Co-developing strategies to reduce exposure to fine particulate matter ($PM_{2.5}$) in Scotland

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COVID-19 Impact Statement

The COVID-19 pandemic occurred 6 months into this PhD, having a substantial impact on the planned project.

Government directives to halt 'non-essential' work and the university's instruction to delay fieldwork resulted in considerable delays of approximately nine months to the original planned project. As such we had to make strategic adjustments, such as reducing the number of follow-up visits (detailed in chapter five) and removing some work around feasibility of application of the intervention (also detailed in chapter five). Fieldwork constraints, however, provided opportunities for unanticipated work, such as the published literature review included in chapter two.

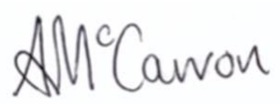
The primary issue however was the project’s target sample (people with asthma) being a group classed as ‘vulnerable’ or ‘extremely vulnerable’ under government COVID-19 guidance and advised to ‘shield’. This prolonged the start of the study further owing to a duty of care we had to ensure participants were safe and comfortable taking part in the project. Shielding advice was to minimise interactions with others. Though by the time fieldwork eventually started shielding restrictions had eased, undoubtedly the residual effects of this will have impacted recruitment.

Logistical changes were necessary for the altered fieldwork, with semi-structured interviews (detailed in chapter three) taking place online via Zoom. These adjustments not only impacted the project's dynamics, but also placed a significant financial burden on the research budget due to the need for shipping equipment instead of in-person handovers.

Statement of Originality

I hereby confirm that this PhD thesis is an original piece of work conducted independently by the undersigned and all work contained herein has not been submitted for any other degree. Where appropriate, I have acknowledged the nature and extent of work carried out in collaboration with others.

All research material has been duly acknowledged and cited, and ethical approval has been obtained for all research activities where necessary.



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Mum and Dad, be it my primary school 'Knights and Castles' and 'Ancient Egyptians' projects, or my (slightly larger) 'Co-developing strategies to reduce exposure to fine particulate matter ($PM_{2.5}$) in Scotland' project, you have selflessly supported and

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Gran, you lit a candle for every test, exam, and interview I ever sat (despite my warnings of the impact this will have had on your indoor air quality!). I truly believe I wouldn't have gotten to this stage without this support. I can see you're still lighting candles for me! You'll have the best seat at graduation!

Abstract

Air pollution is the world's greatest environmental health threat, and exposure to air pollution is responsible for 7 million premature deaths every year, attributed to illnesses such as ischaemic heart disease, stroke and lung cancer. Fine particulate matter is a significant pollutant from a health perspective since it can penetrate the thoracic region. While policies and legislation to improve ambient air quality are vital, these are slow to implement and take effect. It has been argued that for more immediate health benefits, and for people to have greater control over the quality of the air they breathe, air quality-related policies must be supplemented with individual-level behavioural changes aimed at reducing personal exposure to air pollution. Personal exposures, the pollutant concentrations experienced by an individual as they move through space and time, are influenced by the environments people spend time in and the activities they partake in. Thus, personal exposures can be modified by behavioural changes. Air quality-related behaviours and behavioural changes are influenced by complex and interlinked factors, such as information provision and awareness. These need to be considered in public engagement programmes aimed at promoting behavioural change. This interdisciplinary thesis aimed to co-develop strategies, separately with people with asthma (as a group susceptible to the effects of air pollution) and with members of rural communities (often overlooked in air quality monitoring) in Scotland, to promote awareness of air pollution and support exposure-minimising behaviour changes, using methods from environmental science, social science and health behaviour psychology. Interviews conducted with people with asthma found that past experiences, misconceptions, and their sense of control, play a fundamental role in shaping air quality-related behaviours. Exploring the theoretical steps linking air quality information provision to behaviour change suggested that strategies to engage individuals with air quality data for behaviour change require a combined approach which simultaneously increases the relevance of data provided and increases participation. Applying and empirically testing this strategy to different degrees with people with asthma and rural communities, proved that it can enhance engagement and, significantly, demonstrated its ability to alter individuals' misconceptions about their personal exposure or local air quality. However, its ability to support air quality-related behaviour change was more limited, with a more personalised strategy required to achieve this. For exposure-minimising behaviour change and subsequent public health benefit, a personalised approach to monitoring with a more supported behaviour change co-development strategy is therefore recommended. Current air quality information can be improved to better support and empower behaviour change.

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Chapter 1 | General Introduction

1.1 Air quality: an evolving human health issue

Though the observed effects of air pollution on human health far predate the 13th century (Fowler *et al.*, 2020), in the UK context, the first notable formal reference to air pollution as a human health issue in legislation was in the 1273 Smoke Abatement Act which prohibited the burning of 'sea-coal' in London, recognising that it was 'prejudicial to health' (Heidorn, 1978). Targeting emissions of what we now know to have been sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and particulate matter (PM), this was the first piece of UK legislation enacted to stop emissions of harmful pollutants with the goal of improving public health (Sanderson, 1961; Woodin, 1989).

By 1662, John Graunt had started to establish the epidemiological evidence associating air pollution, particularly in fog events, with increased mortality in London, hypothesising that London's public health issues originate from exposure to polluted air (Graunt, 1662). Graunt (1662) observed that "little more than one of 50 dies in the Country, whereas in London it seems manifest that about one in 32 dies, over and above what dies of the Plague", with Graunt attributing the increased mortality to the effects of air pollution (Brake, 1975).

The Industrial Revolution (1772-1840) brought a marked change in UK air quality with increased industrial emissions, emission from domestic burning and emissions from waste (Sutton *et al.*, 2020). However, it was not until the Great Smog of London in 1952 that the air quality landscape fundamentally changed. Resulting in what is now estimated as 12,000 premature deaths, the Great Smog altered air quality legislation, how air quality is monitored, and importantly, political and public perception (Read and Parton, 2019; Fowler *et al.*, 2020). Air pollution was no longer considered as just an inconvenient by-product of industrial and economic growth. In response to the Great Smog of 1952, the UK Clean Air Act 1956 was enacted introducing a number of measures to improve ambient urban air quality and improve public health, including the introduction of Smoke Control Areas, setting minimum heights of chimney stacks and promoting the use of cleaner fuels, as examples, which would eventually lead to the widespread reduction of ambient SO_2 and PM in urban areas (Fowler *et al.*, 2020).

In addition to the UK's Clean Air Act and its subsequent amendments, the introduction of increasingly stringent air quality legislation and regulation (such as the European Union's Air Quality Framework Directive and Industrial Emissions Directive) have helped to tackle ambient air pollution (Sokhi *et al.*, 2022). Additionally, the 2021 revision of the World Health Organisation's air quality guidelines, informed by a more robust body of literature demonstrating the health effects of air pollution at lower concentrations than previously thought, established significantly reduced guideline values for specific air pollutants to safeguard public health (World Health Organisation, 2021). Moreover, recognising the multiple interconnected benefits of good air quality on human health, the environment, society and the economy on a global scale, air quality crosscuts several of the Sustainable Development Goals, namely within SDG 3 (Health and Wellbeing), SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Societies) (United Nations, 2015). Together these initiatives have meant that outdoor air quality in the UK (and in most high-income countries) has significantly improved (Chief Medical Officer, 2022).

The improvement of ambient air quality has led to suggestions that "the world has passed the peak in air pollution problems" (Fowler *et al.*, 2020, pg. 21). Yet, as of 2023, an estimated 7-9 million people die prematurely every year as a result of exposure to air pollution (Murray *et al.*, 2020; World Health Organisation, 2020b; Fuller *et al.*, 2022), predominantly in low- and middle-income countries. Even in the UK however, a high-income country with some of the most stringent air quality legislation globally, and forecast to achieve the interim target of $10\mu g/m^3$ for $PM_{2.5}$ by 2030 (Dajnak *et al.*, 2023), between 26,000 and 42,000 premature deaths occur every year as a result of breathing polluted air (Macintyre *et al*. 2023). Building upon Graunt's initial observations about the impact of air pollution on human health, subsequent research has shown that the health impacts of air pollution span the entire life course (Fuller, Friedman and Mudway, 2023). Foetal exposure has been shown to lead to unfavourable birth outcomes such as low birth weight and preterm birth (e.g., Smith *et al.*, 2017; Fu *et al.*, 2022; Niu *et al.*, 2022). Exposure during childhood and adolescence has been associated with various issues, including both physical and psychological developmental challenges (e.g., Latham *et al.*, 2021; Reuben *et al.*, 2021). Furthermore, exposure in adulthood and old age has been linked to conditions such as cardiovascular and respiratory problems, which can ultimately contribute to premature mortality (e.g., Lelieveld *et al.*, 2015; Khomenko *et al.*, 2021). Additionally, air pollution is recognised as a triggering factor that can worsen pre-existing illnesses. It has been linked to both acute exacerbations of asthma and longer-term deterioration of the condition (Tiotiu *et al.*, 2020).

We also know more about the health effects of specific pollutants. Dockery *et al.*'s (1993) 'Six Cities' study is renowned in the field of environmental epidemiology and public health for establishing a robust evidence base for the association between long-term exposure to fine particulate matter ($PM_{2.5}$; particulate matter $\leq 2.5\mu m$ in diameter) and increased mortality. The study demonstrated that individuals living in cities with higher levels of particulate matter had an increased risk of premature death, firmly establishing $PM_{2.5}$ as a key pollutant from a health perspective (Dockery *et al.*, 1993; World Health Organisation, 2023a). Thirty years after Dockery's work, with advancements in monitoring technologies and techniques (Snyder *et al.*, 2013; Morawska *et al.*, 2018), we have come to understand that an individual's exposure to polluted air is not solely determined by their residential location. Beyond background ambient pollution concentrations, various significant factors play a role. An individual's exposure depends not only on their geographic location but also on their time-activity patterns, occupation, gender, and socio-economic status (Royal College of Physicians, 2016). Moreover, specific behavioural choices, such as cooking methods, home ventilation and use of household consumer products (e.g., cleaning products, candles), have a significant impact on personal exposure to air pollution (Air Quality Expert Group, 2022).

Air quality-related policy has, to date, focused on the ambient environment and on emission reduction strategies rather than exposure prevention (Mazaheri *et al.*, 2018; Public Health England, 2019). In recent years however, there has been increased recognition of the role of indoor air quality on health, not least owing to the fact that most people spend up to 90% of their time in indoor environments (Klepeis *et al.*, 2001), yet indoor air quality has received little attention in policy and legislation. There has been a growing demand to shift policy attention towards the indoor environment (e.g., Lewis, Jenkins and Whitty, 2023; Nature, 2023) and calls in the UK's Chief Medical Officer's 2022 report for the prioritisation of indoor air in research to better understand how we can prevent and reduce indoor air pollution (Chief Medical Officer, 2022). Indoor air pollution, however, unlike outdoor air pollution, which is controlled largely by collective societal emissions, cannot be so easily targeted with policy and legislation. This is because many of the sources of air pollution indoors are linked to the specific activities and behaviours of individuals. As such it has been suggested that targeting individuals' behaviours could be an effective strategy to reduce indoor air pollution exposure from a public health perspective (Air Quality Expert Group, 2022). Improved public health requires a suite of intervention measures, focusing on both emission minimisation and exposure reduction.

The air pollution problem has not passed its peak but has evolved with new challenges emerging. In contrast to the visible smogs of the 1950s, current air pollution is largely invisible (Fuller, 2018; Kim, Senick and Mainelis, 2019), meaning that individuals are typically unaware of the levels of air pollution they are exposed to and the quality of the air that they breathe (Delmas and Kohli, 2020). The indiscernibility of air pollution presents a particular challenge for engaging the public with the issue (Varaden, McKevitt and Barratt, 2018). Yet, encouraging behaviour change for exposure and emission reduction necessitates public awareness and support. Co-developing strategies to address air quality issues with members of the public, government agencies, academics, healthcare providers and charities working alongside one another is essential to encourage engagement and find feasible and sustainable solutions (Riley *et al.*, 2021). Addressing emerging air quality challenges requires innovative strategies.

1.2 Study context

Ambient air quality in Scotland is generally regarded as very good compared to other countries based on ambient air quality monitoring conducted for compliance purposes (Scottish Government, 2021). However, as this study will demonstrate, the available data do not adequately represent individuals' exposures as they conduct their typical daily activities, and the current network of monitoring stations has poor spatial coverage. Consequently, many people are unaware of the quality of the air they are exposed to either indoors or outdoors, and, importantly, they are unaware of suitable behaviours to alter to reduce their exposures. This study applies two case studies based on two different populations: 1) people with asthma, and 2) rural communities.

People with asthma are considered an 'at-risk' group vulnerable to the effects of air pollution, as it can trigger asthma symptoms immediately and cause long-term deterioration of the condition. Asthma is the most predominant chronic respiratory disease (Chan *et al.*, 2019), and over 368,000 people receive treatment for asthma annually in Scotland (Scottish Government, 2020). Health professionals recommend reducing personal exposure to air pollution to help individuals with asthma manage their air quality-related health. However, since many people do not know how their behaviours and environments influence the air they breathe, they are unable to successfully reduce their exposures. This study aims to address this challenge.

The second case study, involving rural villages in Stirlingshire, aims to address the poor spatial coverage of available air quality data. Rural areas are often (sometimes wrongly) perceived to have good air quality, and while this may be true compared to 'hotspots' like city centres, air pollution also exists in rural areas. Since there is no safe level of exposure to air pollution (Marks, 2022; World Health Organisation, 2023a), everyone can benefit from exposure reduction from a health perspective. Consequently, this study aims to raise awareness of local rural air quality issues with the goal of encouraging air quality-related behaviour change.

The primary pollutant of focus in this study is fine particulate matter ($PM_{2.5}$) due to its well-documented health impacts particularly for people with respiratory illnesses, as evidenced by an extensive literature base (e.g., Guarnieri and Balmes, 2014; Landrigan *et al*. 2018; Holst *et al*. 2020). $PM_{2.5}$ is emitted from a wide range of sources, both indoors and outdoors, and is prevalent in both urban and rural areas. We chose to monitor only a single pollutant to streamline data feedback for co-developed behaviour change interventions (chapter five). This decision was made to ensure clarity and ease of understanding for participants.

1.3 Aim, research questions and objectives

The overarching aim of this body of work is to co-develop strategies to promote awareness of air pollution and support exposure-minimising behaviour changes to reduce exposure to $PM_{2.5}$. To achieve this aim, the research questions and objectives are structured as follows:

Research Question 1: What are the lived experiences of air pollution for people living with asthma in Scotland?

O1a) Explore the lived experience of individuals living with asthma in Scotland, investigate how they manage their condition and the role that air quality plays in how they manage their asthma using semi-structured interviews.

Research Question 2: What is the level of exposure to $PM_{2.5}$ of people with asthma in Scotland and does this influence the short-term precipitation of asthma symptoms?

O2a) Develop the exposure monitoring methodology for $PM_{2.5}$ data collection.
O2b) Calibrate 16 PurpleAir sensors and assess their accuracy, precision and bias.

O2c) Monitor individuals' personal exposures to $PM_{2.5}$ over 7 days using PurpleAir sensors.

O2d) Explore the associations between $PM_{2.5}$ exposure and the prevalence of asthma symptoms using time-activity/inhaler diaries and $PM_{2.5}$ data.

Research Question 3: Can co-developed interventions reduce $PM_{2.5}$ exposures for people with asthma in Scotland?

O3a) Co-develop personalised interventions with each intervention group participant with the aim of reducing their exposure to $PM_{2.5}$.

O3b) Test the efficacy of interventions to 1) reduce $PM_{2.5}$ personal exposure and 2) improve asthma symptom management at follow-up campaigns 1-month post-baseline.

Research Question 4: How do we increase community engagement with air quality data and mobilise air quality conscious communities?

O4a) Apply a novel framework for increasing community engagement with air quality data and information via community workshops.

O4b) Investigate air quality priorities and the potential for sustainable behaviour change in five Stirlingshire communities.

O4c) Develop an online resource to disseminate local air quality information.

O4d) Understand how users perceive a co-developed air quality resource using think-aloud testing.

O4e) Compare the useability and usefulness of various publicly available air quality resources using interviews and think-aloud testing.

1.4 Structure of this thesis

This thesis starts with a theoretical exploration of the steps linking air quality data and information with individual exposure-minimising behaviour change. It proposes that to better promote exposure-minimising behaviour change, it is necessary to simultaneously increase the relevance of air quality data and encourage public participation in the process (referred to as the 'expanded approach'; chapter two).

Since the 'expanded approach' is theoretically based, the subsequent data chapters comprise two different case studies designed to empirically test the 'expanded approach.' These case studies apply the 'expanded approach' at different scales (individual-level and community-level) to gain insight into its efficacy, feasibility, and suitability across diverse contexts and with different populations (individuals with asthma and with a broader, more representative sample of the population in terms of health). This acknowledges that different factors will be at play, such as the experience of air pollution, motivation for participation in research, and motivation for exposure reduction. The largest of the case studies- *Asthma and Air Pollution: Scotland Study-* spans chapters three to five, with each chapter detailing a distinct work package within the study (Figure 1.1). Data collection for this study was undertaken between September 2021 and September 2022. Chapter six details the study *Mobilising Air Quality Conscious Communities in Stirlingshire*, conducted alongside the Scottish Environment Protection Agency (SEPA) as part of the CASE partnership. To date, SEPA has focused on engaging school-aged children by developing resources for schools to promote awareness of air quality issues. However, reaching a broader audience has not been within their typical scope of activities. Consequently, my role within the CASE partnership was to address this gap by developing a grant proposal aimed at conducting workshops targeting rural community populations. This project was funded following a successful bid to the Scottish Government, resulting in a grant of £12,000. SEPA provided assistance with the monitoring (i.e., deploying sensors, sending raw data) and digital visualisation aspects of this work (i.e., developing the webpage). Data collection spanned from October 2022 until May 2023. Following the data chapters, chapter seven synthesises discussions, makes recommendations for future research, and suggests implications and applications of the findings.

