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Quantifying human exposure to air pollution - moving from static monitoring to spatio-temporally resolved personal exposure assessment

Running Title: Quantifying human exposure to air pollution

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Abstract

Quantifying human exposure to air pollutants is a challenging task. Ambient concentrations of air pollutants at potentially harmful levels are ubiquitous in urban areas and subject to high spatial and temporal variability. At the same time, every individual has unique activity-patterns. Exposure results from multifaceted relationships and interactions between environmental and human systems, adding complexity to the assessment process.

Traditionally, approaches to quantify human exposure have relied on pollutant concentrations from fixed air quality network sites and static population distributions. New developments in sensor technology now enable us to monitor personal exposure to air pollutants directly while people are moving through their activity spaces and varying concentration fields.

The literature review on which this paper is based on reflects recent developments in the assessment of human exposure to air pollution. This includes the discussion of methodologies and concepts, and the elaboration of approaches and study designs applied in the field. We identify shortcomings of current approaches and discuss future research needs. We close by proposing a novel conceptual model for the integrated assessment of human exposure to air pollutants taking into account latest technological capabilities and contextual information.

Keywords: environment, air pollution, personal exposure, conceptual model, integrated assessment

1 Introduction

Human exposure to environmental pathogens and specifically air pollutants is a highly topical issue. Clean air to breathe is a basic requirement of life and the quality of air both outdoors and indoors is a crucial determinant of health (WHO, 2010). Air quality is affected by pollutants such as nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) and ground level ozone (O_3).

Substantial growth in individual transport activities and energy consumption reflect growing affluence and contribute considerably to high and, in some cases, increasing ambient levels of air pollutant concentrations. Urban areas with high population densities are especially affected.

Air pollutants are ubiquitous and a certain level of exposure is inevitable, whether a person is indoors or outdoors. For risk and impact assessments of air pollution effects and the design of control policies, such as the UK National Air Quality Strategy (NAQS) or the Local Air Quality Management (Environmental Protection UK, 2011) as well as indoor air quality information (Parliamentary Office of Science and Technology), it is necessary to accurately quantify human exposure to air pollution. Traditionally, personal, environmental exposure has not been directly assessed for individuals, but rather by estimating population-wide exposure via networks of fixed monitoring sites deriving annual ambient average concentrations and spatial interpolation of the results. However technological advances have produced sophisticated monitoring devices carried or worn by a person during their regular daily routine allowing for personal exposure to be monitored explicitly. Time-geography accounting for the movement of people and their individual activity-space is a crucial determinant of personal exposure in this context. The following quote from the founding father of time-geography, Torsten Hägerstrand, reflects this well:

"Existence in society implies people are constantly in motion. Virtually every individual possesses his own unique field of movement, with his residence in the centre and with places of work, shops, places of recreation, residences of intimate friends, and other similar locales serving as nodal points." (Hägerstrand, 1967, p. 8)

In this paper the focus is on methods and concepts for monitoring the movement of individuals and their exposure to environmental air pollution in space and time. Following the introduction of methods and concepts for exposure assessment in general, recent papers investigating personal exposure are assessed. Methods, concepts and technologies as well as study design described in these papers are discussed in the subsequent sections. We identify shortcomings and development potentials in this research area. Finally, we derive recommendations for future research needs and introduce a novel conceptual model for the assessment of human exposure to air pollution.

2 Background and scope of the review

Human exposure to a pollutant has been defined as occurring when "*a person comes into contact with the pollutant*" (Ott, 1982, p. 186). Exposure assessment is *"... the process of estimating or measuring magnitude, frequency and duration of exposure to an agent…"* (Zartarian et al., 2007, p. 58). Ideally, it is a complementary concept describing sources, pathways, routes as well as the uncertainties in the assessment. Personal exposure assessment is evolving quickly and latest advances in technology enable the tracking of individuals while simultaneously measuring pollutant concentrations. In this section, methods applied in exposure assessment and for time-activity analyses are reviewed, and their implementation in research discussed. It is beyond the scope of this paper to give a complete account of exposure science and human exposure research; hence the reader is referred to two recent books (Lazaridis and Colbeck, 2010; Ott et al., 2007) and several articles (Ashmore and Dimitroulopoulou, 2009; Hertel et al., 2001a; Monn, 2001) covering the emergence, state and methods of this research area and its subtopics more comprehensively. Moreover this paper concentrates on research in industrialised countries and their specific exposure situations. Time-activity patterns in developing countries are different, as well as emission sources and lifestyle and hence the methods applicable (e.g. Allen-Piccolo et al., 2009; Branis, 2010; Colbeck and Nasir, 2010; Freeman and Saenz de Tejada, 2002).

The assessment of exposure to air pollutant concentrations in space and time is not trivial as it is affected by many determinants and governed by complex relationships and interactions between environmental and human systems. For risk and health impact assessment (HIA), different conceptual models have been developed reflecting these relationships. The modified *Driving forces–Pressures–State–Exposure–Effect-Action* (mDPSEEA) model (Morris et al., 2006; Steinle et al., 2011) for instance represents an impact pathway analysis, structuring and mapping the complex interactions between environmental and socio-economic factors. The “modified” in mDPSEEA addresses the explicit recognition of context, i.e. socio-economic, demographic and environmental factors, as modifiers for potential exposure and effect. Context can thus account for aspects affecting the susceptibility to and severity of an effect due to the same or similar exposure in different receptors.

Air pollutants are ever-present and comprise a range of substances interacting, reacting and creating many heterogeneous pollutant mixes. It is impossible to identify any individual air pollutant as a sole causal agent of an adverse health effect (Branis, 2010; Goldberg, 2007). Environmental, meteorological and microclimatic influences, which are changing dynamically, add to the complexity as well as people moving in space and time, showing individual behavioural patterns (McKone et al., 2008). This means personal exposure is a function of concentration and time (Nuckols et al., 2004). As a consequence, individuals can be exposed in any environment to a large variety of pollutants and pollutant mixes (Branis, 2010; Goldberg, 2007).

