contrast between exposures arising from differences in activity patterns, weekly and seasonally-dependent.

6 Implications and future research

We position this paper as a signalling study; the results emphasise the relevance of an integrated activity-based exposure analysis for all airborne pollutants. From the wide spectrum of implications we consider the following:
- Monitoring - would reveal whether proper ventilation is needed (as currently no legislation covers the indoor air where we spend more than 90% of our time), or restrictions in design, use, and maintenance, required for gas stoves and heaters;
- Activity-based exposure assessment is relevant to identify more susceptible groups to air pollution - derived or exacerbated affections.

There are several limitations of the study worth addressing in the future:
- Comparison of the personal sampler concentration with concentrations resulting from dispersion modelling, allowing for high spatial resolution;
- Monitoring/tracking with a GPS device and a more continuous estimation of concentration would allow for more accurate temporal pattern of exposure.

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References