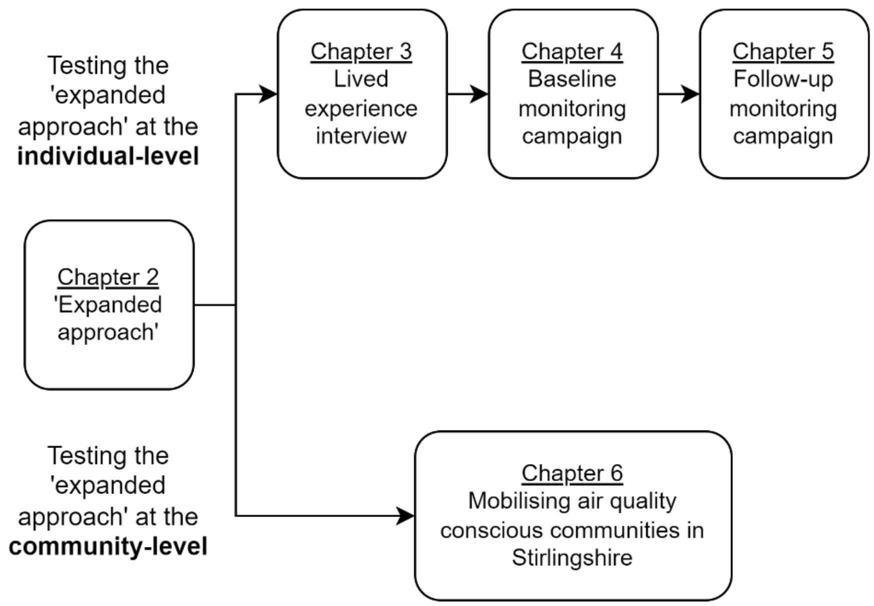

Figure 1.1. The ‘expanded approach’ (Chapter 2) is empirically tested applying two different case studies. Asthma and Air Pollution: Scotland Study spans Chapters 3 – 5 aims to test the ‘expanded approach’ at the individual-level with people with pre-existing respiratory illness. Mobilising Air Quality Conscious Communities in Stirlingshire is detailed in Chapter 6 and tests the ‘expanded approach’ at the community-level with a more diverse and representative sample of individuals.

1.5 Ethical statement

The work undertaken as part of this thesis was reviewed and approved by the University of Stirling’s General University Ethics Panel GUEP 2021 2506 1892 and GUEP 2022 4795 5302

1.6 Positionality statement

As a researcher with a background in Natural Science and with no personal nor second-hand experience (i.e., family members, close friends) with asthma and not living in Stirlingshire, I recognise that I am an ‘outsider’ to the groups of people at the centre of this research project. Prior to undertaking this work, my ‘knowledge’ on this topic was shaped by what exists in the literature (peer-reviewed journals, grey literature) where people with asthma are described as a ‘vulnerable group’ more adversely impacted by exposure to air pollution than the ‘general’ population. In this sense I understand the physiology/aetiology of asthma and I understand the mechanisms behind air pollution being a (potential) asthma trigger, however I do not and cannot understand directly how people with asthma experience air pollution. The related work packages were born out of my belief that people with asthma are 'vulnerable' to the effects of air pollution. Similarly, I am aware that rural air quality is generally better than urban air quality, however there are particular activities which might lead to rural hotspots (e.g., agriculture, domestic burning). However, since I do not live in the rural areas studied, I cannot understand local air quality priorities and perceptions.

1.6.1 Ontological position

My ontological position is critical realism, combining realism (an objective singular reality exists) with epistemological relativism, recognising that different perspectives, interpretations and representations exist shaped by human meanings, emotions, experiences, actions and sense-making.

1.6.2 Epistemological position

My epistemological position is contextualism, believing that human knowledge is context dependent and perspectival, and that my own experiences and practices will influence my engagement with and interpretation of the data. This assumes a generally straightforward relationship between language and reality whilst also acknowledging that my own practices and beliefs shape the research that I produce from the participants.

My positionality has therefore shaped my research questions, research methods and analyses conducted. For example, in exploring the lived experiences of people with asthma in relation to air pollution exposure using semi-structured interviews, I recognise that no singular reality, or truth, exists for people with asthma and this will be shaped by their own meaning-making, experiences and actions. Furthermore, my background as a geographer influences how I approach data collection, balancing both objective measurements and subjective experiences. In using reflexive thematic analysis, I recognise that my own experiences will impact my interpretation of these data, prompting me to think reflexivity and have critical self-awareness during the analysis processes. However, I also recognise the objective measurement of air quality and the established physiological and aetiological connections between air pollution and health, thus demonstrating a more realist perspective. Merging both experiences of and self-reporting of asthma-related health with objective measurements, I integrate critical realism with contextualism within my research. Moreover, my positionality as an outsider to the groups studied has prompted me to incorporate multiple perspectives into my research, ensuring a nuanced understanding of the topic and challenging traditional conceptions of objectivity in research. Ethically, I am mindful of power dynamics between the researcher and participants, and I aim to conduct my research with sensitivity and integrity, ensuring that the voices and experiences of the communities studied are represented.

Chapter 2 | Public engagement with air quality data: using health behaviour change theory to support exposure-minimising behaviours

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Abstract

Exposure to air pollution kills 7 million people prematurely globally every year. Policy measures designed to reduce emissions of pollutants, improve ambient air and consequently reduce health impacts, can be effective, but are generally slow to generate change. Individual actions can therefore supplement policy measures and more immediately reduce people's exposure to air pollution. Air quality indices (AQI) are used globally (though not universally) to translate complex air quality data into a single unitless metric, which can be paired with advice to encourage behaviour change. Here we explore, with reference to health behaviour theories, why these are frequently insufficient to instigate individual change. We examine the health behaviour theoretical steps linking air quality data with reduced air pollution exposure and (consequently) improved public health, arguing that a combination of more 'personalised' air quality data and greater public engagement with these data will together better support individual action. Based on this, we present a novel framework, which, when used to shape air quality interventions, has the potential to yield more effective and sustainable interventions to reduce individual exposures and thus reduce the global public health burden of air pollution.

2.1 Introduction

Air pollution is the world's greatest single environmental health threat, resulting in an estimated 7 million premature deaths globally every year (World Health Organisation, 2020b). The health effects associated with exposure to air pollution include acute health impacts such as asthma attacks, and more chronic illnesses such as stroke, chronic obstructive pulmonary disease (COPD) and lung cancer (World Health Organisation, 2013). Sources of air pollution are numerous and include industry, transport, households, other human activities and natural sources (Karagulian *et al.*, 2015). Acknowledging the importance of good air quality for health, the environment, society and the economy, the United Nations has incorporated improving air quality into its Sustainable Development Goals (SGDs), namely within SDG 3 (Health and Wellbeing), SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Societies) (United Nations, 2015).

Public policy is a key strategy for improving air quality and people's air pollution-related health. For example, the 1979 UNECE Convention on Long-Range Transboundary Air Pollution has reduced emissions of harmful pollutants by between 40 and 80% and prevented 600,000 premature deaths every year since 1990 in Europe and North America (United Nations, 2019). Similarly, the State Council of China's Air Pollution Prevention and Control Action Plan (APPCAP) introduced in 2013, successfully reduced annual average concentrations of $PM_{2.5}$, SO_2 and CO by 33%, 54% and 28%, respectively, resulting in an estimated 47,000 fewer deaths by 2017 (Huang *et al.*, 2018). However, public policy as an air quality improvement strategy can be problematic; most policies designed to reduce air pollution focus on outdoor spaces rather than indoor environments where people spend most of their time (Mazaheri *et al.*, 2018) and public policies are more often very slow to take effect (RoTAP, 2012). For example, in 2017 the UK government announced the ban of the sale of diesel and petrol cars in the UK by 2040, over 20 years after its conceptualisation (DEFRA, 2017b), and only recently (in 2020) have brought this forward to 2030[1]. While public policy remains a key strategy for reducing air pollution, individual actions can play a vital and complementary role in placing the individual in control to reduce their exposure to air pollution (Sierra-Vargas and Teran, 2012).

Air quality policy is assessed and evaluated based on data from traditional static monitoring stations which undergo rigorous calibration and maintenance to ensure output data are highly accurate, precise and comparable (Castell *et al.*, 2017). However, the outdoor static monitoring network does not represent individuals' exposure and is not designed to provide information about indoor exposures or to support the 'personalisation' of air quality data (i.e., enabling individuals to measure their own exposures based on their individual behaviour and time-activity patterns). Recent advances in sensor technology have resulted in lower cost sensors of variable quality (Karagulian *et al.*, 2019) supplementing the static infrastructure in many contexts and, in some cases, is the only viable monitoring option owing to economic, infrastructural, or political factors (Pinder *et al.*, 2019; Quarmby, Santos and Mathias, 2019). While these sensors may be used to monitor air quality in outdoor or indoor contexts, many can also be used to monitor personal exposure by an individual wearing a sensor (Steinle *et al.*, 2015; Quinn *et al.*, 2020). A person's exposure to air pollution will be unique to them and depends on numerous factors including their geographic location, time-activity patterns, occupation, gender and socio-economic status (Royal College of Physicians, 2016). Such personalisation of air quality data may support the design and implementation of individual plans to reduce exposures (e.g., Oltra *et al.*, 2017).

[1] Since publication, this has been delayed until 2035 (Race, 2023).

Consulting air pollution levels (using data from static or personal monitors) is one of the recommended individual action strategies for improving air pollution-related health risk (Carlsten *et al.*, 2020). This, however, requires that air quality data are available and accessible, and, furthermore, for this to inform individual behaviour change, individuals must be able to interpret the information provided. Moreover, exposure to air pollution is an environmentally and societally complex and ‘wicked’ problem (Holgate and Stokes-Lampard, 2017), with various sources producing a ‘cocktail’ of air pollution and therefore no singular ‘correct’ approach or definitive action strategy to reduce exposures. Transcending environmental science, health psychology and public health, tackling air pollution exposure requires transdisciplinary, collaborative and innovative approaches towards a common goal. A fundamental part of this is the inclusion of multiple stakeholders, such as governments, institutions, academia and civil society (Lang *et al.*, 2012), with the participation of civil society in particular crucial to the formulation of multiple solutions and action strategies that are acceptable and feasible to the general public (Lang *et al.*, 2012).

The aim of this paper is to explore the theoretical steps linking air quality data to behaviour changes that improve people’s air pollution-related health. Through an evaluation of different types of air quality data and methods to engage people with such data to promote behaviour change, we argue that a combination of ‘personalisation’ of air quality data and enhanced public engagement with this data will support individual action to reduce exposure to air pollutants and consequently improve public health.

2.2 The theoretical basis for generating behaviour changes from air quality data

Accessing air quality data does not automatically induce changes in behaviour that reduce air pollution exposure and improve public health (Noonan, 2011). Rather, it is a first step in a multi-stage process comprised of external and internal cues motivating and facilitating individual behaviour change which can potentially, in turn, improve public health (Figure 2.1).

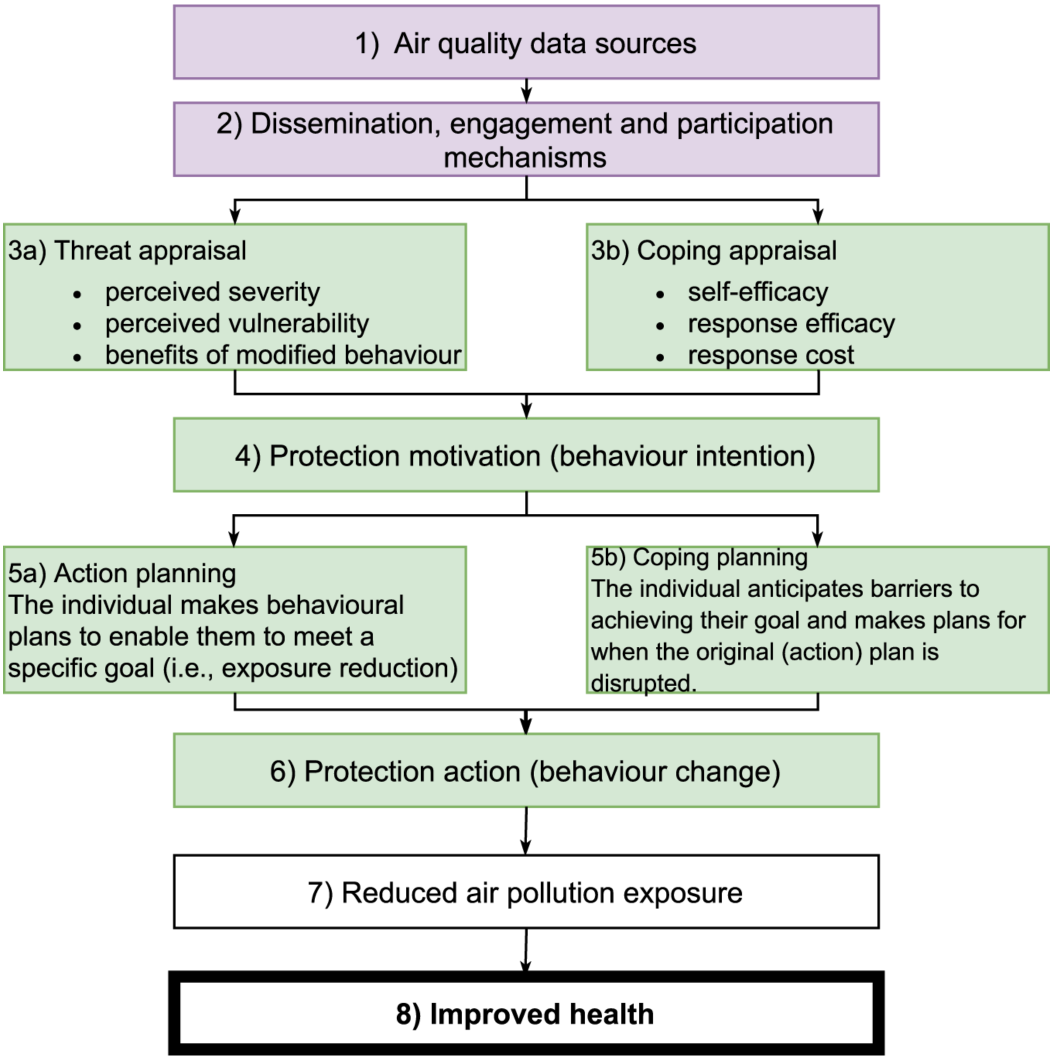

Figure 2.1. For air quality data to influence exposure reduction for improved public health requires a multistage process comprising of external (purple) and internal (green) factors. Internal factors are integrated into the process through (adapted) Protection Motivation Theory (PMT; boxes 3a, 3b and 4) and a section of the Health Action Process Approach (HAPA; boxes 5a, 5b and 6).

Air quality data (Figure 2.1; Box 1) can be generated from a variety of sources ranging from passive samplers and low-cost sensors to in-situ continuous ambient air quality monitoring stations and remote-sensing (Cromar *et al.*, 2019). The data arising from these sources can provide various types of information about air quality including focusing on different pollutants and providing data at different spatiotemporal scales (from individual to global and from every second to annual). From this high-level perspective, there is no immediate expectation that raw air quality data from any source will encourage individual behaviour change, however, the quantification of air pollution (which can be an imperceivable and oftentimes invisible problem) is an important starting point. For data to induce behaviour change, regardless of data source, the public need to be able to access, interpret and be motivated to use these data.

For data to be accessed and used by the public, air quality dissemination strategies and engagement tools are needed (Figure 2.1; Box 2). This stage, as the 'public-facing' part of air quality data and information, is the critical bridge between external raw data (Figure 2.1; Box 1) and internal cues to generate individual motivation to reduce exposure (Figure 2.1; Box 3a and 3b) and can be considered as a spectrum of approaches. This spectrum of approaches fits well with Jules Pretty's (1995) 'typology of participation', most prominently corresponding to *passive*, *consultative*, *functional* and *interactive* participation. *Passive* participation is typified by top-down unilateral announcements used to inform the public and raise awareness. *Consultative* participation approaches are characterised by 'traditional' methods including focus group discussions, interviews and questionnaires which have been designed to investigate predetermined aims and predefined problems. Beyond this, *functional* participation, tends to be more interactive and involve citizens to meet predefined objectives. Finally, *interactive* participation involves interdisciplinary methodologies seeking multiple perspectives with citizens participating in joint analysis and the development of action plans, taking control over local and individual decisions. Co-production projects, bringing together academics and non-academics (Norström *et al.*, 2020) to tackle transdisciplinary, 'wicked' issues sits within *interactive* participation (e.g., Jerneck and Olsson, 2013).

As external cues, data and dissemination, engagement and participation approaches can motivate health protection motivation (Figure 2.1; Box 4). However, the extent to which this happens is ultimately shaped by an individual's assessment of the potential of the threat and their own control over adaptive responses to the threat, as intermediary steps and internal cues (Figure 2.1; Box 3a and 3b). Health self-protection motivation (which preludes behaviour change according to Rogers' (1983) Protection Motivation Theory (PMT)), stems from an individual's threat and coping appraisal. Threat appraisal (Figure 2.1; Box 3a) consists of the assessment by an individual of the perceived severity of the threat (degree of harm), their vulnerability to the threat (likelihood of experiencing harm) and the benefit of behaviour modification. Coping appraisal (Figure 2.1; Box 3b), rather than assessing the threat itself, is a process which assesses the response efficacy (the effectiveness of the adaptation of behaviour), the response cost (the cost of performing the behaviour change i.e., financial, time, convenience) to cope with and avoid the threat, and the individual's self-efficacy (the belief that they can successfully conduct the change in behaviour). Therefore, altering behaviours by applying PMT can be about altering perceived self-efficacy and perceived control as well as giving individuals' *actual* behavioural control. For effective interventions, first the risk needs to be conveyed (i.e., in the communication of air quality information), before then presenting the preferred behaviour as a simple, effective and low-cost solution to minimise the risk (Prestwich, Kenworthy and Conner, 2018).