Exposure to air pollutants has traditionally been assessed based on data from fixed-site air quality monitoring networks. Such network sites usually provide a large quantity of data for a wide range of pollutants, albeit for one point in space. Applying interpolation techniques, spatial maps of air pollutant concentrations are derived, typically for annual average concentrations. With this derived pollution surface, pollutant concentrations can be spatially related to a population or a specific subpopulation such as asthma patients, children or pregnant women (Harrison et al., 2002; Nethery et al., 2008a; Nethery et al., 2008b). Allocating a population to a monitoring site is most suitable for large population studies regarding outdoor air (Chow et al., 2002), but is unavoidably affected by assumptions implicit in the application of this indirect method compared to real exposure scenarios (Cattaneo et al., 2010; Hertel et al., 2001a). Exposure assessment based on averaged measurements artificially diffuses pollution and operates on aggregated demographic data, which is problematic for personal exposure assessment as it does not provide a representative measure of an individual's personal exposure (Rodes et al., 1991). Moreover using such fixed-site data as exposure estimates ignores the impact of individual mobility patterns, especially time spent away from home (Setton et al., 2011).

Suitable alternatives to using data from fixed site monitoring are spatio-temporally explicit modelling, and/or personal monitoring. To determine personal exposure, pollutant concentrations in the pollution-space at each point in time a person is present throughout the day need to be considered (Ott, 1982). Occupational/industrial studies and the portable and wearable monitors developed (e.g. Sherwood and Greenhalgh, 1960) were the basis for the development of specific personal exposure, time-budget and health studies which developed since the late 1970s (Wallace and Ott, 1982). The traditional approach for assessing personal exposure to air pollutants is depicted in Figure 1. Personal exposure is derived from an individual moving in the changing concentration field. The synchronised measurement of air pollution and the individual's movement is implemented either with one integrated or several parallel running sensors, with a trend towards the use of GPS-enabled devices. Personal monitoring data serves also as input to and for the validation of exposure models (Duan, 1991; Gerharz et al., 2009; Gulliver, 2005; Hertel et al., 2001a; Hertel et al., 2001b).

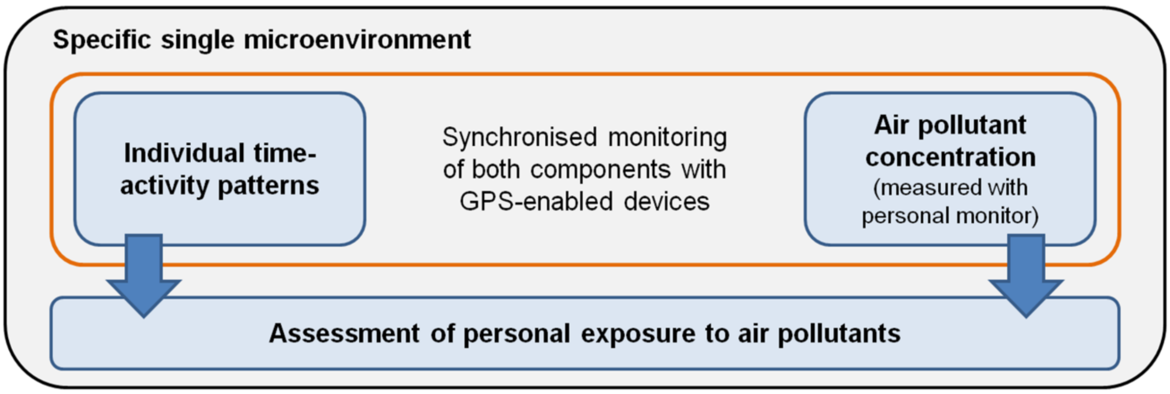

Figure 1. Conceptual model illustrating the traditional approach for the assessment of personal exposure to air pollution.

Air pollution has often been associated solely with outdoor air, since sources such as power plant stacks or road traffic emit key pollutants which are visible (smog events, columns of exhaust fumes) and are generally considered to be harmful to human and environmental health. Indoor air quality, in contrast, has been neglected in exposure research for a long time (Jantunen and Jaakkola, 1997; Lippmann and Lioy, 1985) even though it is not a new phenomenon (Colbeck and Nasir, 2010). Notably, people in industrialised countries - depending on the climate zone - spend most of their time indoors. According to WHO (2005b) two thirds of an average person's time-activity is spent at home, and one fifth at the workplace. Particularly children and elderly spend most of their time in indoor environments (Franklin, 2007; Harrison et al., 2002). As Quackenboss et al. (1986) noted in their study on exposure to NO_2, using only the outdoor component of exposure is not sufficient as several potentially confounding variables are omitted from the exposure assessment process. Indoor air quality has become an inherent part of exposure research in recent years, gaining particular attention in policy making (Colbeck and Nasir, 2010) and for the development of guidelines for certain pollutants (WHO, 2010). Indoor air quality and health are discussed by several authors, for instance Colbeck and Nasir (2010), Mitchell et al. (2007) or Wallace (1996) provide a good overview of research focusing on indoor air/environments since the 1980s. Diffusion of outdoor air into buildings contributes to a mixture of indoor and outdoor pollutants and resulting indoor exposure levels (Branis, 2010; Lai et al., 2004) depending on ventilation, air conditioning and on the indoor-outdoor temperature gradient. Indoor environments also have a wide and varied range of primary sources of potentially harmful substances (e.g. environmental tobacco smoke (ETS), cooking and heating with natural gas or solid fuels) which are independent of the outdoor environment, but can modify a resident's exposure substantially since they are often within immediate personal space(Ferro et al., 2004; Franklin, 2007; Freeman and Saenz de Tejada, 2002; Lai et al., 2006; Rodes et al., 1991; WHO, 2005b). However, small area variations and fluctuations over time imply that even a group of people e.g. working in the same building are subject to their own individual exposure due to their daily activity pattern (Elliott et al., 2000).

Personal exposure does not only arise from pollutant concentrations in outdoor and indoor air. Pollutants generated by the person's activities itself - known as the personal cloud effect (Rodes et al., 1991; Wallace, 1996) contribute as well. This personal cloud effect was one of the findings of the Total Exposure Assessment Methodology (TEAM) studies carried out between 1980 and 1990 by U. S. EPA and is discussed in more detail by Ozkaynak et al. (1996), Wallace (1993); (Wallace, 1987) and Wallace et al. (1986).

Table 1 summarises methods for the assessment of exposure based on air quality networks and personal exposure to air pollution. The latter requires the pollutant measurement to be taken near the breathing zone, i.e. within 30 cm of nose and mouth (Nieuwenhuijsen, 2000). According to McKone et al. (2008), personal exposures of individuals in a population can be lower, equal or higher than those derived from ambient pollutant concentrations.

3 Methods and concepts for personal exposure assessment

Personal exposure assessment requires the recording of a person's time-activity patterns, as well as the pollutant concentrations in the environment through which the person is exposed (Sabel et al., 2009).

A person's movement, having a spatial and temporal component, can be described as a *path* (Thrift, 1977). Traditionally, the tool to record such a path as well as additional information, for instance on the transport mode used, is a so-called *time-activity diary* (TAD). Study participants would typically fill in a TAD detailing the time spent in specified locations during a day's activities.

An essential part of all exposure studies is the development and application of suitable monitors for pollutant concentrations. A range of portable, personal monitors and different types of stationary monitors either for individual pollutants or multi-pollutant concentrations have been developed and applied in research (Branis, 2010; Demokritou et al., 2001; Wallace, 2007; Wallace and Ott, 1982).

Knowing when an individual was exposed to which concentration and for how long is a key factor to understand the causal chain of exposure related health impacts. Studying the heterogeneity of individual exposure provides a basis to draw conclusions for larger populations.

Table 1. Assessing human exposure to air pollutants – comparing static and dynamic personal exposure approach.

Exposure assessment	**Personal exposure assessment**
"*Contact between and agent and a target. Contact takes place at an exposure surface over an exposure period."* (Zartarian et al., 2007, p. 58)	"*…measurement of a pollutant of concern performed by a monitor (or sampler) worn by a person while the sample is taken from a point near the breathing zone of the person…*" (Branis, 2010, p. 100)
• Pollutant concentration(s) taken from national air quality networks or specifically set up monitors • Fixed monitoring sites (static) • Mean values (statistics) • Exposure estimates assigned to a population/geographic unit • Long term exposure	• Specifically set up monitoring campaigns and equipment • Monitor(s) worn by a person • Real-time concentrations • Exposure estimates for the person wearing the monitor • Short term exposure

3.1 Microenvironments - Monitoring pollutants where the action takes place

The concept of microenvironments (MEs) is used in most exposure studies to connect exposure to a specific, homogenous "space". Within the EXPOLIS study (Schweizer et al., 2006), for instance, the amount of time participants spent in certain indoor MEs has been analysed and compared for seven regions in Europe, as individual's whereabouts largely determine their exposure. The term microenvironment is defined as "*a chunk of air space with homogenous pollutant concentration*" (Duan, 1982, p. 305). Two possible approaches to assess human exposure based on the concept of MEs exist (Duan, 1982): One is the *direct approach* where exposure is measured directly, the second option is the *indirect approach* where time allocations and pollutant concentrations are measured separately and subsequently combined to reconstruct exposure. It is important and necessary to categorise different MEs into groups or categories, as people move around and are exposed in many different environments and activity spaces with different pollution levels. These categories are also a crucial element of structured questionnaires and TADs, relating activities to a spatial unit.

According to WHO (2005b) most people spend around 20% of their time at work, school or other locations away from their residence and approximately 4% in transit. The most common MEs used for measurements in exposure studies (e.g. Jantunen et al., 1998; Lai et al., 2004; Wu et al., 2005) reflect this: *indoor home*, *outdoor home*, *other indoor/outdoor* (work, school) and *transport*. It has to be noted, that air quality within any ME may differ substantially depending for instance on the location of pollution sources. The *home* environment is an important ME, also regarding the time-budget, within which the pollution level is highly variable. More research in form of detailed case studies would be beneficial for this specific ME. Commonly, only one monitor representing indoor exposure is combined with measurements from a monitor outside a subject's house. Cost factors often limit the number of monitors applied as well as the sampling time (Briggs, 2000). Such ME measurements can be integrated with or compared to personal monitoring (e.g. Harrison et al., 2002; Lai et al., 2004; Monn et al., 1998). The validation of ME measurements with personal monitoring data provides a comparatively detailed exposure assessment on individual level. Pollutant concentrations measured in the MEs are usually combined with time-activity data to derive the time a person has spent in a ME.

Data from a routine air quality monitoring network site is often incorporated for comparison and to investigate relationships between concentrations observed in MEs and personal measurements respectively (e.g. Gulliver and Briggs, 2004; Physick et al., 2011; Piechocki-Minguy et al., 2006; Wu et al., 2005). This allows to test if the fixed-site monitor can be considered representative of the area of interest, which is often not the case, Micro-environmental and personal measurements can be quite different for the same person/location (Rodes et al., 1991).

Study designs regularly focus on a single ME which is then investigated in detail. The *transport* ME has received much attention in environmental exposure studies (Colbeck and Nasir, 2010; Hertel et al., 2001b; Kaur et al., 2007; Knibbs et al., 2011; WHO, 2005a). Road traffic represents one of the most important sources of air pollutants, accounting for about half (49%) of total emissions of NO_x in the UK in 2000 (Air Quality Expert Group, 2004). People spend a considerable amount of time, in general 1-1.5 hours per day (WHO, 2005a) in this ME, be it commuting to work or travelling for leisure. As a result, some studies focus on different aspects in the transport ME applying a wide range of monitoring and modelling approaches to gain detailed information about exposure (e.g. Gulliver and Briggs, 2004; Kaur et al., 2005; Thai et al., 2008).