Whilst these factors are important motivators for behaviour change, a further step is required for translation into protection action (Figure 2.1; Box 6) to bridge the motivation-behaviour gap (Norman and Conner, 2017). Where PMT explains the role of risk perception as one aspect of motivation, Schwarzer's (1992) Health Action Process Approach (HAPA) explains that action and coping planning are prerequisites of actual (rather than intentional) behaviour change, with the enactment of behaviours included within HAPA and helps to bridge the motivation-behaviour gap whereby planning is a key stage between motivation and behaviour. Action plans (Figure 2.1; Box 5a) are formed by the individual to decide in what situation they will perform a specific behaviour to meet a specific goal (e.g., "To reduce my exposure to air pollution, I will avoid walking along busy roads on my commute to work"). Coping plans (Figure 2.1; Box 5b) connect coping responses to situations that can jeopardise one's goal achievement (e.g., "If I am leaving for work and air quality is poor, then I will wear a facemask while walking"). Ultimately these planning processes place the individual at the core of the behaviour change, allowing an individual assessment of feasibility and acceptability. The individual is placed at the centre- or the core- of Social Ecological Models (e.g., Bronfenbrenner, 1979), which recognises that individual's behaviours (and behavioural determinants) vary and are shaped by multilevel influences, not only at the individual-level (e.g., personal beliefs), but by social (e.g., norms) and environmental (e.g., situational) factors also. To the authors' knowledge, the socio-ecological model has not been directly applied in an air quality-specific context. In the exposure-minimisation context, shifting from motorised to active transport, moderating outdoor physical activities in poor air conditions, using 'cleaner' household fuels and staying indoors during pollution episodes (Laumbach, Meng and Kipen, 2015; Carlsten *et al.*, 2020) are examples of protection actions (Figure 2.1; Box 6). Protection actions must be considerate of the individual context. The COM-B model (Michie, van Stralen and West, 2011) also focuses on the person in context, and notes that for any behaviour change intervention to be effective, three factors need to be present at the individual-level: capability, opportunity and motivation. Only when an individual has the capability and opportunity to engage in the preferred behaviour (determined by physical and psychological capability, and physical and social environments for opportunity), and is motivated to enact the preferred behaviour over any other behaviours, will a behaviour change occur (Michie, van Stralen and West, 2011). The COM-B model, in contrast to more specific theories and models (such as the Theory of Planned Behaviour (TPB), PMT and HAPA), generally serves as a broad, foundational framework that facilitates the analysis of behaviours and guides the development of interventions, and has been used to promote behaviour change in air quality-related interventions. For example, D'Antoni et al. (2019) used the components of COM-B to design smartphone air quality alerts, finding the theory-based intervention more successfully made participants consider more permanent behaviour changes to reduce exposures. Similarly, Thompson et al. (2018) used COM-B to inform a cookstove intervention. The COM-B model has also been used as part of an indoor air quality intervention evaluation, successfully highlighting the components which act as barriers to behaviour change in relation to indoor air quality (e.g., O'Donnell *et al.*, 2021). Health and behaviour change theories aid our understanding of the mechanisms of action and thus can lead to more effective interventions to improve health behaviours. Taking a theory-driven approach to air quality data generation and communication is needed to reduce air pollution exposure (Figure 2.1; Box 7) and improve public health (Figure 2.1; Box 8).

Air quality data (Figure 2.1; Box 1), and dissemination, engagement and participation approaches (Figure 2.1; Box 2), are external malleable cues that feed directly into threat and coping appraisal, making them key stages to target in order to inform and influence an individual's protection motivation. For subsequent protection action to occur, the personal context is key. These are critical first steps as part of a multistage process to reduce exposures and improve public health.

In the following section we outline the traditional mechanisms used to promote individual behaviour change to reduce air pollution exposure, examining its underpinning data (section *2.3.1 AQI data sources*) and the mechanisms by which air quality information is shared (section *2.3.2 AQI dissemination mechanisms*) separately.

2.3 Traditional mechanisms to promote individual exposure-minimising behaviours

The traditional suite of mechanisms used to promote individual behaviour change are ‘top-down’ in terms of both data sources and citizen involvement, whereby active data *dissemination* and public *informing* are frequent. A key example of this is the Air Quality Index (AQI) which is a common tool employed in communicating air pollution information to the general public (Schulte *et al.*, 2020). Different AQI are used globally (e.g., EU Common Air Quality Index [CAQI], UK Daily Air Quality Index [DAQI], US AirNow AQI; Figure 2.2A, B and C, respectively) to describe air pollution as an understandable standardised summary of ambient air quality and its associated health risk to the public (Kowalska *et al.*, 2009). Where AQI are available, data are frequently converted from physical units to a unitless index value, which, though it may compromise precision and accuracy (Laumbach, Meng and Kipen, 2015), is an effort to increase public accessibility and understanding of air quality data (Monteiro *et al.*, 2017). Here we examine the underpinning data (section *2.3.1 AQI data sources*) and the dissemination strategy of the AQI (section *2.3.2 AQI dissemination mechanisms*), exploring its potential for generating individual behaviour change.

A

AQ index	General population	Sensitive populations
Good	The air quality is good. Enjoy your usual outdoor activities.	The air quality is good. Enjoy your usual outdoor activities.
Fair	Enjoy your usual outdoor activities	Enjoy your usual outdoor activities
Moderate	Enjoy your usual outdoor activities	Consider reducing intense outdoor activities, if you experience symptoms.
Poor	Consider reducing intense activities outdoors, if you experience symptoms such as sore eyes, a cough or sore throat	Consider reducing physical activities, particularly outdoors, especially if you experience symptoms.
Very poor	Consider reducing intense activities outdoors, if you experience symptoms such as sore eyes, a cough or sore throat	Reduce physical activities, particularly outdoors, especially if you experience symptoms.
Extremely poor	Reduce physical activities outdoors.	Avoid physical activities outdoors.

B

Recommended Actions and Health Advice

Air Pollution Banding	Value	Accompanying health messages for at-risk individuals*	Accompanying health messages for the general population
Low	1-3	**Enjoy** your usual outdoor activities.	**Enjoy** your usual outdoor activities.
Moderate	4-6	Adults and children with lung problems, and adults with heart problems, **who experience symptoms**, should **consider reducing** strenuous physical activity, particularly outdoors.	**Enjoy** your usual outdoor activities.
High	7-9	Adults and children with lung problems, and adults with heart problems, should **reduce** strenuous physical exertion, particularly outdoors, and particularly if they experience symptoms. People with asthma may find they need to use their reliever inhaler more often. Older people should also **reduce** physical exertion.	Anyone experiencing discomfort such as sore eyes, cough or sore throat should **consider reducing** activity, particularly outdoors.
Very High	10	Adults and children with lung problems, adults with heart problems, and older people, should **avoid** strenuous physical activity. People with asthma may find they need to use their reliever inhaler more often.	**Reduce** physical exertion, particularly outdoors, especially if you experience symptoms such as cough or sore throat.

C

AQI Basics for Ozone and Particle Pollution

Daily AQI Color	Levels of Concern	Values of Index	Description of Air Quality
Green	Good	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk.
Yellow	Moderate	51 to 100	Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.
Orange	Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
Red	Unhealthy	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects.
Purple	Very Unhealthy	201 to 300	Health alert: The risk of health effects is increased for everyone.
Maroon	Hazardous	301 and higher	Health warning of emergency conditions: everyone is more likely to be affected.

Figure 2.2. Examples of the information available as part of various AQI including the EU CAQI (A), UK DAQI (B) and US AQI (C).

2.3.1 AQI data sources

AQI calculations are most often based on data from static regulatory monitors and many monitoring networks are structured around a country's commitment to report air quality data and modelled forecasts to the general public (Kelly *et al.*, 2012). Data collected from static site monitoring stations are generally accepted to be representative of average ambient concentrations within the local community (COMEAP, 2011), and provide highly accurate and precise monitoring data (Snyder *et al.*, 2013). Though most frequently the raw data from regulatory monitoring stations are accessed and used by researchers, governments and industry via government websites and research databases (Snyder *et al.*, 2013), the output data from these monitors are available to the wider public in only some countries in a 'fully-open' manner (OpenAQ, 2020). Air quality data that are actively shared with the public (see section *2.3.2 AQI dissemination mechanisms*) tend to be converted to an AQI. Though it has been argued that variances between AQI at country-level makes comparisons of values challenging (Baldasano, Valera and Jiménez, 2003; van den Elshout, Léger and Nussio, 2008; Kanchan, Gorai and Goyal, 2015), as well as ‘global’ AQI (e.g., the World AQI (WAQI)), and most ‘daily’ AQI fail to report short-term peaks, these are often the highest spatiotemporally resolved data available to the general public.

The ability of the data communicated as part of the AQI to motivate behaviour change (i.e., protection motivation; PMT) assumes that the public understand and engage with the AQI and accessing the AQI promotes self-protection behaviours (i.e., protection action; HAPA) (Oltra *et al.*, 2017). However, evidence for the AQI in engaging and enabling exposure reduction behaviours is limited (Noonan, 2011; Carlsten *et al.*, 2020). D’Antoni *et al.* (2017) found that, despite AQI alerts increasing perceived severity (magnitude of negative health consequences of exposure to air pollutants), the perceived susceptibility (personal vulnerability) was a barrier to behaviour change. This suggests that though the AQI can successfully communicate the risk of air pollution exposure, these remain as distant problems with impersonal risks (van den Elshout, 2007), thereby unable to influence or demonstrate perceived vulnerability in one’s own threat appraisal (Figure 2.1; Box 3a). Additionally, it must also be considered that AQI may have an unintended effect on threat appraisal, particularly in settings with generally ‘good’ (according to the AQI) ambient air quality. The publics unintended interpretation of an AQI value suggestive of ‘good’ air quality will shape their risk perception (Wu *et al.*, 2021) and can diminish the sense of threat posed by air pollution more generally, despite there being no safe threshold level of exposure below which no adverse health impacts occur (World Health Organisation, 2013). Personalising AQIs and air quality data (e.g., by characterising air pollution in the more immediate local or home environment) has the ability to personalise risk, influence threat appraisal and help promote individual protection motivation. For example, communicating personal vulnerability via personalised air quality data has been found to help individuals revisit their prior perceptions about air pollution and demonstrate the impact individual actions have on personal exposures (Zappi *et al.*, 2012). In another study, providing participants with personal sensors on the commute to school resulted in the majority identifying air pollution as a ‘threat’, caused many to perceive air pollution as a greater ‘problem’ on the school commute than previously thought and resulted in the majority of participants taking protective action in response to the monitoring data (Heydon and Chakraborty, 2020).

Increasing the representativeness of air quality data, in addition to its potential to alter threat appraisal, has potential to alter one’s coping appraisal (Figure 2.1; Box 3b). Lack of self-efficacy has been identified as a barrier to adherence to AQI-recommended behaviours (D'Antoni *et al.*, 2017). Perceived behavioural control, as a distinct but related construct to self-efficacy, is one of the most important psychological factors for behaviour change (Wallston, 2001). As a dynamic but vital determinant of behaviour, perceived behavioural control (in addition to actual behaviour control) needs to present in coping appraisal for protection motivation. Particularly regarding air pollution (ambient especially), which is sometimes considered as a 'distant' and uncontrollable problem, creating perceived behavioural control is fundamental to behavioural intentions and change. Bandura (1997) identified that individuals' efficacy beliefs are based upon four factors: mastery experiences, vicarious experiences, verbal persuasion and physiological states. Mastery experiences (or performance outcomes) are the experiences gained by altering behaviour successfully and the most influential source is the interpreted result of an individual's previous performance (Bandura, 1997). More personally representative data can demonstrate behaviour change performance outcomes (i.e., response efficacy) and simultaneously increase self-efficacy. For example, Wong-Parodi *et al.* (2018) found that microenvironmental air quality data can help people make the connection between exposure, attitudes and behaviour change actions, and found that subsequent to sensor use, participants felt more confident about knowing how to mitigate the risk of exposure, as well as participants tending to take more action to reduce pollution. Similarly, Bales *et al.* (2019) noted that participants were more "empowered" to alter their behaviours and reported individual changes such as avoiding busier roads when walking, reducing idling, and avoiding bus exhaust fumes. In these instances, more personally representative data have increased self-efficacy (and perceived behaviour control as a related construct), response efficacy and demonstrate benefits to change, thus protection motivation. Together, this suggests that making air quality data 'more personal' has the potential to encourage behaviour changes that reduce exposure and improve air pollution-related health.

2.3.2 AQI dissemination mechanisms

AQIs are designed for the active dissemination of air quality information to the public for the protection of public health (Kelly and Fussell, 2015). As such, the AQI has traditionally been disseminated via television, radio and newspaper (Dye *et al.*, 2004), forecasting aggregate pollution levels and offering (primarily avoidance) behaviour advice. As technology and how we use it has advanced, so too have the various dissemination strategies. Now AQIs are, where available, frequently accessible via government, environment agency and third-sector websites and apps- both specific (e.g., IQAir AirVisual) and non-specific (e.g., weather and maps apps) to air quality- and increasingly on social media. These are *passive* participation methods according to Jules Pretty's 'typology of participation' (Pretty, 1995), characterised by unilateral announcements without citizen input with unbalanced power dynamics between the lay public and researchers/officials. This resembles a one-way flow of information from officials to the public, which has key advantages around efficiency, cost-effectiveness and awareness raising (Barnes *et al.*, 2020).

However, this dissemination approach relies on the public understanding and interpreting AQIs, which has been previously identified as a barrier to behaviour change (Radisic and Newbold, 2016; D'Antoni *et al.*, 2017; Ramírez *et al.*, 2019). Reflecting on the complexities of air quality information and difficulties interpreting this by the public, Hubbell *et al.* (2018) recommend two-way dialogue between air quality monitoring experts and the lay public, and it has been suggested that engagement with the general public is required (over simply providing data), to support individual behaviour change (Loroño-Leturiondo *et al.*, 2018). Ultimately, informing people about high pollution episodes via traditional dissemination strategies such as AQI alerts or advisories has had limited effectiveness (Johnson, 2012) and though information provision has importance, it is insufficient, on its own, to trigger behaviour response (Noonan, 2011).

Public engagement is believed to be a key part of the solution when it comes to exposure-minimising behaviour change (e.g., Finn and O'Fallon, 2017; Ramírez *et al.*, 2019; Delmas and Kohli, 2020). For interventions to promote behaviour change, 'one size fits all' does not work ('What works for behaviour change?', 2018; World Health Organisation, 2020a). Information is effective for behaviour change, not due to its accuracy, precision or completeness, but the extent to which it captures its audience, gains their involvement and overcomes scepticism (Stern, 1999). Issue involvement is a key moderator in shaping an individual's attitude or favourability toward a message (Petty and Cacioppo, 1981) and thus its ability to persuade for behaviour change (i.e., adherence to the suggested behaviour of the AQI). Messages with high issue involvement have a high degree of personal relevance to the recipient (Petty and Cacioppo, 1981), and in turn are more likely to induce attitude change via central route processing (that is, the individual carefully considers, elaborates and engages with the persuasive message [see Petty, Cacioppo and Berkowitz (1986) *Elaboration Likelihood Model*]) since the issue is of direct interest to them. Attitude change via central route processing is more likely to be sustained and stable (Prestwich, Kenworthy and Conner, 2018). It has been argued that the health and behaviour messages communicated as part of AQI advisories do not effectively support individual behaviour change (Radisic and Newbold, 2016), owing to their lack of specificity (O'Keefe, 2015). Applying the theory of issue involvement and the *Elaboration Likelihood Model*, AQI could be more persuasive for behaviour change if more engaging and using more personally involving, specific and tailored messages (and data, see section *2.3.1 AQI data sources*).

2.4 An expanded approach for public engagement with air quality data

Using the key example of the AQI, we argue that traditional approaches to supporting behaviour change through the dissemination of air quality data have limited effectiveness. Following on from this, we propose that by; 1) supplying people with more personally representative data (or supporting people to collect their own data) (section *2.4.1 More personally-representative data*); and 2) engaging people in the process (section *2.4.2 More participatory engagement*), we can better support individuals to change their behaviours and improve their air pollution-related health. We discuss these ideas in turn below, before considering the benefits of combining these two approaches in section *2.4.3 Pairing personally relevant data with participatory engagement*.

2.4.1 More personally-representative data

Rapid advances in sensor technology are revolutionising air pollution monitoring (Snyder *et al.*, 2013). Instead of having few or no static air quality measurement stations to characterise the air quality of a geographic area, the development of smaller, cheaper, portable sensors has enabled air pollution measurements by various users and for a wider variety of purposes (Morawska *et al.*, 2018). These sensors have commonly been used to investigate air pollution concentrations in specific microenvironments (e.g., Shen *et al.*, 2021), in exposure assessment studies (e.g., Steinle *et al.*, 2015) and in behaviour change intervention studies (e.g., Haddad and de Nazelle, 2018), and their use in ambient air pollution monitoring studies is also growing (de Souza *et al.*, 2017). There are numerous critiques of these sensors for measuring air pollution, particularly around accuracy (Buonanno *et al.*, 2012), robustness, repeatability (Castell *et al.*, 2017), reliability (Giordano *et al.*, 2021), nominal range and response time (Saini, Dutta and Marques, 2021) compared to reference-grade monitors. Despite their technical nature, which poses challenges for individuals without expertise in air quality monitoring or sensor technology, these limitations and uncertainties must be communicated openly and clearly and in a way that is accessible and understandable to the lay-public to ensure appropriate data interpretation and risk perception. However, these limitations are balanced against the relatively cheaper cost of sensors, the ability of the sensors to demonstrate relative change in exposure, the ability to get more people involved in measurements and the potential increase in spatiotemporal resolution of generated data (e.g., Munir *et al.*, 2019), in addition to the benefit of allowing for monitoring where otherwise regulatory monitoring is not economically or politically viable (Pinder *et al.*, 2019; Gulia *et al.*, 2020).