3.2 Report based approaches - Time-activity diaries and questionnaires

TADs and questionnaires are essential tools in personal exposure research covering data on human behaviour and activities (Lioy, 2010). Exposure studies such as the TEAM studies (Hartwell et al., 1987; Wallace, 1989) or the *Air Pollution Exposure Distribution of Adult Urban Populations in Europe* (EXPOLIS) study (Jantunen et al., 1998), have applied these tools to gather data about the participants' whereabouts and activities. This data is transformed into information needed to relate exposure to certain places, times and activities. Indoor exposure, for instance, results from interactions between building characteristics, furnishings, outdoor environment and the individuals acting in this environment. These indicators can all be qualified and quantified with the help of TADs and questionnaires (Mitchell et al., 2007). Compiling TADs and questionnaires is relatively inexpensive and can be used in manifold ways. But while they are traditional tools for time-location studies, concerns regarding recall bias and reliability have been discussed by Crosbie (2006) and Freeman and Saenz de Tejada (2002). Such concerns are of a generic nature for these tools but forms should in any case be tested beforehand regarding reliability and validity (Freeman and Saenz de Tejada, 2002; Monn, 2001).

Complication or bias can be introduced by posing confusing questions or questions being framed in a way leading participants to answer in a particular direction. Bias is also a problem when people need assistance to complete the forms (Freeman et al., 1999). Another difficulty can be the language barrier for non-native speakers (Elgethun et al., 2007). In general, time requirements of the survey process need to be kept low in the interest of the participants, encouraging them to fill in the form without getting bored and to reduce recall bias (Crosbie, 2006; Freeman et al., 1999; Freeman and Saenz de Tejada, 2002).

The format of TADs and questionnaires is crucial. An open format enables participants to record their activities and other characteristics in their own words. Often, however, a more structured format where activities and MEs are pre-grouped is preferential as answers are easier to evaluate (Crosbie, 2006). Historically, TADs in paper format were used, but more recent studies employ small electronic devices such as smart phones or PDAs (Wu et al., 2005). This resulted in data recording becoming more flexible in space and time (Ohmori et al., 2005) and the burden for study participants being minimised (Dons et al., 2011).

A questionnaire has to be filled in usually only once during the study period or it is conducted as an interview (Freeman and Saenz de Tejada, 2002). In addition to the detailed information of the TADs, questionnaires collect supporting contextual data about the participants, including their residence. In the same way as for recording TADs, well structured and precise electronic questionnaires can provide a viable, low-impact option. However, TADs and questionnaires require literacy, a sense of time and a certain degree of commitment. It is useful to train the participants beforehand in how to correctly use the forms (Elgethun et al., 2007; Freeman et al., 1999; Freeman and Saenz de Tejada, 2002) especially when they are presented on electronic devices.

Electronic communication also enhances direct contact between researchers and participants during the study period. In order to get satisfactory response rates, Crosbie (2006) note that this direct contact with the person during the study was conducive to the quality and quantity of the responses received. Face-to-face-interviews instead of (or in combination with) electronic questionnaires can be considered a reliable method.

Keeping a detailed and accurate record of time-activities can be laborious and the active cooperation of the participants in the monitoring process has to be fostered. Interference with the participants' usual behaviour and lifestyle needs to be reduced to a minimum. Facilitating the process of gathering time-activity data for example by utilising Global Positioning Systems (GPS) (e.g. Elgethun et al., 2003; Houston et al., 2011) aims at achieving this. This method provides objective time-activity data and can help reduce the intensity of keeping TADs (Wu et al., 2012). Relating data from GPS devices and TADs, however, can be challenging because it requires the translation of geographic coordinates into descriptions of real locations and activities. Time mismatches between the two datasets are an issue and the common way to match this data by manual processing is time intensive (Mavoa et al., 2011; Wu et al., 2012). In addition to that, not all study participants may be familiar with or keen on using electronic devices. Thus, the application of advanced communication technology may result in anxiety and misuse, potentially limiting the applicability of these methods (Bricka et al., 2012).

3.3 Personal monitors - Monitoring pollutants while the action takes place

Personal monitoring studies are often conducted as non-representative pilot studies as they are cost-, time- and labour-intensive. Derived exposure estimates form part of the bigger picture aiming to eventually improve or contribute to policy advice and Health Impact Assessment (HIA) (Quigley et al., 2006). According to Flachsbart (2007), many exposure analysts believe that this direct approach provides the most accurate estimates of exposure as the actual exposures of people during their activities is surveyed, in contrast to calculations from static concentration data from fixed-site network monitors.

Personal monitoring approaches assess an individuals' exposure based on measuring the concentration of a pollutant ideally within a person's breathing zone for a defined time. As people move through the changing pollution field, their individual exposure varies. To record these variations, portable devices are required (Briggs, 2000). Ideal monitors allow measuring the pollutants as closely as possible to the breathing zone providing the most accurate information about the actual exposure variability (Elliott et al., 2000). As a general rule, personal monitors should be portable and not interfere with the person's usual behaviour and habits throughout the day. They should be flexible, robust and user friendly, as well as lightweight and battery operated (or passive) (Branis, 2010; Lippmann and Lioy, 1985; Monn, 2001; Nieuwenhuijsen, 2000; Wallace and Ott, 1982). Sophisticated devices are capable of measuring air pollutant concentrations at resolutions ranging from seconds to minutes. Short-term or peak exposures can be measured reliably in time (Adams et al., 2009) which is often not feasible with methods integrating concentrations over larger time scales, especially passive samplers, which tend to miss peak exposures. Early versions of personal monitors allowing conducting actual personal monitoring studies have emerged from industrial/occupational studies (Sherwood and Greenhalgh, 1960; Wallace and Ott, 1982). Those devices were, however, not yet capable of sampling, storing and manipulating data. Wallace and Ott (1982) describe the issue of manually writing down large quantities of data and the development of a personal CO monitor with an internal data-logging system to successfully generate personal exposure data.

With a scripted study design (i.e. technicians or volunteers follow scripted activities in certain locations which are representative for high exposure situations (Lioy, 2010) the issue of behavioural changes of the participants when wearing a monitor is avoided. Several such studies applied passive NO_2 samplers (Monn et al., 1998; Physick et al., 2011; Piechocki-Minguy et al., 2006). Passive samplers have the advantage of being comparatively inexpensive, not requiring power and being wearable on outer clothing. However, lack of accuracy and the ability to only record time-integrated concentrations (Branis, 2010; Monn, 2001) are downsides of passive samplers.