Though increasing the representativeness of data has the potential to alter threat and coping appraisal for protection motivation (see section *2.3.1 AQI data sources*), this has not been found universally. For example, both Boso *et al.* (2020) and Oltra *et al.* (2017) found that having access to a sensor (compared with only having access to ‘traditional information’ analogous to that provided in advisories or AQI) generated increased awareness among participants, however a low sense of self-efficacy and control over personal exposure remained. Similarly, Varaden (2021), in a participatory monitoring study conducted with school children, found that awareness of air pollution was raised among most participants after taking part in the study and increased parents’ sense of autonomy over their children’s exposures, while positive protection action was reported in a much smaller proportion of participants. Lastly, despite Heydon and Chakraborty (2020) finding that sensors increased awareness, threat appraisal and changed participants’ behaviours, they found that when participants were unable to reduce the risk (evidenced by exposure data during a follow-up monitoring campaign), this led to inaction. Together, these examples demonstrate the complexity and nuance associated with behaviour change in relation to the ‘wicked’ problem of air pollution and suggests that greater support is required to transform air pollution awareness into protection action. Oltra *et al.* (2017) acknowledged that behavioural interventions need to take internal and external determinants into account, and simply increasing information availability does not always prompt individual action (Skov *et al.*, 1991). Therefore, while increasing data representativeness is a fundamental component to better support exposure-minimising behaviours, alone it is not enough to guarantee the generation of protection action.

2.4.2 More participatory engagement

Public engagement can span a spectrum of approaches designed to generate two-way dialogue with the public. Engagement approaches can range from more ‘traditional’ and *consultative* mechanisms, such as focus group discussions, interviews, and questionnaires, to more *interactive* and creative engagement methods. Traditional engagement mechanisms may generate some dialogue to better understand community perceptions of air pollution (e.g., Muindi *et al.*, 2014) and drivers of behaviour change. However, their ability to generate protection action through participation are constrained by the frequently limited depth and/ or scope and the focused research agenda of studies undertaken (Barnes *et al.*, 2020; McCarron *et al.*, 2020). Creative methods, ranging from physical events, such as street art and creative play, to more technologically driven methods, including for example drone imagery and wearable cameras (Cinderby *et al.*, 2021), are *interactive* by design and can support two-way dialogue between researchers and participants (Cinderby *et al.*, 2021) and generate participant relevance, uncover lived experiences, build individual confidence and capacity, facilitate solution-orientated discourse and stimulate actions (Hammond *et al.*, 2018; Cinderby *et al.*, 2021). Focussing on storytelling and theatre as specific examples of creative *interactive* participatory methods, we examine their efficacy for generating protection motivation and protection action.

Storytelling, as a tool for learning, empathising, educating, reflecting and advocating (Rotmann, 2017) has the potential to influence change in attitudes, behaviour, culture and policy (Van De Carr, 2013). Behaviour change is not generated from scientific knowledge, but from dialogues created between a listener and teller, and more personalised communication offers the opportunity for social change (Howarth, 2017). Storytelling places more emphasis on actions and consequences with more exploration of emotional, psychological and cultural matters (Moezzi, Janda and Rotmann, 2017) drawing on past knowledge and experiences, and making it relevant with the present (Sunday, 2018). This can be used to engage communities and give a voice to those usually without, in a manner very different from traditional scientific or governmental communications and allows individuals to express complex thoughts and feelings through a narrative relatable and understandable by themselves (Atalay *et al.*, 2019). Knowledge that is incorporated into storytelling, in a manner different than traditional scientific communications, generates greater engagement, attention (Dahlstrom, 2014) and willingness to act (Downs, 2014; Sundin, Andersson and Watt, 2018). While Dahlstrom (2014) described storytelling as a tool to communicate with nonexpert audiences, it can be argued that in fact it is a tool to enable narrative between different types of expert. Stories can draw on memories and emotions and stimulate actions (Cinderby *et al.*, 2021) that data and statistics simply cannot.

Theatre for Development, developed by Boal for the 'oppressed', works across individual, group and social levels, using visual and tangible interaction to disrupt language, literacy and educational barriers that may otherwise limit engagement and fail to explore the full extent of feasible solutions, whilst simultaneously promoting tools for behaviour change (Österlind, 2008). Theatre for Development is an umbrella term used to describe many different types of theatre including forum, legislative, image and invisible theatre, and range in how they fit within the 'typology of participation' and the extent to which they include the lay public as active participants. Theatre for Development (of any kind) is proactive, not only acknowledging the existence of a problem but actively seeking feasible solutions to said problem. Focussing specifically on forum theatre, whereby the audience is comprised of community members who share similar lived experiences, forum theatre is a form of *interactive* participation and an audio-visual tool in which participants (known as spect-actors (Boal, 2008)) spectate as an audience and can interact and participate as an actor, joining the scene to change the outcome scenario and help resolve an issue by offering their own solution. This can give those usually unheard, a voice to identify before unconsidered solutions (Hammond *et al.*, 2018), by exploring past and present situations to find solutions as a "rehearsal for the future" (Boal, 2006). The difficulties of behaviour change in the 'real-world' are imitated with the other actors opposing the proposed changes of the spect-actor. West *et al.*, (2021) developed forum theatre storylines from community members own accounts of how air quality had affected them and presented the play at various community hubs around Mukuru (an informal settlement in Kenya), allowing community members to contribute to the scene and offer their suggestions for resolving the various issues. It has been suggested that the personal relevance of forum theatre is a key motivator for individual behaviour change (Thambu and Rahman, 2017).

Interactive participatory research methods, including creative methods, can result in more effective and sustainable outcomes and solutions (Brem and Puente-Díaz, 2020) and offer an important role in bringing together multiple stakeholders and challenging traditional power dynamics to tackle complex issues (Cinderby *et al.*, 2021). Complex and 'wicked' problems, such as air pollution (Holgate and Stokes-Lampard, 2017), require practical and relevant knowledge which is not best uncovered through traditional research methods and instead requires transdisciplinary, collaborative and innovative approaches. Co-production speaks to participatory research in that it challenges the traditional power dynamics within research, but goes beyond *consultation* or collaboration, and instead is a commitment to working in equal partnership throughout the entirety of the project, with benefits to all parties. In doing so, co-production gives equity to all forms of knowledge, realising that all stakeholders have knowledge and skills of equal importance, and recognises that those affected by a research project are best-placed to design and deliver it (Hickey *et al.*, 2018). Instead of developing interventions 'for', this approach develops interventions 'with' relevant stakeholders that fit the needs and priorities of those they impact (Batalden, 2018). For example, West et al. (2021), using creative methods in a co-production approach, found that this enabled the production of several solutions to air pollution which were designed around and suitable for the local context informed by communities' priorities and contributing toward "improved outcomes and achievable solutions" (Ostrom, 1996). Where there is a need to induce behaviour change, co-production is believed to be particularly valuable (Bovaird and Loeffler, 2012), yet the value of such research is only now being realised for the 'wicked' issue of air pollution.

2.4.3 Pairing personally relevant data with participatory engagement

For protection action (or behaviour change) toward exposure-minimising behaviours, targeting only the components of protection motivation (i.e., threat and coping appraisal) is insufficient. As this and other papers have identified (e.g., Riley *et al.*, 2021), data representativeness and increased engagement independently have an important role to play in effectively communicating air quality information to the public to generate behaviour change. As distinct features, we discuss their ability to shape and alter threat and coping appraisal (sections *2.4.1 More personally-representative data* and *2.4.2 More participatory engagement*), however as detached and distinct steps, we argue that these are limited in their ability to bridge the motivation-action gap. This paper establishes the value of concurrently targeting data *and* engagement to evoke behaviour changes that improve people's air pollution-related health.

Pairing more personally representative data with suitable, enhanced participatory mechanisms has the potential to better support individual behaviour change. This has already been evidenced in the second-hand smoke literature, which, while we acknowledge is a different behaviour to change and is underpinned by different psychological, physiological, social and environmental determinants, does provide a useful comparison. Coupling personalised, low-cost air quality data feedback with motivational interviews (creating two-way dialogue between researchers/healthcare practitioners and participants to increase self-efficacy and create plans, for example), has been found to successfully promote smoking behaviour change (Wilson *et al.*, 2013; Myers *et al.*, 2020). Yet mixed-methods interventions have not been limited to smoking behaviours. Barnes *et al.* (2011) used personalised baseline data as the basis for discussions with participants about their behaviours and possible modifications they could make to reduce household air pollution concentrations. Using a community counselling strategy, starting with knowledge sharing before engaging in discussion over feasible and acceptable behaviour modifications, household PM_{10} and CO concentrations were reduced (Barnes, Mathee and Thomas, 2011).

Building on this previous work, we propose a framework to better support individual behaviour change to reduce exposure to air pollution and improve health (Figure 2.3). This framework recognises the importance of air quality data that are more personally representative (x-axis) and enhanced participation of the individuals whose behaviour we aim to change (y-axis) as two distinct but coactive variables.

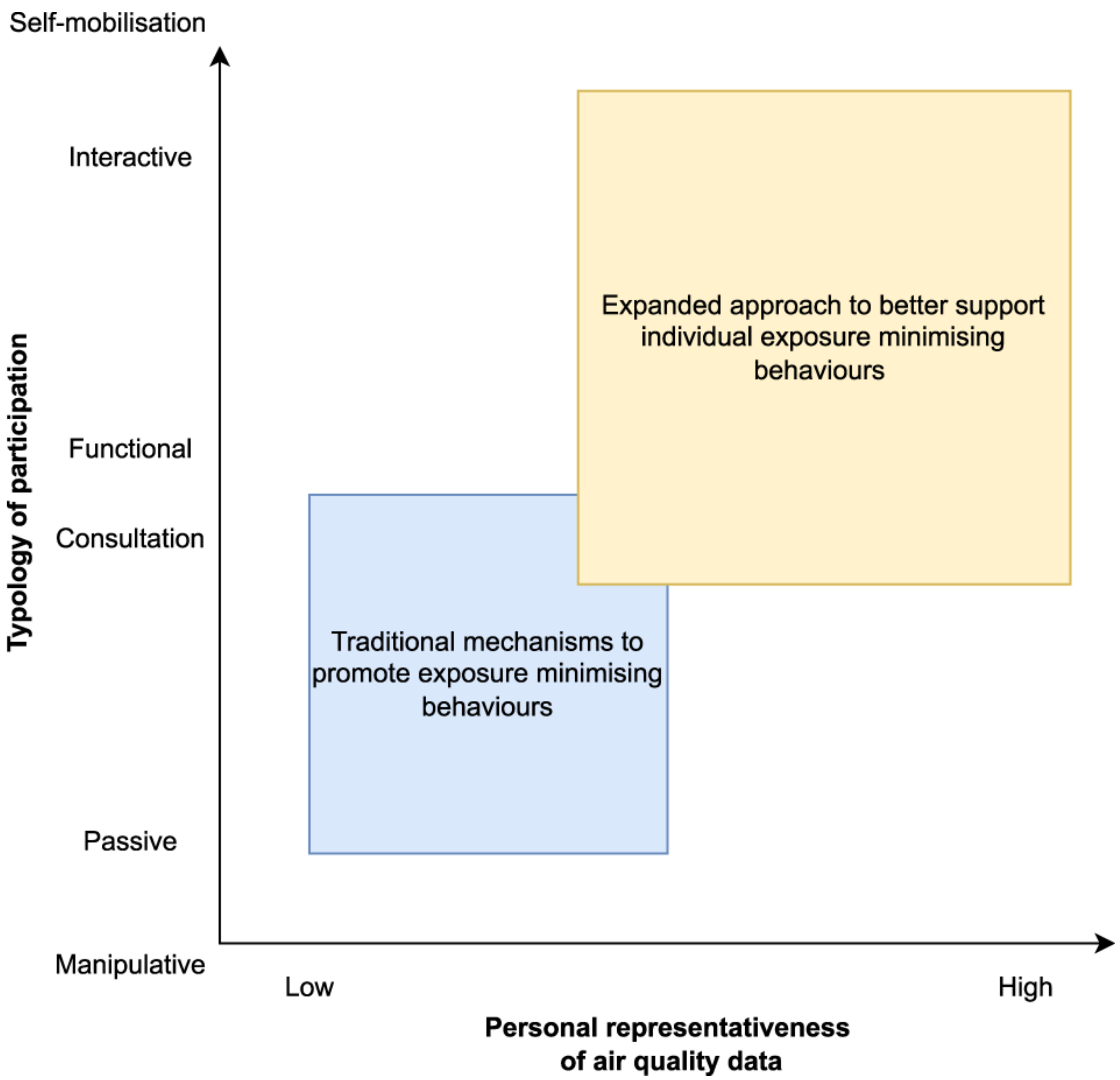

Figure 2.3. The expanded approach to promote individual behaviour change relies simultaneously on more personally representative data and increased citizen participation moving away from passive participatory processes towards interactive participation (Pretty, 1995). Participation for material incentives has been omitted from the y-axis because it does not generally fit within participatory methods used for behaviour change. Self-mobilisation goes beyond engagement towards empowerment and so is outwith the scope of participatory mechanisms.

A technocentric approach to supporting behaviour change, relying on sensor technology and personal exposure data can only encourage individual exposure-minimising behaviours so far (i.e., horizonal trajectory). Similarly, whilst increasing and enhancing citizen participation is positive, only investing resource into this (i.e., vertical trajectory) or capping this at *consultative* or *functional* participation, will not fully support individuals to change their behaviour. To better support individual behaviour change that will reduce air pollution exposure, requires a shift in the diagonal trajectory, adopting tools to both increase data representativeness (Figure 2.4; Box 1) and citizen participation (Figure 2.4; Box 2) in tandem. Summarising the contrasts in air quality data sources and dissemination, engagement and participation mechanisms between the traditional and expanded approaches (Figure 2.4), highlights how, by specifically targeting these key stages (as external variable factors), we have the potential to provoke internal triggers which can spread throughout the multistage process for exposure reduction and to better support the likelihood of achieving improved public health.

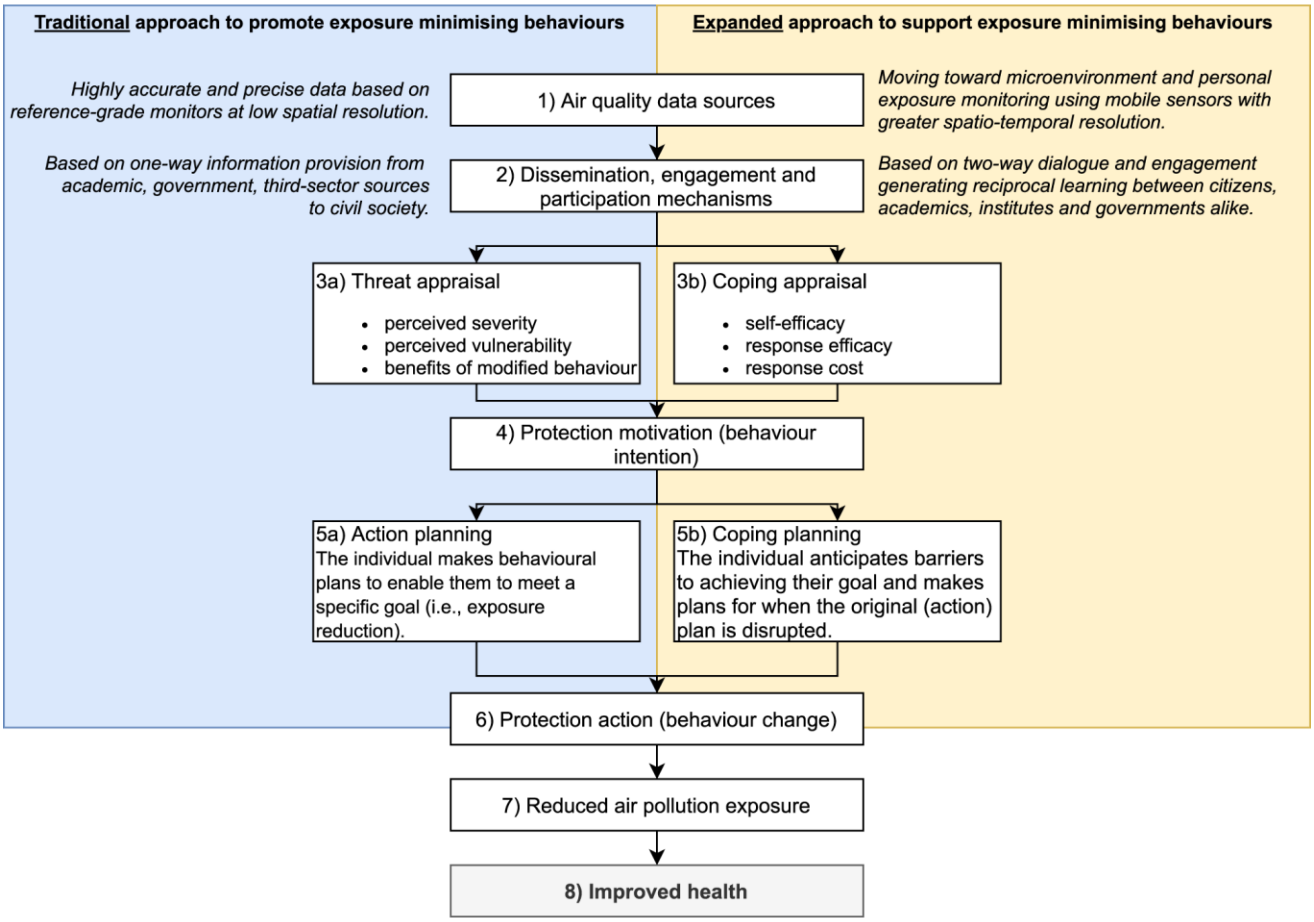

Figure 2.4. Left: the traditional approach to promoting exposure-minimising behaviours is based on top-down dissemination using highly accurate data with limited personal representativeness. Right: an alternative ('expanded') approach to supporting exposure-minimising behaviours could be more inclusive and collaborative with dialogue between all stakeholders and making use of more interactive data collection methods increasing personal representativeness. Note, both types of appraisal and planning exist in either side of the figure.

In comparison to the traditional approach, the expanded approach does have some key drawbacks, including the resources needed (e.g., human, social and financial), the availability of personalised air quality data, requiring practitioners to have a robust knowledge base, and greater input from citizens (Table 2.1). A specific concern is the transfer of the weight of responsibility for air quality and air quality-related health away from governments and institutions toward citizens. For this reason, we do not advocate replacing the traditional approach (i.e., regulatory monitoring by governments and institutions and the use of AQIs) with the expanded approach. By adopting the expanded approach, we can gain from the combined benefits of increasing data availability and engaged dialogue between stakeholders to aid the collection, analysis and interpretation of air quality information in a way meaningful to the public. This, in turn, will generate greater citizen autonomy and empowerment over personal exposures. Adopting the expanded approach and using a suite of approaches across the participation- representativeness space (Figure 2.3), will better support behaviour changes in relation to air pollution exposures.

Table 2.1. Advantages and disadvantages of the transition from the 'traditional' to an 'expanded' approach.

	Advantages	**Disadvantages**
Traditional approach	Though monitoring is expensive to set up and maintain, this is balanced by minimal costs associated with disseminating air quality information which can be automated.	Mismatch between the spatial resolution of the air quality data (community-level) and the actions being encouraged to minimise exposure (individual-level).
	Meets regulatory/legislative need for monitoring and dissemination.	Mechanisms not accessed (or indeed known about) by a large proportion of the population.
	Citizen engagement doesn't require continual input from researchers/ healthcare practitioners and thus more viable in the longer-term.	In settings without the infrastructural or technical capabilities such mechanisms to promote behaviour change are not yet feasible.

Expanded approach	Personally relevant and tailored solutions taking into account personal capabilities and opportunities.	More resource intensive (i.e. human capital), yet by their nature only work when engaging smaller groups of people.
	Empowers citizens by equipping them with relevant knowledge to gain control over their personal exposures.	Requires researchers/practitioners to have a robust knowledgebase, requiring an understanding of air quality, behaviour change psychology and public health.
	Greater opportunity to improve individual and public health.	Continual human input required to facilitate pairing citizen engagement with personally/locally representative data meaning that most work is time limited.
	Rooted within the community meaning greater ownership and trust.	Requires engagement and effort from citizens, weighed against their other more immediate needs and priorities, for it to be successful.

2.5 Recommendations for future work

The expanded approach should be seen as a ‘must do’ rather than a ‘nice to do’ to help combat the health impacts of air pollution. While the theoretical basis for the expanded framework is robust, future exposure reduction studies should evaluate the efficacy of the approach. Many data feedback intervention studies conducted to date- and included within this paper- lack robust evaluation reporting self-reported behaviour change or conducted with a homogenous population (e.g., school children, geographic area). A particular shortcoming within behaviour change studies is the sustainability of the intervention. Longitudinal studies which make a quantitative and qualitative assessment of the sustainability of behaviour change are needed. To this end, more work is needed to understand whether behavioural changes made using the approaches proposed under the expanded approach are sustainable in the longer term. We recommend that further work is undertaken in a variety of global contexts with different population subgroups (e.g., age, education level, pre-existing disease) to further test the potential for a combination of personalised air quality data and enhanced engagement to lead to reduced air pollution exposure and improved health. In particular, there is a need to explore the potential of co-production approaches, where participants are involved in all stages of the research process to support behavioural changes. Keeping in mind the individual-level differences in engaging in protective behaviours, future work should have emphasis on exploring individuals' capabilities, opportunities and motivations for behaviour change with respect to air pollution exposure protective behaviours and should consider the Social Ecological Model, starting with the individual at the core. Generating autonomy and prompting protection action requires working not only across disciplines, but also across stakeholder groups, and placing greater emphasis on the co-production of air quality projects that involve civil society, researchers and policymakers equally in the conception through to analysis and dissemination stages of projects is a key part of this. However, for improved public health this needs to reach beyond personal exposure autonomy; more emphasis is needed on population exposure and the role individual behaviours play in modifying local concentrations of pollutants.

2.6 Conclusion

In this paper we have shown that participation mechanisms and their underpinning air quality data are two distinct but related key external steps preceding health protection motivation, protection action, reduced exposure and improved public health. As external cues which lead directly to (and can influence) internal determinants of behaviour change, these are crucial in shaping an individual's threat and coping appraisal and are the first steps in a multistage process for improved public health. Considering the traditional approaches to the promotion of exposure-minimising behaviours regarding these key stages from a health psychology perspective, it is apparent that they fail to support significant individual protection motivation and protection action. Examining alternative approaches to both data sourcing and citizen participation and evaluating their success at targeting the psychological elements of protection motivation, we argue that both increasing the personal representativeness of air quality data and increasing citizen involvement can better support protection action when used simultaneously.

Top-down, government policy is vital to reduce the health impacts of air pollution but can (and should) be supported by individual action. We acknowledge that the expanded approach represents a resource-intensive approach that will not be achievable in all global locations and that it requires citizens to have high protection motivation, the capacity and interest to be 'engageable' with the topic. The expanded approach framework proposed in this paper is also not attempting to promote personal monitoring or participatory methods as ‘silver bullet’ techniques, instead it is an attempt to highlight the additional benefits such methods can have on behaviour change and motivation at the individual-level. Additionally, this paper is not proposing a shift away from traditional, static, regulatory monitoring. Simply, from a behaviour change perspective, the evidence presented in this paper suggests that such an approach is not adequate to support personal protective action against air pollution exposure.

Air pollution is a major health and sustainability challenge of modern times. While not a panacea for the ‘wicked’ problem of air pollution, making air quality data more personal and involving citizens in research processes simultaneously has the potential to support the reduction of the global public health burden of air pollution and accelerate progress towards the SDGs.

Chapter 3 | "I have to stay inside…": Experiences of air pollution for people with asthma

Research Question 1: What are the lived experiences of air pollution for people living with asthma in Scotland?

> Objective 1a) Explore the lived experience of individuals living with asthma in Scotland, investigate how they manage their condition and the role that air quality plays in how they manage their asthma using semi-structured interviews.

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Author contributions: **AMcC**: Conceptualisation, formal analysis, data curation, writing-original draft, visualisation. SS: Conceptualisation, writing- review & editing. CB: Conceptualisation, writing- review & editing. VS: Conceptualisation, writing- review & editing. CG: Conceptualisation, writing- review & editing. HP: Conceptualisation, writing- review & editing

Abstract

Asthma, characterised by airway inflammation, sensitisation and constriction, and leading to symptoms including cough and dyspnoea, affects millions of people globally. Air pollution is a known asthma trigger, yet how it is experienced is understudied and how individuals with asthma interact with air quality information and manage exacerbation risks is unclear. This study aimed to explore how people living with asthma in Scotland, UK, experienced and managed their asthma in relation to air pollution. We explored these issues with 36 participants using semi-structured interviews. We found that self-protection measures were influenced by place and sense of control (with the home being a “safe space”), and that the perception of clean(er) air had a liberating effect on outdoor activities. We discuss how these insights could shape air quality-related health advice in future.

3.1 Introduction

Asthma, characterised by inflammation, sensitisation, and airway constriction, causes symptoms such as cough, wheeze, chest tightness and breathlessness. It is globally the most widespread chronic respiratory condition (Chan *et al.*, 2019), and more than 368,000 people (7% of the Scottish population) receive treatment for asthma in Scotland (Scottish Government, 2020). While there are several genetic and environmental factors that contribute to the onset, exacerbation and deterioration of asthma (World Health Organisation, 2023b), air pollution, including pollutants such as particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2), has emerged as a significant environmental trigger (Guarnieri and Balmes, 2014).

The air quality-related aetiology of asthma is well established (Tiotiu *et al.*, 2020) and is supported by a robust literature base that includes systematic reviews and meta-analyses (e.g., Fuller et al., 2023). Epidemiological studies highlight the adverse effects of air pollution on asthma-related health outcomes, often utilising population-level data, such as emergency room visits (e.g., Yadav *et al.*, 2021) or hospitalisations (e.g., Priyankara *et al.*, 2021). Notably fewer studies have focused on individual-level evidence, investigating the impact of personal exposures on health outcomes such as symptom prevalence and medication use (e.g., Williams *et al.*, 2019) or on patient wellbeing and quality of life (e.g., Ścibor *et al.*, 2022). Such patient-reported outcomes provide a more holistic understanding of the consequences of air pollution on the individual and allows for a more nuanced assessment of the health impacts of air pollution, such as if or how air pollution exposure impacts their physical activity, or how use of their medication can help combat pollution-triggered exacerbations.

While air pollution as an environmental entity is objectively measurable and uninfluenced by personal subjectivity, air pollution has also been defined as a hybrid phenomenon at the intersection of environmental processes and social practices (Booker *et al.*, 2023). Peoples' experiences of air pollution differ. Even within a seemingly homogenous group, such as those with asthma, individuals' asthma triggers and physical symptoms can vary greatly (McCarron *et al.*, 2023; World Health Organisation, 2023b) resulting in individual realities, and therefore experiences, that differ from person to person (Hauge, 2013). Additionally, personal exposure to air pollution varies between individuals, influenced, at least in part, by the places a person spends their time, such as where they live and work and how they commute (e.g., Panchal et al., 2022; Reis et al., 2018). Not only does this influence their 'objective' personal exposure to air pollution, but these experiences, in turn, influence how individuals come to understand, make sense of, and perceive air pollution (Bickerstaff and Walker, 2003), which can be more influential than objective information (Calvillo and Garnett, 2019), though may not necessarily align with measured pollution concentrations. Additionally, perception as a construct is influenced by several factors, including the social, economic and political context and individuals' previous knowledge and experiences (Noël *et al.*, 2022). In addition, individuals' demographic characteristics such as gender, socioeconomic status, age and level of education are known to play a role in influencing and shaping perceptions (Guo *et al.*, 2016; Kowalska-Pyzalska, 2022). Consequently, the way in which individuals experience and make sense of air pollution is contextual and highly subjective (Noël, Vanroelen and Gadeyne, 2021) which influences behavioural responses. To date, there has been limited attention paid to the lived experiences of individuals with asthma regarding air pollution and its actual impacts on their condition and management strategies (An *et al.*, 2018).

Personal exposure to air pollution can be modified – to a considerable degree – through behaviour changes (Chatzidiakou *et al.*, 2019; Ma *et al.*, 2021; Riley *et al.*, 2021). Health behaviours have frequently been explored through psychological theories and models identifying and measuring determining factors. A key approach is the Theory of Planned Behaviour (TPB; Ajzen, 1991), a psychological model that predicts and explains intention and behaviour based on three constructs: subjective norms, attitudes and perceived control. These factors explain the underlying mechanisms which influence individuals' intentions and subsequent actions. As such, understanding how individuals with asthma practically experience and manage their condition in the context of air pollution is valuable. Gaining insight regarding how and why people with asthma adhere to current advice, access healthcare resources in relation to pollution exposure, and access air quality information for their local area is an important part of this. Understanding the nuances of the challenges faced and strategies employed for managing asthma in relation to air pollution is vital for developing effective interventions, enhancing asthma management strategies, reducing health inequalities and improving overall quality of life (Apps *et al.*, 2019). Therefore, this study aimed to explore how people living with asthma in Scotland experience and manage their asthma in relation to air pollution.

3.2 Methodology

3.2.1 Study overview

To explore how people living with asthma in Scotland experience and manage their asthma with respect to air pollution, this study adopted a qualitative research approach using semi-structured interviews. Ethical approval was granted by the University of Stirling's General University Ethics Panel [GUEP 2021 2506 1892].

3.2.2 Data collection

Semi-structured interviews were conducted with non-smoking adults living in Scotland who reported having been diagnosed with asthma by a healthcare practitioner. Participants were recruited as part of a larger randomised control trial design study whereby, following the interview, participants conducted personal exposure monitoring (McCarron *et al.*, 2023) and co-developed exposure reducing behavioural interventions (McCarron *et al.*, 2024a), hence smoking being an exclusion criterion. Recruitment was conducted primarily via Facebook marketing and was designed to reach users across Scotland. This consisted of an advert for the study and an online form where prospective participants could leave their contact details. Each prospective participant was contacted with more information about the study and asked to confirm they met the eligibility criteria before the information sheet and consent form were sent. A more targeted campaign displaying recruitment posters in sports centres was launched at the research mid-point (and following review of participation) to promote participation of younger males. The number of interviews conducted was determined by the number of participants enrolled as part of the larger study, however our focus was on topic coverage, quality and depth, rather than assigning a required sample size. Participation was incentivised with a shopping voucher of up to £30 for completion of the study. Interviews took place between September 2021 and August 2022. Owing to the COVID-19 pandemic, all interviews took place online. Informed signed consent was obtained from all participants and demographic information collected via survey prior to participation.

Semi-structured interviews were used to gain both retrospective and real-time accounts of participants' experiences of air pollution. A topic guide was developed to ensure interviews flowed easily and to aid interaction between the interviewer and interviewee. The topic guide was separately piloted with five individuals (meeting the same eligibility criteria as participants) prior to the main study taking place and amended according to feedback. Questions were designed to be open and comprehensive, with the aim of prompting participants to provide detailed responses, however, prompts and probes were also prepared to facilitate and stimulate elaboration when necessary. To address our specific research aim, this analysis focused on one section of the interview which covered discussion of participants' experiences of air pollution. The air quality section of the interview topic guide can be found in Supplementary Material A. All interviews were conducted by the lead author and were transcribed verbatim.

3.2.3 Data analysis

To explore patterns across the dataset, reflexive thematic analysis was undertaken following Braun and Clarke's (2022) six phase approach. Reflexive thematic analysis aligns with the lead author's ontological and epistemological stances, and was a suitable approach given that, though this work set out to be inductively orientated, connections with pre-existing theory could be recognised within the data (e.g., Theory of Planned Behaviour (Ajzen, 1991)). Additionally, the flexibility of reflexive thematic analysis allowed the possibility of capturing both semantic and latent meanings to gain a comprehensive understanding of the participants' experiences of air pollution and uncover deeper insights.

Given that interviews were conducted over the course of a year, familiarisation with the data was an important initial stage of the analysis process in order to have equal familiarity with all cases, but also to engage with the data more critically than was permitted at the point of collection. Coding was a systematic and iterative process conducted using NVivo software v1.7.1. Several rounds of coding were conducted before generating initial themes which were then refined to ensure they were descriptive, interpretative and explanatory. Four final themes were developed from the data.

3.3 Results

Interviews were conducted with 36 participants (Table 3.1) and lasted between 25 and 86 minutes. Most participants did not report respiratory comorbidities which minimised the likelihood of symptom confusion. Participants were relatively well dispersed by health board, though we had no participants residing within NHS Ayrshire and Arran, NHS Orkney or NHS Shetland. Most participants (61%) resided in urban areas and were from areas categorised as least deprived as indicated by Scottish Index of Multiple Deprivation (SIMD) quintiles (>50% from quintile 4 and 5), however it has been shown that within the Scottish context, SIMD decile and ambient pollution concentrations are not strongly associated (Bailey *et al.*, 2018).

Table 3.1. Interview participant demographic information. †n=33 due to nonresponse. *SIMD: Scottish Index of Multiple Deprivation.

Participant characteristic	**Statistic**
Age (mean years (range))	49 (24-74)†
Sex (n (%))	
Female	25 (69.4)
Male	11 (30.6)
Other respiratory condition (n (%))	
No	32 (88.9)
Yes	1 (2.8)
Missing	3 (8.3)
SIMD* Quintile (n (%))	
1	0 (0.0)
2	5 (13.9)
3	12 (33.3)
4	6 (16.7)
5	13 (36.1)
Health Board (n, %)	
NHS Ayrshire and Arran	0 (0.0)

NHS Borders	1 (2.8)
NHS Dumfries and Galloway	2 (5.6)
NHS Fife	2 (5.6)
NHS Forth Valley	5 (13.9)
NHS Grampian	8 (22.2)
NHS Greater Glasgow and Clyde	5 (13.9)
NHS Highland	3 (8.3)
NHS Lanarkshire	3 (8.3)
NHS Lothian	3 (8.3)
NHS Orkney	0 (0.0)
NHS Shetland	0 (0.0)
NHS Tayside	3 (8.3)
NHS Western Isles	1 (2.8)
Urban-rural Classification (n (%))	
Large urban area	10 (27.8)
Other urban area	12 (33.3)
Accessible small town	2 (5.6)
Remote small town	3 (8.3)
Accessible rural	6 (16.7)
Remote rural	3 (8.3)

Exploring how people living with asthma experience and manage their condition with respect to air pollution, we have developed four themes: 1) Home is a safe space; 2) Disconnection from air quality information; 3) Behaviour change ultimately depends on perceived control; and 4) Clean(er) air is liberating. We elaborate on and explain these in the following sections (summarised in Figure 3.1).

1st order concepts	2nd order themes	Aggregate dimensions
The need to travel further to get away from air pollution Remove self from situation with poor air quality Go (towards) somewhere with better air quality	Outrunning air pollution (short-term)	Home is a safe space
Only option is to relocate home to place with better air quality (hypothetical) Only option is to relocate home to place with better air quality (actual)	Move away from air pollution (long-term)	
Need to 'block out' air pollution from outdoors 'They' cause air pollution	Trapped indoors by air pollution	
Knowing about air quality doesn't change anything I don't need to know about air quality I don't want to know about air quality I don't think about air pollution	Ignorance is bliss	Disconnection from air quality information
Laziness prevents me from accessing air quality data Air quality information isn't easily understandable Air quality information isn't easily accessible Accessing air quality information takes time	Barriers prevent me from accessing using air quality data	
Nothing I can do about air pollution You cannot avoid air pollution	Conceding to air pollution	Behaviour change ultimately depends on perceived control
Try to avoid air pollution (self-efficacy) It's not always possible to avoid air pollution (external factors)	Attempt to avoid air pollution	
I can avoid air pollution I want to avoid air pollution	I am able to avoid air pollution	
I do not try to avoid air pollution Air pollution will not stop me doing what I enjoy (determination)	I don't avoid air pollution	
I can't do some things that I want to do	Air pollution limits me	Clean(er) air is liberating
Air pollution can be smelled Air pollution can be tasted Air pollution is dark and dirty (can be seen) Air pollution is stuffy and warm (can be felt)	Air pollution causes a negative sensory experience	
Air pollution makes me feel ill Air pollution causes my asthma symptoms	Air pollution makes me feel ill	
Air was brighter during lockdown (visual) Air was fresher during lockdown (feeling)	Senses are liberated in the absence of air pollution	
Lack of inhaler use during lockdown Able to be more active during lockdown	Lockdown was liberating	

Order of process

Figure 3.1. Codes (1st order concepts), initial themes (2nd order themes) and final codes (aggregate dimensions) (based on Gioia, Corley and Hamilton, 2013*)*.