Passive particulate matter monitors are applied as well for different size fractions (Kaur et al., 2005). More often real-time devices are used to measure particulate matter in different size fractions (Cattaneo et al., 2010; Gulliver and Briggs, 2004; Wu et al., 2005), as well as for gaseous pollutants such as O_3 (Wu et al., 2005) and CO (Kaur et al., 2005). Ambient concentrations are often below the detection limit of commercially available gas samplers and these are thus mainly used in occupational settings (Monn, 2001).

3.3.1 GPS enabled personal monitoring

The use of Global Positioning System (GPS) receivers, which record location and time simultaneously, provides a freely accessible technology to determine an individual's location at a given time. GPS operates by measuring the time delay of radio signals that have been transmitted from satellites to GPS receivers on earth (U.S. EPA, 2003). Precision of the coordinates given by the GPS receiver varies based on the receiver design as well as on the signal strength and potential blockage of signal. Elgethun et al. (2003) for instance utilised GPS units integrated in clothing with resulting root mean square errors for a spatial resolution of between 3 - 3.4 m outdoors and 5.7 - 5.9 m inside a wood-frame house.

Traditionally, studies looking at human exposure to environmental air pollution such as the TEAM studies (Wallace, 1987), the National Human Exposure Assessment Survey (NHEXAS) (Freeman et al., 1999) or the National Human Activity Pattern Survey (NHAPS) (Klepeis et al., 2001) were relying on TADs and/or questionnaires to gain information about the participant's activities and locations visited during the study period. GPS receivers and technology have been applied successfully, often in addition to these traditional methods, in small, non-representative, studies to facilitate the study of human time-activity patterns to a certain degree. The idea of using these active locating devices in combination with active (often miniature size) pollutant sensors is to measure and consolidate concentration, location and time directly without requiring the participant's intervention. It has to be emphasised that GPS is not a standalone tool for exposure research since it can only give information on location and time. A well designed integration of GPS with personal pollution monitors, ME measurements and activity and behaviour information though can enhance exposure research (Lioy, 2010). Personal exposure profiles towards changing environmental influences, which differ from other individuals as well as the population average, can be derived. GPS data also serves as model input for exposure studies based on individual movement patterns or routes (e.g. Davies and Whyatt, 2009; Gerharz et al., 2009).

A series of recently published, non-representative, (simulated) personal exposure studies applied GPS receivers as a tool for monitoring people's movement to derive potential exposure. Zwack et al. (2011) investigated the contribution of local traffic to PM concentrations in street canyons of Manhattan. GPS receivers continuously tracked the volunteer's movements along designated walking routes at specific times. All instruments were placed in a backpack, measuring pollutant levels of ultrafine particles (UFP) and $PM_{2.5,}$ as well as temperature and relative humidity, averaged over a one minute time-step. Volunteers also recorded traffic flow characteristics in a log-sheet. A similar approach, using predefined routes and sampling times in urban environments, was developed for measuring real-time particle number concentrations (PNC), $PM_{2.5}$ and noise while cycling and driving in a car in eleven cities in The Netherlands (Boogaard et al., 2009). GPS receivers were also applied together with portable aerosol monitors in a simulated study investigating pedestrian exposure in busy traffic MEs in Sydney (Greaves et al., 2008). Thai et al. (2008) investigated exposure to PM along designated bicycle routes in Vancouver applying particle counters and GPS receivers. A similar set up was used by Cole-Hunter et al. (2012) who investigated exposure to inhaled particle counts on bicycle commutes in Brisbane.

In a study in Belgium (Dons et al., 2011) eight couples were observed during their normal activities, one being a homemaker, the other partner being in full-time employment, thus both having very different time-activity patterns. The study investigated the impact of time-activity differences on personal exposure to black carbon (BC) over a week. A portable monitor measuring BC in five minute intervals was carried in a backpack or handbag with the inlet exposed to the air. GPS coordinates were recorded on a PDA that also served to record the TAD; questionnaires were handed out at the beginning of the monitoring period. A stationary monitor was installed outside the house for simultaneous measurements. Results for the respective categories are shown in Table 2. Findings emphasise the relevance of studying everyday exposure over several days: *"Differences in exposure between members of a family originate from differences between their time-activity pattern and the corresponding locations visited."* (Dons et al., 2011, p. 3597). Differences between the households have been found to be larger than between the partners of one household, highlighting the challenges of up-scaling from individual to population exposure.

Table 2. Concentrations of Black Carbon (BC) measured per activity, per location and per transport mode (based on Dons et al., 2011).

Categories analysed	Activity	Location	Transport mode
Highest concentration	In transport	In transport	Car
	Shopping	Other	Bike
	Social and leisure	Work/School	On foot
BC measured (ng/m^3)	Go for a ride	Family/Friends	Train
	Other	Home	-
	Work	-	-
Lowest concentration	Home-based activities	-	-
	Sleep	-	-

GPS and time-activity data also serve as an input to exposure models. A novel model for individual exposure has been developed by Gerharz et al. (2009) (Figure 2). GPS data and information from TADs and questionnaires were collected and combined with $PM_{2.5}$ concentrations from existing data sources and models to derive a novel approach for modelling indoor and outdoor exposure. Daily average exposure values of derived profiles show a strong influence of individual behaviour. Although functional, there are limits to the general applicability of this methodology due to simplifications and assumptions adopted such as the qualification of indoor activities for which the TAD was used and where the GPS sensor cannot receive a signal.