3.3.1 Theme 1: Home is a safe space

The theme 'home is a safe space' reflected the interpreted contrast between the home environment (being somewhere that is secure and controllable) and the external outdoor environment (where air pollution exists and is inflicted upon people). Air pollution was described as something that engulfed the home from the outdoor environment, and many participants described the need to close windows as a defence mechanism to prevent air pollution from entering their homes.

…if it's bad you know the traffic's heavy, I'll make sure that the windows are shut rather than open. (Participant 12, Female, 45-49).

I suppose just like, if it's smoky outside, I would shut all the windows. (Participant 9, Female, 55-59).

Frequently, this defensive behaviour was to directly combat air pollution enforced upon them from their adjacent outdoor environment (Figure 3.2). In particular, neighbours' solid fuel burning behaviours were highlighted by participants.

… if they light that (pizza oven) I've got to shut every window in my house. (Participant 9, Female, 55-59).

I've a neighbour a few doors down who has a fire in his garden…I have to stay inside and shut all the windows when he's got it on because once the smoke comes into my garden, and it just makes my chest congested and feels a bit wheezy. (Participant 13, Female, 45-49).

Participants suggested that the behaviours of others, in this case solid fuel burning behaviours, had a significant impact on their home environment and/or their asthma symptoms. The concept that air pollution originated and was imposed from the outdoor environment was reinforced with some participants reflecting on the need to stay indoors – in their safe home environment- when air quality was poor.

Every vent's to be shut it can stop me going out. (Participant 30, Female, 55-59).

If the air quality is poor, I just don't go out…I wouldn't go out. I stayed indoors, um, did what I had to do from home. (Participant 25, Female, 55-59).

Participants were proactive and had a willingness to take measures to protect themselves by staying indoors or creating a barrier between the outdoor environment and their living space. In this sense, the home became a refuge, providing relief from air pollution exposure.

Within the home, there was a confidence over the decisions participants could make and action they could take to directly control pollution within their home (Figure 3.2; centre circle).

…something that affected my asthma is washing powder and softeners. So again, I use unscented washing powder. (Participant 19, Female, 55-59)

I avoid frying stuff now… (Participant 11, Male, 30-34)

Away from the immediate home environment, participants' no longer actively and directly faced air pollution, but rather evaded air pollution (Figure 3.2), indicating the need to create physical distance between themselves and air pollution. The need to 'outrun' air pollution was a short-term, in-the-moment response.

Then [I] have to cycle further just to kind of get rid of it. (Participant 31, Female, 30-34).

I would like always walk quickly through Charing Cross [Glasgow] when I was going into town… I guess subconsciously I always walk a bit faster if it's next to busy roads to like get away from it [air pollution]. (Participant 24, Female, 25-29).

This was not limited to active travel users, but vehicle users also.

I took the step with the dust in the atmosphere of actually driving somewhere else…Driving to get away from it. (Participant 32, Male, 50-54).

Outrunning air pollution was not specific to avoidance behaviours but also encapsulated participants consciously seeking out and moving toward areas perceived to have better air quality, namely more natural areas such as parks and wooded areas.

There's a nature trail about five minutes' walk away from me. So I can go there and it is trees and it, there's no cars allowed. It's just footpaths. And I can go there and that is really nice. So just being able to do, go to that and it is only literally five minutes from my, my house. It's, it's comforting… (Participant 30, Female, 55-59).

…I like to spend time in the, in the woods - so that I can have some nice clean air. Erm, so I tend to do that... Erm, so I tend to do a lot of walking in the woods if I, if I just need to like catch a breath. (Participant 22, Female, 40-44).

Similar to the home environment, natural environments were regarded as havens for participants, offering a retreat from air pollution. These areas served as comforting spaces, allowing them to escape the sources of air pollution and find relief from their symptoms.

Creating physical distance between themselves and the air pollution inflicted upon them from the outdoor environment was also a longer-term, more permanent option for some participants, both as a prospective action, or, in one case, an implemented action.

> *I'm planning to move somewhere more rural. I've not did it at the moment but erm that's in my head to do that. (Participant 13, Female, 45-49).*

> *And my GP said that the only way my asthma would improve is if I moved over to somewhere like [redacted] and that's how we moved up to [redacted]. (Participant 20, Female, 55-59).*

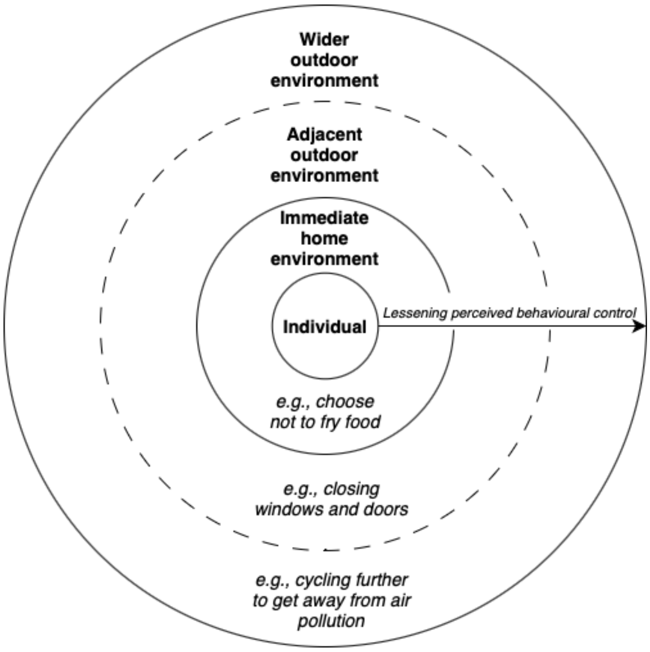

Figure 3.2. Constructed from the theme 'home is a safe space', participants' response to air pollution was determined by perceived behavioural control over the environment in which the individual found themselves. In the home, participants had the greatest perceived control and could choose what behaviours to perform to preserve indoor air quality. Individuals protected indoor air quality by closing windows and doors. Away from the home, perceived control diminished and thus participants' response switched to avoidance.

3.3.2 Theme 2: Disconnection from air quality information

Our second theme, 'disconnection from air quality information' was developed from participants' discussions around accessing air quality data and information as something that they did not generally do. Generally, participants indicated that they had a limited understanding of air pollution. Many participants expressed a desire to access air quality data and information to enhance their knowledge on the subject.

I would like for my own knowledge to actually see what links and stuff there is… (Participant 12, Female, 45-49)

I don't know enough about it to be honest with you…if someone was to explain to me exactly what's going on then I'd be a lot happier, I'd be a lot more knowledgeable and I'd know whether I could go to certain places or avoid, you know, avoid them, yeah. (Participant 28, Male, 60-64)

This demonstrated a belief that increased knowledge can enhance self-confidence in making informed decisions, particularly with reference to identifying places or areas to avoid.

Regarding accessing air quality information (and as discussed later, implementing behaviour changes to reduce exposures), participants could be categorised into one of four categories sharing common characteristics: *able*, *attempting*, *conceding* or *resisting* (Figure 3.3).

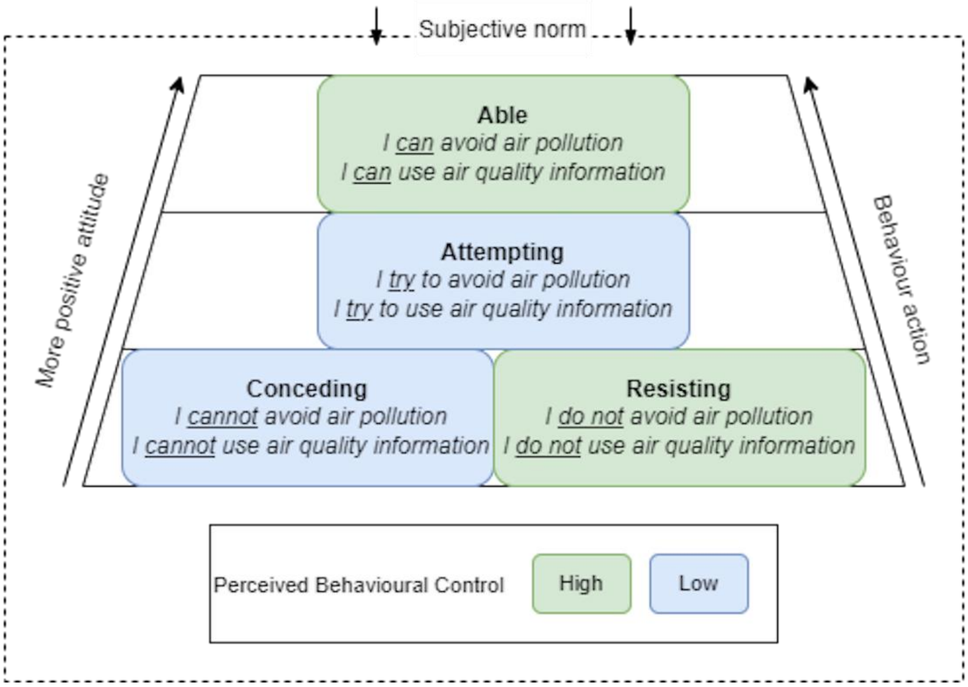

Figure 3.3. Categories of behaviour action observed in themes two and three in the context of the Theory of Planned Behaviour (Ajzen, 1991). The *able* group possess the most positive attitudes and high perceived behavioural control resulting in action. *Attempting* also have a positive attitude but are constrained in their actions by a low perceived behavioural control. *Conceding* evaluate behaviour change more negatively (negative attitude) and low perceived behavioural control, resulting in inaction. *Resisting* similarly have a more negative attitude toward behaviour change but high perceived behavioural control over their (in)action. Subjective norms are the external social influences acting across all groups. See Supplementary Material B for a more detailed description of each category.

Some participants *conceded* to being unable to access local air quality data and information, and highlighted barriers that had hindered their access to information and subsequent knowledge. In addition to accessibility, the practical aspects of effectively utilising these data and information were addressed.

> *…I wouldn't know where to go to get live information to be honest. I also wouldn't know what use to make of it… (Participant 26, Female, 55-59)*

Even when participants were aware of how and where to access information, some expressed that the inaccessibility of the language was a cause of disconnectedness. Specifically, complex 'jargon' and an overall lack of comprehensibility deterred them. Although they technically had the ability and *attempted* (Figure 3.3) to engage with the data and information, its complexity was off-putting.

> *I think if it was more easily accessible, more readily understandable because, I mean, while I can read things like textbooks and academic articles …it becomes boring after a while, because it becomes jargon and then, there's no explanation of that jargon and so you're just there like well I'm off…. (Participant 36, Male, 25-29)*

In addition to external barriers related to access and comprehensibility of air quality data and information, participants also emphasised the presence of internal barriers that hindered their ability to access and utilise such resources. They expressed that the burden of responsibility of finding and utilising air quality data and information lay with them as individuals and required the investment of their own time and effort.

> *…it's not something that I would normally have time to sit down and look at, you know. (Participant 10, Male, 50-54)*

Relating to the effort required, some participants discussed that their own 'laziness' was a preventative barrier to access.

> *Laziness I suppose because you're not, you're not affected by it, so you don't think about it. (Participant 9, Female, 55-59)*

> *Sometimes you're just lazy... (Participant 22, Female, 40-44)*

The perceived effort of seeking out air quality data and information, interpreting technical language or investing time and energy into understanding the information was a deterrent and thus 'laziness' stemmed from the perceived difficulty of the task, influencing individuals' motivation and willingness to engage with the data. As well as being an extrinsic barrier, this bridged with internal barriers. This self-referenced ‘laziness’ also suggested a general apathy, a lack of motivation, willingness and energy to engage with air quality data and information and indicated a general lack of interest or desire to take action. For some participants, air pollution was not something that they prioritised or thought about and as such *resisted* (Figure 3.3) to act on it.

> *No, it’s not something I regularly think about…I don’t really ever think about it. (Participant 2, Male, 20-24)*

> *I’ve never [engaged with air quality information] but I suppose I would go to one of these sites that gives information about the weather. But I’ve never thought about going to… (Participant 17, Male, 70-74)*

While some exhibited ambivalence towards accessing air quality information, for others, this was motivated by a perceived lack of necessity, referencing a lack of pollution where they live.

> *I certainly don’t think about it where I live. I'm up in Perthshire [rural area]. So you know I don’t think about air pollution here. (Participant 18, Male, 60-64)*

> *I think I don’t engage with it because I feel where I live is not, it’s not heavily polluted so it’s not an issue. (Participant 34, Female, 45-49)*

In contrast with those who believed knowledge was empowering and could lead to better, more informed decision-making, others suggested that knowing about air quality does not bring about any significant changes, interpreted as a perceived lack of behavioural control. Some individuals expressed feelings that acquiring information about air quality would not result in any meaningful impact or give them greater control over the situation.

> *I think definitely it would have made me more aware, but I wouldn’t- I don’t know that I’ve done anything differently as a result of it. (Participant 7, Female, 55-59)*

> *…I’d sort of check that on occasion, but I sort of feel because there’s not necessarily much I can do about it, I just put up with it. (Participant 12, Female, 45-49)*

Those who were *able* (Figure 3.3) to access air quality data and information, used it as an explanatory tool to verify their symptoms, rather than using it as a reference tool to inform their decision-making.

> *So just kind of check the air quality to see if it's matching, sort of how I am feeling. (Participant 33, Female, 20-24)*

> *Erm, I think it's more to figure out if the increase in wheeziness is because of outside or if it's something with me, you know…I might be starting to come down with something else. It sort of helps me differentiate between the two. (Participant 12, Female, 45-49)*

Finally, some participants did not make the connection between air pollution and their own health. Rather than referring to themselves, participants referred to air pollution as something that impacts other people.

> *Well, I know obviously that for some people air pollution will affect their asthma (Participant 9, Female, 55-59)*

> *I mean it can really affect some, some people (Participant 29, Female, 50-54)*

In summary, both external factors (such as air pollution being considered as an outdoor phenomenon) and internal factors (such as perceived control) prevented people from accessing air quality data and information which, in turn, resulted in, or at least contributed to, inaction.

3.3.3 Theme 3: Behaviour change ultimately depends on perceived control

Our third theme was developed from participants' descriptions of adapting their behaviours to limit their exposure to air pollution and the differing approaches taken and perspectives on these behaviour changes.

There was a consensus amongst participants, whether explicitly stated or not, that the avoidance of air pollution was a 'normal' and sensible thing to do. Avoiding air pollution was something that they had been told by a healthcare professional or something that was "common sense" and learned from previous experience.

But that's the only advice I received [from a healthcare professional], basically to avoid exposure to allergens, or to like pollution… (Participant 33, Female, 20-24)

I think I just kind of realise certainly anything strong like bonfires I couldn't erm, you know be next to them. Erm, I don't think anyone ever sort of, I think it's just kind of common sense I suppose? (Participant 19, Female, 55-59)

However, for many participants, air pollution was something that they *concede* to and consider themselves to have no control over. Inaction in these cases was driven by impotence and apparent inability to alter air quality.

…because I live in the city and there's not really, yes, there's nothing I feel like I can do really. (Participant 16, Female, 30-34)

And at the end of the day, I can't see that pollution levels are ever going to change in my lifetime to make a difference to my asthma so there's no point in getting into it too deeply for me because nothing's going to- I can't change anything anymore than I've done already, you know… (Participant 23, Female, 55-59)

Because I feel impotent, there's nothing I can do about traffic pollution, I just have to live with it. (Participant 5, Female, 70-74)

Participants emphasised the externality of air pollution (e.g., existing in the 'city' or related to 'traffic pollution') as the reason for their lack of control. In addition to a sense futility, some participants had come to regard air pollution as a part of day-to-day life that they had no option but to accept and endure.

It just became a way of life for me. (Participant 30, Female, 55-59)

Just live, you don't have an alternative, get on with life. (Participant 32, Male, 50-54)

While *conceding* implied giving into or accepting air pollution and its impacts, some participants demonstrated inaction stemming from *resistance* or defiance; either as defiance to not be stopped by air pollution or determination to not give in to their asthma. In contrast to those who *conceded*, these individuals seemed to actively oppose developing adaptive behaviours, such as avoidance of a place or area.

But I've never thought about going to – I doubt whether I would change my plans if I found out that Glasgow is high in [air pollution]. I would still go. It wouldn't stop me going. (Participant 17, Female, 70-74)

…I wouldn't avoid an area because of air pollution. (Participant 24, Female, 25-29)

No. No, I would not change what I do because I don't let it define me. I won't let it be- I'm not going to give into it. I don't think I'll ever give into it. I'll have it. I've always had it. (Participant 23, Female, 55-59)

While both *conceding* and *resisting* ultimately result in inaction and thus no impact in relation to exposure-related behaviour change, the fundamental difference between the two is attitude and perceived control (Figure 3.3). *Conceding* reflected a sense of defeat, accepting that "there is nothing [they] can do" about air pollution owing to it being a problem where they live and caused but outdoor sources and as such, do not actively engage in developing adaptive behaviours to reduce exposures. In contrast, the *resisting* standpoint conveyed a defiant or determined stance, actively opposing or challenging the need for adaptive behaviours. Despite both resulting in inaction, it was the contrasting attitudes and perceived control that distinguished these two positions.

Perceived control played a key role in fostering the development of adaptive behaviours. *Attempting* signified participants' endeavours to adapt their behaviours to reduce their exposure to air pollution. On a semantic level, this was evident in participants use of the word "try".

… you can't obviously always avoid things, but I just try and be a bit aware of triggers and modify my life a little bit to avoid as much as I can. (Participant 13, Female, 45-49)

Outside I try not to like, we've got a main road which is very, you know it's gridlocked with cars most of the day. It's dreadful. So I try not to go via the main road, you know I take the back streets. I, having said that it's not always possible because you have to, the shops are down there. (Participant 19, Female, 55-59)

This conveyed an intention and willingness to act and adopt avoidance behaviours whilst also portraying an uncertainty of achieving the desired outcome. Individuals who *attempted* to alter their behaviours exhibited feelings of limited efficacy.

> *… I always felt like I was running through just, like pollution wherever I went. I tried different times of the day, and it was always just as bad. So I did change that route. (Participant 31, Female, 30-34)*

Despite adopting adaptive action and choosing to run a different route to avoid pollution exposure, they could not escape air pollution and thus assessed a lack of impact from the behaviour. Additionally, some participants referred to their adaptive behaviours with a sense of insignificance and triviality.

> *No probably not actually no. I don't really. Other than the wee air filter in my bedroom at night, no. I've nothing else. (Participant 27, Female, 40-44)*

> *I must admit though when I get to that junction, this is daft, but when I get to that junction, rather than having my car having air coming in from the outside and circulate round the car, I close that off and just have it circulating inside the car until I get past it… (Participant 9, Female, 55-59)*

Despite participants taking what are viable actions to reduce their exposures, these were spoken about with a sense of worthlessness. Much like *conceding*, there was a sense of being constrained by perceived behavioural control.

Finally, some participants actively took steps to (and do) avoid air pollution. Participants acknowledged that they were in a privileged position in that they were *able* to avoid air pollution by not traveling to certain places or being able to stay indoors, recognising that, as previously discussed in this section, it is simply not a choice many people are able to make.

> *I'm fortunate that I don't have to go, I don't have to travel on a daily basis. So you know, I've reached a stage in my life where I can avoid heavily polluted areas. (Participant 5, Female, 70-74)*

> *Well I was working so I was in air-conditioned hotel, and I was thinking you know, 'thank God I'm in here' you know. (Participant 18, Male, 60-64)*

3.3.4 Theme 4: Clean(er) air is liberating

The fourth and final theme, ‘clean(er) air is liberating’, was a theme of contrasts, developed from participants’ reflections on their experiences of ‘clean’ air compared with polluted air arising from the various lockdown and travel restrictions brought about by the COVID-19 pandemic.

Air pollution was described as an unpleasant sensory experience that participants could see, smell, taste, hear and feel, and was portrayed as something which dulls and dampens the senses. In contrast, clean(er) air, or the absence of air pollution, liberates the senses and makes for a more pleasant sensory experience (Table 3.2).

Table 3.2. Illustrative quotes of air pollution as a sensory experience emphasising the contrast between polluted and clean(er) air. Key phrases relating to the senses are highlighted in bold.

	Illustrative quotes	
Sense	**Polluted air**	**‘Clean’ air**
See	*My husband always used to say when we were going back to Bo’Ness for a visit. Look there’s the **black clouds** we’re heading for Bo’Ness…Just **look for the black clouds** and you’ll see you’re nearly at your granny’s. (Participant 6, Female, 60-64)*	*…you know the air seemed cleaner somehow and the **trees seemed brighter**. **Everything seemed brighter**…we were like, have trees always been **so green**? (Participant 9, Female, 55-59)*
Smell	*Sometimes the air’s just **heavy with the horrible scent**. Yes, I think it’s certainly to do with your sense of smell… (Participant 19, Female, 55-59)*	*…I felt like when you were walking about the air **smelled cleaner** as well because you **weren’t smelling the exhaust fumes**. (Participant 13, Female, 45-49)*
Taste	*…you can feel like a **sweet taste** in your mouth. (Participant 33, Female, 20-24)*	*You know the **taste that I mentioned before, going away**. I really only noted the taste actually in the street when the traffic is bad. (Participant 10, Male, 50-54)*

Hear	*It's just, you can just, there's a kind of* ***constant hum of traffic*** *I guess, yes,* ***constant kind of hum of traffic****. (Participant 29, Female, 50-54)*	*You know, because there was less cars on the road,* ***you could hear the birds singing****, you know, that's the type of thing we noticed,* ***we could hear the birds outside****… (Participant 9, Female, 55-59)*
Feel	*And you just always notice the air quality* ***it's so like warm*** *and like you feel like you really breathe it in…And it just* ***feels like dirty****… (Participant 24, Female, 25-29)*	*…I mean,* ***the air definitely felt clean****…It just –* ***it felt fresher****. It felt like there was more oxygen in it. (Participant 36, Male, 25-29)*

The senses shape participants' experience of place. As well as the *feeling* of air pollution being superficial or external, participants described the 'internal' feeling of air pollution as something that can be sensed *within* the body. Moreover, some participants made the direct link between exposure to air pollution and their own ill-health.

…it would kind of make you cough a bit…yes sometimes you feel a bit lightheaded as well with it… (Participant 31, Female, 30-34)

It catches the back of my throat…it does feature in the back of my throat, it catches my inhalations. (Participant 17, Male, 70-74)

Some participants developed this feeling deeper, describing it in a more severe way. They described the sensation of air pollution as making them choke, evoking a feeling of suffocation being imposed upon them.

…you know and it's nice to have a real fire – but I can't really…it makes me wheezy and choked up. (Participant 13, Female, 45-49)

And I woke up choking in the middle of the night… because obviously the air quality in London is shocking, so it affects me. (Participant 22, Female. 40-44)

…it just seems to sort of choke you… (Participant 1, Female, 45-49)

Furthermore, some participants made the association between air pollution exposure and increased use of their inhaler, making the connection with how this was influenced by where they were.

…the air quality feels totally different to what it does when I'm at home in the country. Erm, so just memories of having asthma symptoms and coughing and needing to use my inhaler more frequently, just constant reminder to having asthma. (Participant 4, Female, 45-49)

I've been to Santiago in Chile and [the air quality] was horrible, it was actually like, I remember climbing, hiking and actually always my inhaler I took. (Participant 10, Male, 50-54)

In contrast to being constrained by their symptoms and their medication with exposure to air pollution, in the absence of air pollution in the outdoor environment, participants described the liberation from their asthma symptoms with 'clean' air relieving them from their asthma.

I wasn't having asthma attacks every day, and I connected it in my mind with the lack of road pollution… Like I could go out I didn't need my salbutamol [reliever inhaler]. (Participant 13, Female, 45-49)

I think [the lack of air pollution] also helped me get less inflammations… I think also the fact that the cut down based on the traffic, and exposure to that type of pollution, it was kind of like a rest for the lungs…. Yes, I kind of feel that I think partly the reason why I'm not taking that medication at the moment is because I kind of had like a rest from traffic pollution. (Participant 33, Female, 20-24)

In contrast to some of the interpretations in theme one specifically relating to being trapped indoors by air pollution, a shift in participants' experiences was detected during COVID-19 lockdowns. In the lockdowns air quality was perceived to be better, enabling engagement in various activities that would previously have been limited by air pollution. This ranged from simply being able to spend time outdoors, to being able to take exercise outdoors.

I could sit, sit for a couple of hours outside, which is something that I wouldn't have done before…Because, you know, it would have been uncomfortable. (Participant 30, Female, 55-59)

Erm, I noticed that when I was going for walks, I wouldn't need masks, salbutamol [reliever] inhaler, and I was able to walk for longer

and longer. Erm, and then so I was able to exercise a lot more…
(Participant 13, Female, 45-49)

Participants no longer had to outrun air pollution but could enjoy the outdoor environment.

3.4 Discussion

This study has explored how people living with asthma experience and manage their condition with respect to air pollution exposure. To our knowledge, this is the first qualitative study to explore how individuals with a respiratory condition experience air pollution in their day-to-day lives. We have identified four themes that describe how people experience air pollution and the various ways in which they manage (or do not manage) this: 1) Home is a safe space; 2) Disconnection from air quality information; 3) Behaviour change ultimately depends on perceived control; and 4) Clean(er) air is liberating. Below we will situate this in the existing theory with reference to the Theory of Planned Behaviour (where applicable) and existing literature, and highlight the novel findings of this work.

3.4.1 The sensory experience of safety

The work of French philosopher Merleau-Ponty on the Phenomenology of Perception (1945) posits that individuals' perceptions, emotions and actions are shaped by their bodily experiences, and the body is a medium through which we engage with, and make sense of, the world. Embodiment theory, at its most fundamental level, recognises that psychological processes are influenced by the body, including its sensory systems (Glenberg, 2010). Therefore, sensory phenomenology is fundamental to making meaning of the world.

Participants depicted their experience of air pollution as a lived embodiment of sensory phenomenology, describing air pollution, for example, as a visible manifestation (e.g., "black clouds"), a haptic manifestation (e.g., feeling "choked"), or, in some cases, making the direct association with their asthma symptoms, such as cough. The senses play a role in how we interact with and perceive our environment and thus shape our experience of place (Pramova *et al.*, 2022). Air pollution as a sensory encounter is well explored (e.g., Bickerstaff and Walker, 2001; Noël, Vanroelen and Gadeyne, 2021), with the presence of air pollution resoundingly being associated with negative sensory experiences (e.g., Zajchowski and Rose, 2020). Within this study, the sensory experience of air quality was reframed by participants, as something which can be positive in the absence of pollution. The described sensory experience of clean(er) air, particularly during global COVID-19 travel restrictions, was in stark contrast to polluted air. They perceived it as an enlightening experience for their senses, using words like "brighter," "fresher," and "cleaner." Participants explained that this experience can lead to an alleviation in the physical symptoms of their asthma and provide relief from using their reliever inhaler.

Moreover, respite from the negative sensory and physical effects of air pollution enabled participants to engage in activities in the outdoor environment that would have been previously hindered by air pollution such as sitting outside or going for longer walks. In other words, the feeling of external liberation was driven by internal liberation. Based on embodiment theory, the sensory absence of air pollution, and the physical alleviation of asthma symptoms, can create a sense of freedom and agency in the behaviours and actions of individuals (Hauge, 2013). Feeling free from the burden of symptoms and/or medication may lead to a perception of greater control over their bodies and environments, and their ability to engage in activities that were previous restricted or limited by air pollution. Many studies have reported inactivity induced by increased concentrations of air pollution (e.g., Alahmari *et al.*, 2015; An and Xiang, 2015; Zhang *et al.*, 2021), while others have examined reduction in outdoor behaviours influenced by perceived air quality (e.g., Wen, Balluz and Mokdad, 2009). This study, though theoretically aligning with these findings, explored this from a different perspective and suggests that an improved perception of air quality leads to greater outdoor activity amongst people with asthma. Therefore, air which is sensorily perceived to be cleaner and fresher, may have wider benefits than improved respiratory health, including improved physical and mental health and wellbeing. Reframing clean(er) air as enabling rather than polluted air as restrictive can increase perceived behavioural control.

The senses clearly have a role to play in risk perception and participants' sense of safety (Bickerstaff, 2004) and this work has indicated, as previously published studies have, that this can oftentimes be more influential than data (Calvillo and Garnett, 2019; Kim, Senick and Mainelis, 2019). Our findings suggest that, contrarily to advice (Laumbach, Meng and Kipen, 2015; Carlsten *et al.*, 2020), people with asthma do not use air quality data as intended to inform their decision-making, but rather as a tool to explain and verify their symptoms and physical experiences. Promoting engagement with air quality data is critical for health decision-making since it has previously been found that perceptions of air quality do not always match measured pollutant concentrations (e.g., Reames and Bravo, 2019), since some pollutants (e.g., carbon monoxide (CO)) are entirely imperceivable, meaning that behavioural choices to minimise personal exposure may be wrong (Marquart, Schlink and Nagendra, 2022). Questions remain regarding how best to encourage engagement with air quality data and information to deliver behaviour changes aimed at reducing exposures, which in turn, may improve asthma-related health. We have previously argued that personalising air quality data and information could increase engagement (McCarron *et al.*, 2022). With particular reference to 'vulnerable' groups, a potential approach to implement this could be via health professionals such as general practitioners (GPs) or asthma nurses. For example, Howard (2023) suggests that GPs can contribute to addressing air pollution by raising awareness and enhancing risk perception among patients, helping them identify their likely exposures. A shift towards personalising air quality data and information may facilitate its more proactive utilisation.

3.4.2 Facing or evading air pollution

Individuals' evaluations of safety in relation to air pollution were influenced by psychological processes, and our first theme, 'home is a safe space', described participants' differing opinions of (and responses to) air pollution within and outwith their home environment. Participants expressed a desire to protect and preserve the air quality within their home by barricading themselves in by closing vents, windows and doors, and with some expressing a willingness to relocate elsewhere to escape the air pollution which is imposed upon them from the outdoor environment. This suggests that participants viewed their homes as cleaner and more desirable environments. This aligns with the 'halo effect' (Thorndike, 1920), a cognitive bias whereby an individual's perception is shaped by a singular trait. In the context of air quality, this has been extensively studied (e.g., Hofflinger, 2019; Boso *et al.*, 2020) and coined the 'neighbourhood' or 'home' halo effect, whereby individuals subjectively perceive air quality in their neighbourhood/home to be comparatively better than their wider environment or objective measurements. Our interpretations demonstrated that the home halo effect persisted for people with asthma.

The home halo effect plays a key role in the development of coping strategies (Hofflinger, 2019), with a more positive perception of air quality - thus a reduced risk perception - reducing the likelihood of developing coping strategies within the home.

Risk perception influences individuals' motivation for protective action with regard to personal exposure reduction (McCarron *et al.*, 2022). Though the home halo effect was apparent in this study, the association with the development of coping behaviours did not hold true. Instead, our findings suggest that for people with asthma an inverse or reverse association occurs. The inverse: a more positive perception of air quality is linked to greater protective action, is feasible. Within the home, participants demonstrated the most proactive behaviours, taking the most opposing action to prevent air pollution from entering their homes and preserving the perceived 'good' air quality that already exists within their home. Szasz (2007) describes the development of coping behaviours to protect from health risks as an "inverted quarantine" whereby individuals engage in self-protection against potential dangers and threats that arise from the external environment. This can be linked with participants being more acutely aware of their own vulnerability as a person with asthma. Comparatively, in the wider outdoor environment, coping strategies weakened and switched from actively and directly facing the problem within the home to reactive avoidance, despite air pollution being more notably perceptible (Xu, Chi and Zhu, 2017) (participants did not mention the sensory experience of air pollution in their home), with participants describing the ways in which they avoid air pollution. Rather than at-home coping behaviours being determined by perception of air quality as Hofflinger (2019) propose, this was dictated by control and the options available (or options perceived to be available) to the individual and sense of control (as in Sun, Kahn and Zheng, 2017) (Figure 3.2).

The reverse: taking (or being able to take) protective action creates a stronger sense of protection and invulnerability within the home is also possible. When participants perceived that they had the necessary resources and opportunities at home to improve indoor air quality and reduce their exposure (such as the ability to close windows or the choice to not fry food), they experienced a greater sense of autonomy and control over the air quality in their own environment and thus reduced risk. Control (or lack thereof) has a strong influence on risk perception. For example, Tomsho *et al.*, (2022) found that sense of control over air quality within the home environment impacts the actions taken (or not) and the sense of security within the home environment. Therefore, perceived control over actions and environments, plays a fundamental role in participants' experiences of air pollution and the formulation of their management strategies.

Though those with asthma considered home to be a safe space, several studies have found that indoor air quality can be worse than outdoor air quality, with increased concentrations of pollutants as a result of indoor behaviours, such as particulate matter (PM) from smoking, cooking and solid fuel burning; volatile organic compounds (VOCs) from consumer products and materials; and nitrogen dioxide (NO_2) from gas boilers and cookers, for example (Vardoulakis *et al.*, 2020). Additionally, the home cannot be considered in isolation to the outdoor environment since air exchanges between the environments (e.g., Vu et al., 2022). Further, the timing of this study may have influenced this particular finding. “Stay at Home” was the UK Government’s strapline during the pandemic, with this emphasised for the most vulnerable ‘shielders’, which included people with asthma. The message was clear, the home was a safe space, and it is possible that this message has had a residual effect beyond the context of coronavirus.

3.4.3 Control is pivotal to intention and action

The Theory of Planned Behaviour (Ajzen, 1991) and its constructs provide a framework for understanding both participants' information-seeking (theme two) and protection action behaviours (theme three), as well as the limiting factors that influence these behaviours, since these theme directly related to participants’ behaviours. Perceived behavioural control is an important construct within the Theory of Planned Behaviour which directly influences both intention and action and governs the relationship between them. In addition to perceived behavioural control, behavioural intention, which precedes actual behaviour, is influenced by subjective norms and attitudes (Supplementary Material C). Although the constructs within the Theory of Planned Behaviour are considered independent, complex interactions exist between them.

Subjective norms reflect the individual’s perceptions of normative expectations and social influences surrounding a behaviour of interest. It is influenced by salient others’ beliefs and opinions of the behaviour and what is perceived to be a socially desirable or acceptable behaviour. In this study's context, participants demonstrated a common shared expectation and agreement that air pollution should be known about and avoided, even if they do not always adhere to this norm. They referenced advice from healthcare professionals, learnings from their own personal experiences and implied that avoiding air pollution is tacit knowledge, indicating a social expectation and external influence to mitigate exposure. Encouraging avoidance behaviours during episodes of poor ambient air quality is a common practice globally (e.g., Graff Zivin and Neidell, 2009; Yoo, 2021). In the UK, guidance from Asthma + Lung UK and the

Daily Air Quality Index (DAQI) and its associated health advice, for example, recommend certain activities to be avoided during air pollution episodes and for outdoor exposure to be minimised for at-risk individuals, such as those with asthma. Our findings suggest that these messages are being received and may contribute to the 'normalisation' of pollution avoidance in the outdoor environment, although adherence may vary (Janke, 2014; D'Antoni *et al.*, 2019). Awareness and action in relation to sources of indoor air pollution still lagged outdoor, which may, in part, be a result of the outdoor-centric nature of these messages. For most participants, subjective norms facilitate intentions to learn more about air quality and intention to take action to avoid it, even if this does not fully translate into action. The 'normalisation' of information-seeking and protective action has a fundamental role to play in the development of behaviour change strategies (Simpson *et al.*, 2022) in both indoor and outdoor environments.