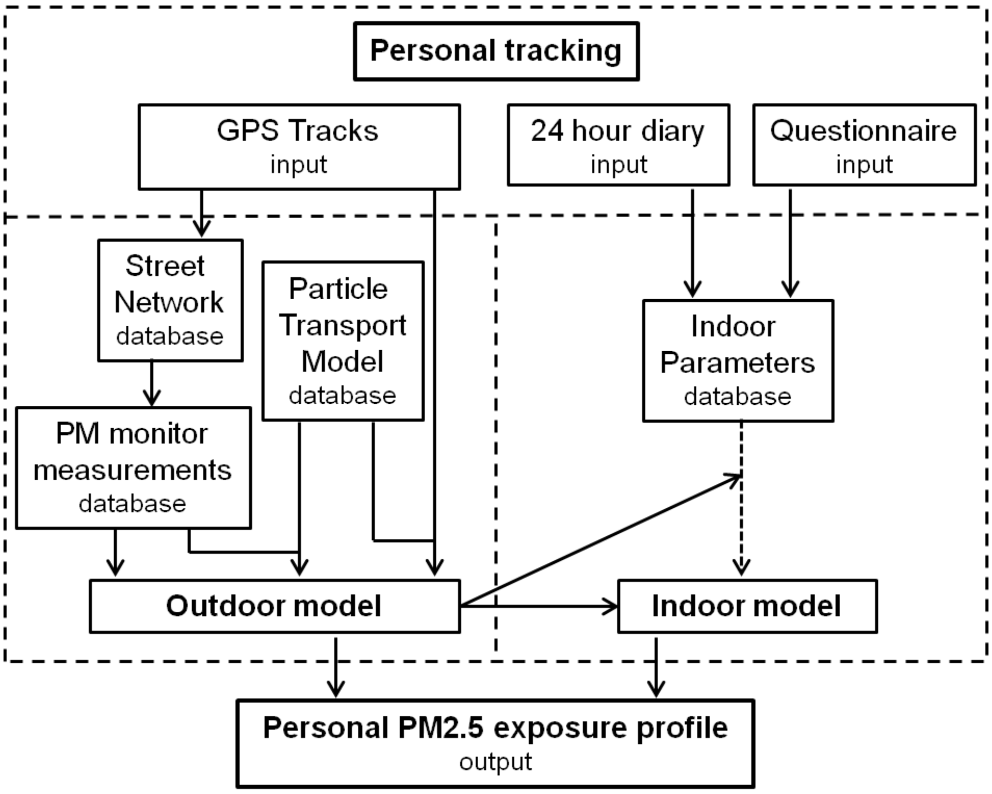

Figure 2. A novel approach for modelling individual exposure to $PM_{2.5}$ (adapted from Gerharz et al., 2009).

Differences in survey-reported and GPS-reported trips for a 24 hour period were investigated by Bricka et al. (2012). Data were selected from the 2009 Indianapolis regional household travel survey. As a conclusion, the authors recommend the use of both a GPS receiver and traditional time-activity survey methods in tandem. However, the authors also highlight the fact that not all individuals are "…*technology savvy*…" (Bricka et al., 2012, p. 87) and the use of traditional survey methods is thus recommended for some population groups.

The application of both methods, TADs and GPS, for data collection also significantly improved the amount and quality of time-location data in comparison to collecting data solely through TADs in a study in Los Angeles (Houston et al., 2011). Mobility information collected with GPS receivers and TADs also improved exposure models in a study in Vancouver even though only about half of the GPS tracks were "complete" i.e. did not have large time and/or space gaps between logs (Nethery et al., 2008a). The feasibility of using GPS receivers for tracking individuals in their everyday environments has also been studied by Adams et al. (2009), (Elgethun et al., 2003; Elgethun et al., 2007), Phillips et al. (2001) and Rainham et al. (2008) who were looking into methodology, potential and limitations when using GPS sensors for exposure assessment and the validation of TADs. The main problem when using GPS devices is that the satellite signal is often not strong enough for use inside buildings or near certain materials such as steel–reinforced constructions, body panels and other electrically conductive material (Phillips et al., 2001). There are certain factors which limit the accuracy and operability of GPS receivers, which are unavoidable or beyond the researcher's control (Rainham et al., 2008) such as (overseas) military control over GPS satellites, although new commercial GPS satellite networks are launched which will not be subject to military control. Most of these influences are usually measurable and well known and can be taken into account when studies are designed. Adams et al. (2009) highlight alternative and supplementary technologies to improve GPS signal strength such as a GPS signal repeater or radio-frequency-identification (RFID) for improving positioning indoors. Other alternatives are ultrasound (Allen-Piccolo et al., 2009) or small cameras which not only help locating where the person has been but also record behaviour objectively (Broich et al., 2012). To distinguish between indoor/outdoor activities, light, temperature and/or humidity sensors can provide relevant information.

The development of portable personal exposure monitoring devices is a fast evolving field and incorporates everyday devices, such as smart phones. An example is the portable, real-time exposure monitoring system which was developed and described by Negi et al. (2011). It consists of the monitoring device which is able to *"...reliably detect low ppb concentrations of total hydrocarbons and total acids..."* (Negi et al., 2011, p. 425). This device communicates wirelessly with a smart phone which serves as user interface as well as for processing monitoring data, adding GPS information and to display concentration profiles. The authors anticipate that this device will be applied as a tool for personal exposure monitoring. In the future we might also consider clothes with in-built sensors (Van Laerhoven et al., 2002) as a progression from the ideas presented by (Elgethun et al., 2003).

4 Discussion

4.1 Personal monitoring – pieces of the puzzle?

Personal monitors measure pollutant concentrations as close as possible to a person's breathing zone and provide the most accurate data about actual personal exposure. Regularly conducted comparisons of concentrations measured by personal monitors, fixed-site monitors, stationary ME monitors or even in the direct vicinity of the subject indicate substantial differences in concentration and thus establish a preference for the use of personal monitoring techniques to collect reliable individual exposure information (Cattaneo et al., 2010; Greaves et al., 2008; Gulliver and Briggs, 2004; Kaur et al., 2005; Piechocki-Minguy et al., 2006; Wu et al., 2005).

Requirements for personal monitor devices are similar to those for TADs – interference with the person's everyday habits should be kept at a minimum. Applying personal monitors and collecting time-location information requires a careful study design and substantial commitment from study participants. Hence most of the studies focus on measuring exposure utilising scripted setups. The emphasis of these studies is on specific exposure processes which are an important part of the whole picture. Personal exposure in other MEs is not taken into account by these simulated study designs, which are thus not contributing to a comprehensive assessment of every-day exposure. Personal monitoring studies are required, and so are further development and novel approaches in study design and sensor technology. Based on a growing pool of commercially available sensors and other technologies it is possible to produce custom made monitors for specific study aims and designs. The general popular use of electronic devices simplifies the use of such technologies for recording exposure information to some extent. Younger generations are familiar with these devices whereas difficulties can arise when study participants are not used to handling smart phones or PDAs. We have developed a novel conceptual model, reflecting the potential of these new developments (Figure 3). This new model incorporates latest technological and methodological developments and goes beyond traditional approaches as outlined in Figure 1.

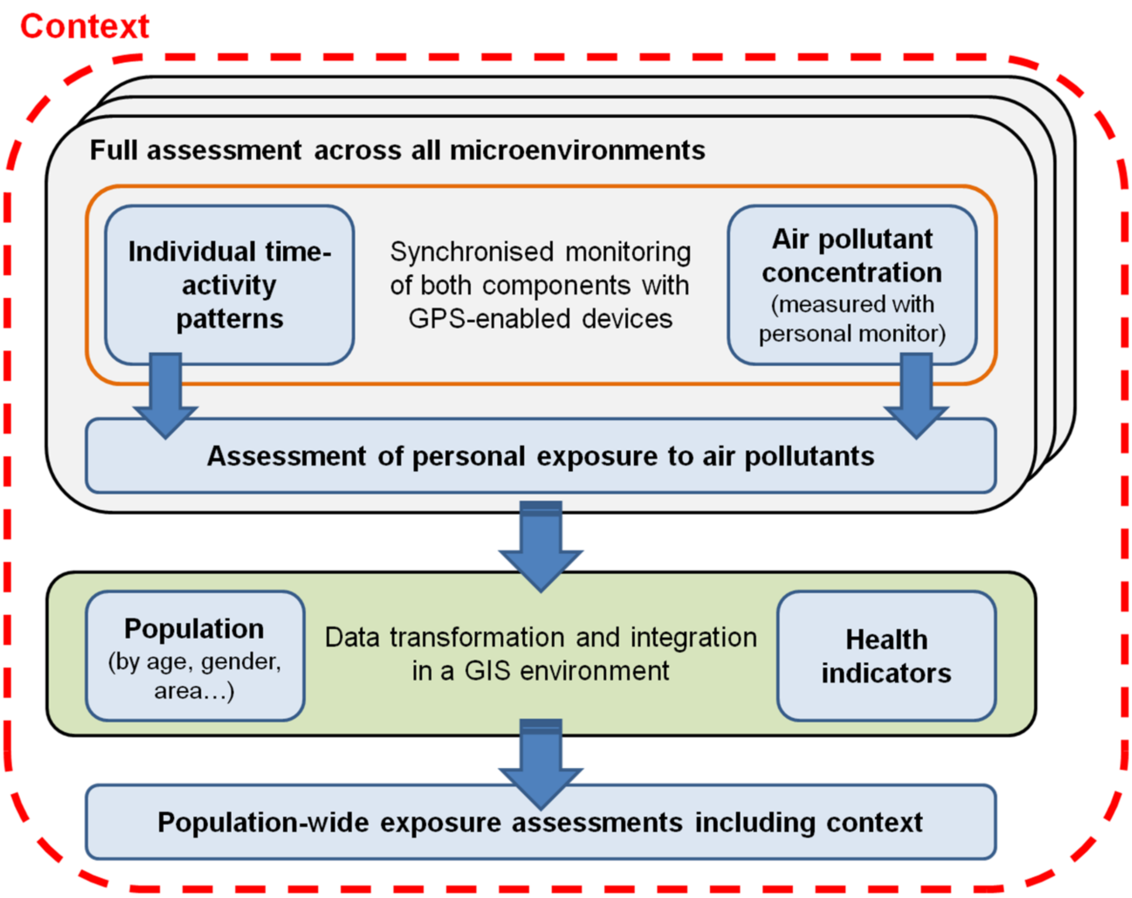

Figure 3. Novel conceptual model for the assessment of individual and population-wide exposure to air pollution including effects (health factors) and context

The literature reviewed generally applies a simulated observational study design focussing on specific exposure situations. These are mainly selected urban areas and the comparison of transport modes used. It is clear that there are many more pollution sources beyond traffic and outside of busy urban areas. While the heterogeneity of individual exposure in a certain ME has to be considered, it is also vital to reflect the heterogeneity of MEs in an individual's life. This requires greater acknowledgement when implied in future studies, by expanding the monitoring area into other MEs of people's everyday life.

4.2 Personal monitoring – Following every move?

Portable GPS receivers represent the latest technique for tracking movement patterns as they actively log location and time. Study designs applying GPS technology (e.g. Greaves et al., 2008; Zwack et al., 2011) are similar to personal monitoring studies which do not apply GPS receivers - looking at designated routes and times in specific MEs (e.g. Gulliver and Briggs, 2004; Kaur et al., 2005). Few studies so far (e.g. Dons et al., 2011; Gerharz et al., 2009) cover the heterogeneity of a person's everyday MEs. Results from studies investigating the potential and feasibility of GPS receivers in exposure assessment (e.g. Adams et al., 2009; Rainham et al., 2008) encourage the use of GPS tracking to monitor individuals in the full range of environments.

Inherent problems with signal quality/interference in certain areas can be detected and logged to take account of and correct for in the analysis. Further research will need to evaluate alternative technologies and methods which can support or substitute GPS technology in certain situations. These can be methods to improve the actual GPS receiver, or other technologies such as radio frequency identification (RFID), ultrasound or cameras. Additional sensors for measuring environmental factors such as light, temperature and humidity could complement this.

Regarding the design of exposure monitors, the most promising way forward is the development of small and light-weight devices which are non-intrusive and have a low impact on a person's everyday activities. Improvements in this area depend strongly on developments in sensor technology and miniaturisation which is progressing steadily. There are also requirements for the packaging as the device needs to be portable. High sensitivity, small footprint, lightweight and battery operated are a few features that describe the challenges in designing monitoring equipment, carefully taking into account the potential trade-off between individual features. It is also worth considering the integration of all sensors in one device and synchronising their data logging to generate a common output file with one timestamp. Such an integrated, GPS enabled (or alternative technology) personal monitoring device could substantially improve data handling and accuracy (which becomes more important with the increasing size of datasets generated), while reducing the potential for time shifts and human error when aligning datasets. It is also necessary to reduce costs of these monitors to increase sample size for exposure models or eventually apply this technology in representative studies. Exposure models also need to integrate a wider context (e.g. social, economic and demographic factors), to assess relations and associations between human exposure to environmental air pollutants and potential health effects.

4.3 Privacy or confidentiality concerns

Environmental monitoring is necessary to generate robust evidence for the development of effective environmental and public health policies. It is partly done by volunteers who, for instance, changeover samples at an air quality monitoring site or monitor a species occurrence (e.g. BTO http://www.bto.org/about-bto). According to Mackechnie et al. (2011) volunteers sometimes have pre-existing personal interest in the topic encouraging them to be part of the research community.

Assessing personal exposure to environmental air pollution does not only rely on measurements of the state of the environment, but equally on tracking individuals, their activity patterns and behaviour. This means it needs to be based on the willingness of individuals to take part in the research and reveal details of their personal activity and environment. People are increasingly under surveillance nowadays and concerns of being constantly tracked and observed is more present than ever. CCTV cameras, smart phones, loyalty cards, for example, record our movements and habits often without the knowledge or consent of individuals. We are aware that a personal exposure study design needs to record an individual's activities, habits and personal circumstances. This could be seen as an infringement of personal space and territory. However, anonymisation of data and a dedication to good practice and the implementation of secure data storage in handling individual datasets contribute to reducing the potential for misuse of datasets. With these precautions taken, we propose that the advantages gained through personal exposure studies for air quality improvement and health protection both for the individual and the general population outweigh the disadvantages for an individual taking part in the study.

5 Conclusions

The literature discussed indicates a trend towards real-time tracking of individual time-activity patterns for personal exposure assessment. GPS receivers are becoming widely used to analyse how people move through different MEs and hence experience varying exposure to air pollutants in the respective MEs. In combination with GPS receivers, portable active pollutant monitors can directly relate pollutant concentrations to time and location.

At the same time, small electronic devices such as smart phones are gradually substituting the classic paper-format questionnaires and TADs for recording additional contextual information. Overall, technological developments enable less time-consuming and more efficient, user friendly and inexpensive monitoring and documentation techniques which provide the opportunity for low-cost environmental exposure studies.

Active personal pollution monitors provide concentrations measured with high spatial and temporal resolution in contrast to fixed site or stationary indoor monitors that usually generate temporally aggregated, averaged data for a certain spatial unit. Personal exposure estimates derived from real-time monitors are inherently different from approaches using aggregated data. One limiting factor for the development of small, real-time mobile devices is the availability of low-power, high sensitivity sensors for priority air pollutants.

There is room for improvement regarding the accuracy of GPS based exposure studies. Methods for improving the applicability of GPS receivers especially in indoor environments need to be considered and assessed for future studies. Combining sufficiently accurate GPS data with information from TADs and questionnaires enables a detailed assessment of time-activity.

Regarding personal exposure study design, we question whether the development of study design is keeping up with the development in monitoring technology. Many of the studies analysed are scripted and focus on single MEs only. By not taking into account all exposure situations people experience during their daily routine, personal exposure assessment remains incomplete and conclusions on total personal exposure are thus not possible.

A reason for a lag in new technologies influencing study design may be that the study designs, in spite of the potential offered by new technologies, are often limited by past experiences and previously applied approaches. An interesting example of a novel study design is given in a study from Belgium (Dons et al., 2011), which focuses on monitoring exposure in people's everyday environments rather than a selected ME only. Findings show that time-activity patterns as well as the general setting of an individual's activity-space (urban/rural/suburban) determine personal exposure to environmental pollutants. As a consequence a combination of exposure monitoring methods (TAD, questionnaires and GPS) as recommended by several studies can be seen as the way forward. By tracking the actual movements of a person in space and time while at the same time collecting information on environments and other characteristics such as transport mode, housing type, residential area, more determinants of exposure can be incorporated.

Having reviewed the literature we can see that the approaches applied are sufficient to assess the exposure situation in a specific single ME. To gain information about exposure in all MEs a person is moving in during a specified period of time however, the simulated approach has to be taken a step further. It is time to expand studies to include the observation of personal exposure in everyday environments. Thus, we expand the traditional approach depicted in Figure 1 towards a comprehensive conceptual model for personal exposure assessment in the full heterogeneity of MEs as well as for population-wide exposure assessment, including context (Morris et al., 2006 and Figure 3). Taking into account context can, in particular in connection with TADs and questionnaires, provide additional socio-economic, demographic and environmental information that may affect health effects of a potential exposure.

The conceptual model incorporates, for the first time, the diversity of MEs a person spends time in during a day and enables analysis of exposure in a more realistic setting including everyday activities..

Secondly, this conceptual model has been designed to use individual exposure estimates to derive population-wide exposure estimates and investigate their implications for public health. The up-scaling process is necessary as health policies target the improvement of population health, rather than focusing on individual health outcomes.

It is evident for the design of future studies that utilising new technologies which are now mature enough to be applied is of vital importance. The same can be said for moving away from analysing specific, selected MEs towards directly monitoring exposure in people's everyday life. This is particularly important if the monitored data is used as input for exposure models. The technological leap for monitoring pollution and tracking activity patterns has been considerable in recent years. Main areas of improvement identified are the incorporation of an expanded environment, the improvement and combination of monitoring methods, including the direct measurement(s) of a wide range of indoor and outdoor pollutant concentrations. GPS-enabled monitoring devices enhance a detailed analysis of human exposure to environmental determinants of health. Still, we believe that a more integrated approach using a device logging location, time and environmental variables simultaneously can substantially improve the accuracy of the data analysis.

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