Regarding air quality information-seeking behaviours and the development of behaviour change strategies to reduce personal exposures, the constructs of attitude and perceived behavioural control within the Theory of Planned Behaviour appear to be more limiting. Attitudes represent individuals' general evaluations of a behaviour as either positive or negative (Prestwich, Kenworthy and Conner, 2018) and are shaped by their beliefs regarding the benefits and penalties associated with engaging in that behaviour (Ajzen, 1988). This assessment is based upon individual beliefs about the consequences of a behaviour or outcome expectancy (perceived positive or negative consequences of performing the behaviour). Attitudes are further influenced by personal values, preferences, and emotional responses linked to the behaviour, which in this case are embedded within place, and play an important role in the development of coping behaviours to protect from pollution exposure (Lin and Bautista, 2016; Xu *et al.*, 2021).

A contrast in attitudes was observed amongst different categories of participants. The *resisting* and *conceding* groups demonstrated a more negative attitude towards accessing information (which in the Scottish context consists primarily of Daily Air Quality Index (DAQI) information and advice via air quality specific websites (e.g., https://www.scottishairquality.scot) and apps, or via non-specific resources such as weather apps) and taking action to reduce their exposures. This sentiment was reflected in quotes such as *"…I don't know that I've done anything differently as a result of [accessing air quality information]"*, indicating a lack of positive evaluation or perceived benefits associated with information access or action. In contrast, the *attempting* group held a more favourable attitude towards the potential positive outcomes of altering behaviours to reduce personal exposures. These individuals believed that taking action can lead to tangible effects and displayed a willingness to make efforts to alter their behaviours or seek air quality information.

While it has been suggested that those most at risk from pollution exposure tend to have a more concerned attitude (De Pretto *et al.*, 2015), our results indicate that this may not be universal for people with asthma. Although improving knowledge and awareness can enhance favourable attitudes (Hensher and Li, 2013; Unni *et al.*, 2022), knowledge-centric strategies must be complementary to existing information dissemination techniques by acknowledging the intricate psychological processes at the individual-level that encourage engagement (or not) (Riley *et al.*, 2021; McCarron *et al.*, 2022). Persuasive messages can play a role in changing attitudes to promote health behaviour change (Prestwich, Kenworthy and Conner, 2018) and these are more likely to be more influential and elicit greater attitude change if delivered by an expert or someone viewed as an authoritative figure (Petty, Cacioppo and Berkowitz, 1986), such as healthcare professionals. Therefore, healthcare professionals, as health experts, could have an important role to play in forming and altering people with asthmas' attitudes relating to exposure-minimising behaviours. Though conversations around exposure-minimising behaviours should be current practice (e.g., NICE guideline NG149 and NICE Quality Standard QS181) more research into how to alter attitude towards such behaviours is needed.

Participants' actions were also limited by perceived behavioural control, as participants ultimately discontinued their efforts due to disbelief in their own ability to successfully carry out the behaviour or comprehend the information, or doubt that the behaviour can have a positive outcome. This was influenced by a combination of internal and external factors that shaped their confidence in their capability to execute the behaviour successfully. Where attitudes represent an individual's feelings towards a behaviour, perceived behavioural control is based on control beliefs and refers to an individual's perception of the ease or difficulty of performing a behaviour. It is influenced by external control factors, such as dependence on others and external barriers or constraints, and internal control factors, such as past experiences, self-efficacy beliefs and personal deficiencies (Prestwich, Kenworthy and Conner, 2018). Within the *able* group, perceived behavioural control serves as an enabling factor (being the key distinction compared to the *attempting* group), supporting participants' abilities to access information and engage in effective behaviours to minimise exposures.

Participants portrayed a sense of confidence and self-assurance in themselves that they could successfully and effectively take action to reduce their exposure or access information to inform their decision-making about air quality. In contrast, for the *attempting* group, perceived behavioural control was the limiting construct, preventing them from feeling like they can access necessary information for decision-making and impeding their ability to adopt successful and sustainable behaviours. Even when individuals possessed a positive attitude, they perceived themselves as incapable of responding (Barnes *et al.*, 2020).

Previous research has shown a significant correlation between increased risk perception and a decreased sense of perceived behavioural control (Xu *et al.*, 2021). Individuals with asthma, who may be more conscious of their own vulnerability owing to targeted messaging and advice, may therefore exhibit a higher risk perception, which could explain their reduced perceived behavioural control in outdoor environments. Since individuals need to feel that a behaviour is within their capacity to enact (Barnes *et al.*, 2020), self-efficacy (related to perceived behavioural control) has been found to exert the strongest influence on the development of intentions to engage in self-protective behaviours against air pollution exposure (Kim and Kim, 2021). This is evidenced in this study, as discussed in section *3.4.2 Facing or evading air pollution*, in the home environment where participants demonstrated the greatest confidence and perceived behavioural control to minimise their exposures. A focus on enhancing perceived individual control, for example by promoting small step changes such as changing walking route (Ahmed *et al.*, 2020) or increasing use of extractor fans (Tang and Pfrang, 2023), would therefore be likely to promote greater uptake of protective actions across environments.

3.5 Study limitations

Undoubtedly this work has been influenced by the COVID-19 pandemic and the various lockdown restrictions in place as a result. Though this has offered a unique and novel perspective particularly on the sensory experience of air pollution, it is important to recognise, though difficult to estimate, the impact this may have had on participants experiences and perceptions more generally (e.g., home as a safe space was a key message during lockdowns).

It is also important to note that though for the purpose of this study we have considered people with asthma as a homogenous group, different phenotypes exist (e.g., exercise-induced, allergic, occupational) meaning that the clinical features and symptomology of asthma varies between individuals. Though we have acknowledged that people with asthma experience air pollution differently, future work may wish to explore exactly how this differs by phenotypic subgroup separately.

Finally, the role of weather was not explored within this study. Weather is a potential confounding variable, influencing both ambient air pollution and the precipitation of asthma symptoms. Cold and calm weather conditions can exacerbate air pollution by creating still atmospheric conditions where pollutants accumulate and disperse more slowly, leading to a higher concentration of pollutants in the air. Cold weather can also exacerbate asthma symptoms as cold air can irritate the airways, leading to an exacerbation of asthma symptoms. It can therefore be difficult for people with asthma to distinguish between weather and pollution related triggering of their asthma.

3.6 Conclusions

Even within a homogeneous "vulnerable" group such as people with asthma, people experienced air pollution differently and adopted individual approaches to manage it based upon their personal experiences. Therefore, a one-size-fits-all approach to air pollution-related asthma management will be ineffective. Current exposure reduction advice, such as avoiding outdoor activities when ambient air quality is poor, is generic, failing to accommodate the specific options available to individuals and focusing solely on one environment. Our findings also suggest that these messages are being received and are helping to normalise the avoidance of air pollution. However, we suggest that these messages need to be updated to include advice across microenvironments, with a particular emphasis on indoor air quality (as a controllable environment) to raise awareness of sources of indoor air pollution and make indoor air quality exposure reduction behaviours a norm, for example with a strategy to engage people with asthma at regular intervals such as annual asthma reviews in GP surgeries.

Further, people with asthma rely on their own senses to shape their behaviours or use observed air quality data to verify how they are feeling, instead of using it proactively. There is no safe objective level of exposure to air pollution (Marks, 2022; World Health Organisation, 2023a), and even at lower concentrations that do not produce a direct irritant and inflammatory effect (resulting in the precipitation of asthma symptoms such as cough and wheeze), exposure to air pollution can result in negative health consequences which may not be immediately perceivable by an individual (e.g., oxidative stress) (Guarnieri and Balmes, 2014). Therefore relying on senses or feelings to take protective health measures does not work. This could potentially lead to poor exposure-minimising decision-making since perceptions of air quality do not always match measured concentrations. This highlights the need to promote proactive engagement with air quality data. Future work should explore the feasibility and efficacy of the proactive use of air quality data to inform decision-making and behaviour change.

This study has emphasised the crucial role of personal agency in individuals' sense of safety and the influence this has on making behavioural changes. Individuals with asthma were more likely to embrace behaviour change when they felt empowered and had a sense of control over their environment, as demonstrated within their homes. This highlights the importance of providing education, support, and resources that empower individuals to make informed choices and actively manage their exposure to air pollution across the microenvironments in which they spend their time. We suggest that expert guidance, such as that provided by GPs and asthma nurses, can be enhanced to increase engagement and better promote individual behaviour change.

Ultimately, a reconceptualization of air quality communication, with clean(er) air framed as enabling (rather than polluted air being restrictive), and encouraging strategies which enhance an individual's personal control over their exposure to air pollution will enhance confidence to enact these protective behaviours to reduce exposures outwith the home environment.

Chapter 4 | Personal exposure to fine particulate matter ($PM_{2.5}$) and self-reported asthma-related health

Research Question 2: What is the level of exposure to $PM_{2.5}$ of people with asthma in Scotland and does this influence the short-term precipitation of asthma symptoms?

Objective 2a) Develop the exposure monitoring methodology for $PM_{2.5}$ data collection.

Objective 2b) Calibrate 16 PurpleAir sensors and assess their accuracy, precision and bias.

Objective 2c) Monitor individuals' personal exposures to $PM_{2.5}$ over 7 days using PurpleAir sensors.

Objective 2d) Explore the associations between $PM_{2.5}$ exposure and the prevalence of asthma symptoms using time-activity/inhaler diaries and $PM_{2.5}$ data.

Published in *Social Science & Medicine* (2023). Instrument validation sections (4.2.2 – 4.2.5), and the instrument validation results (4.3.1) were not included in the published version of the manuscript since this was not suitable for the scope of the journal but are included here for completeness.

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Abstract

$PM_{2.5}$ (fine particulate matter ≤2.5μm in diameter) is a key pollutant that can produce acute asthma exacerbations and longer-term deterioration of respiratory health. Individual exposure to $PM_{2.5}$ is unique and varies across microenvironments. Low-cost sensors (LCS) can collect data at a spatiotemporal resolution previously unattainable, allowing the study of exposures across microenvironments. The aim of this study is to investigate the acute effects of personal exposure to $PM_{2.5}$ on self-reported asthma-related health.

Twenty-eight non-smoking adults with asthma living in Scotland collected $PM_{2.5}$ personal exposure data using LCS. Measurements were made at a 2-minute time resolution for a period of 7 days as participants conducted their typical daily routines. Concurrently, participants were asked to keep a detailed time-activity diary, logging their activities and microenvironments, along with hourly information on their respiratory health and medication use. Health outcomes were modelled as a function of hourly $PM_{2.5}$ concentration (plus 1- and 2-hour lag) using generalized mixed-effects models adjusted for temperature and relative humidity.

Personal exposures to $PM_{2.5}$ varied across microenvironments, with the largest average microenvironmental exposure observed in private residences ($11.5 \pm 48.6\mu g/m^3$) and lowest in the work microenvironment ($2.9 \pm 11.3\mu g/m^3$). The most frequently reported asthma symptoms; wheeze, chest tightness and cough, were reported on 3.4%, 1.6% and 1.6% of participant-hours, respectively. The odds of reporting asthma symptoms increased per IQR in $PM_{2.5}$ exposure (odds ratio [OR] 1.29, 95% CI 1.07-1.54) for same-hour exposure. Despite this, no association was observed between reliever inhaler use (non-routine, non-exercise related) and $PM_{2.5}$ exposure (OR 1.02, 95% CI 0.71–1.48).

Current air quality monitoring practices are inadequate to detect acute asthma symptom prevalence resulting from $PM_{2.5}$ exposure; to detect these requires high-resolution air quality data and health information collected in situ. Personal exposure monitoring could have significant implications for asthma self-management and clinical practice.

4.1 Introduction

Exposure to air pollution is the leading environmental health threat, responsible for illnesses such as stroke, chronic obstructive pulmonary disease (COPD) and lung cancer (World Health Organisation, 2013), and resulting in 7 million deaths globally each year (World Health Organisation, 2020b). Though 99% of the global population breathe polluted air, the burden of morbidity and mortality are not equally shared, with some groups (e.g., those with pre-existing disease such as asthma) most at risk (Royal College of Physicians, 2016).

Asthma is the most prevalent chronic respiratory disease (Chan *et al.*, 2019) and over 368,000 people in Scotland receive treatment for asthma (Scottish Government, 2020a). The physiological and epidemiological links between exposure to air pollutants such as fine particulate matter ($PM_{2.5}$) and acute asthma exacerbations, deterioration of asthma, and the onset of asthma are well established (e.g., Kampa and Castanas, 2008; Landrigan *et al.*, 2018; Holst *et al.*, 2020), with air pollution exposure linked with oxidative stress, airway inflammation, hyperresponsiveness and, overtime, airway remodelling (Guarnieri and Balmes, 2014). Most of the epidemiological evidence that exists is based upon observational population-level health data, such as accident and emergency/emergency room visits, hospitalisations and medication administration (e.g., Hales *et al.*, 2021; Priyankara *et al.*, 2021; Yadav *et al.*, 2021; Hoffmann *et al.*, 2022). While these approaches provide a useful perspective of health impact, the associations are spatiotemporally aggregated (Su *et al.*, 2017) and can be influenced by underlying factors such as socioeconomic status and access to healthcare (Williams *et al.*, 2019) and therefore may undermine epidemiological assessments linking health effects specifically with air pollution.

Recognising the issues associated with using aggregated health data, several studies have explored the links between air pollution exposure and individual-level asthma symptom prevalence (e.g., de Camargo Matos *et al.*, 2022; Phaswana *et al.*, 2022) or medication (predominantly bronchodilator inhaler) use (e.g., Su *et al.*, 2017; Williams *et al.*, 2019). However, these studies have been based on exposure assessments modelled from air quality data collected via ambient fixed-site monitoring (often at some distance from the participants' home address). Vitally, such exposure assessment approaches fail to examine links with indoor or household exposures linked to an individual's unique behaviours such as cleaning and cooking (AQEG, 2022). Moreover, using modelled or surrogate exposure data can introduce bias into the personal exposure assessment (Butland *et al.*, 2019).

Difficulties of accurately investigating personal exposure to air pollution have, at least in part, been eased by the development of low-cost air quality monitors (Chambers *et al.*, 2018). Low-cost monitors, owing to their small size, portability, low power requirements and high temporal resolution (Snyder *et al.*, 2013; Loh *et al.*, 2017) can allow the assessment of exposure across microenvironments (e.g., Steinle *et al.*, 2015). Such exposure data, paired with individual-level health data, can be used to assess linkages between microenvironmental air pollution exposures and health measures (e.g., Rabinovitch *et al.*, 2016; Turner *et al.*, 2021; Hao *et al.*, 2022). However, such studies have, to date, mainly examined associations between exposures and asthma symptoms/medication use in prescribed microenvironments, been based on exposure metrics aggregated over relatively long timeframes and/or based upon clinical measures (e.g., PEF, FEV_1) which are not necessarily responsive to acute environmental change nor reflect patient wellbeing (Juniper *et al.*, 1996). The aim of this study is to investigate the acute associations between personal exposure to $PM_{2.5}$ and self-reported asthma-related health.

4.2 Materials and methods

4.2.1 Study design and participants

Thirty-seven non-smoking adults with asthma were recruited from across Scotland (see section 3.2.2) between February 2021 and July 2021. Eligibility criteria included that participants must be aged 18 or older, be a non-smoker, have been diagnosed with asthma by a healthcare professional and live in Scotland. This study was nested within a larger project involving semi-structured interviews, co-design of behavioural interventions and follow-up monitoring campaigns, with the same group of participants recruited to take part in all elements. Due to the mixed methods approach of the study, focusing on achieving a specific target sample size was not feasible or appropriate. Power calculations for the intervention work indicated that a sample of 110 would be necessary for adequate statistical power. However, due to constraints such as time limitations inherent in conducting this research as part of a PhD, as well as the inclusion of qualitative components, achieving this sample size was deemed unrealistic. We acknowledge that this is a limitation which has impacted the depth of analyses performed and the conclusions drawn from the study. A participant advisory group consisting of five individuals meeting the same eligibility criteria was consulted to refine the project design and pilot the methodology (Objective 2a). This informed the design of crucial study elements such as diary templates (format and resolution) and customised backpack design (described in more detail below). Data collection for the main study took place between September 2021 and September 2022, with participants divided into 6 cohorts who took part sequentially over the course of the year, with each participant enrolled for approximately 1 month. This study was reviewed and approved by the University of Stirling's General University Ethics Panel [GUEP 2021 2506 1892].

4.2.2 Instrument validation – co-location

Prior to personal exposure monitoring campaigns taking place, the ensemble of sixteen PurpleAir PA-II-SD air quality sensor units (PurpleAir, Draper, UT, USA; hereafter referred to as PurpleAir) to be used in the study were co-located to assess their accuracy, precision and bias 'out-of-the-box' (Objective 2b), and to calibrate the units with one another. The PurpleAir is a small, lightweight and portable sensor, which has shown to perform well against reference grade instruments (S. Park *et al.*, 2023), and measures particles using Plantower PMS 5003 air quality sensors, in addition to relative humidity, temperature and barometric pressure (Bosch, Reutlingen, Germany). Laser counters take readings every five seconds, with averages logged to an SD card every 120 seconds. Since co-location could not take place with a reference-grade monitor (owing to COVID-19 fieldwork restrictions), the ensemble of sixteen units were installed outdoors for a week-long monitoring campaign between 17th November and 23rd November 2020 in a suburban residential area near Glasgow in an area of moderate population density. The units were positioned approximately 1.9m above ground level and were connected to mains power and Wi-Fi (Figure 4.1). At the end of the week-long campaign, data were recovered from each unit's SD card and two-minute resolution data were matched by closest timestamp. Since co-location at a reference station was not possible and as such the 'true' value was unknown, it was accepted that the 'true' value was the median of ensembles' range for each timestamp. Each sensor was individually plotted against the 'true' value and subsequent equations were used to adjust sensor outputs for chapter four and five (Equation 4.1, where b is y-intercept and m is slope).

Figure 4.1. Ensemble of sixteen co-located PurpleAir units.

$$Adjusted\ concentration = \frac{measured\ concentration - b}{m} \quad \textbf{Eq. 4.1}$$

4.2.3 Instrument validation – accuracy

Instrument accuracy refers to how close measured values are to the 'true' concentration. The accuracy of each instrument was evaluated by measuring its correlation with the true value using the coefficient of determination (R^2). However, since R^2 only measures the strength of association and not the agreement between variables (Alexander et al. 2015), the mean absolute error (MAE) was also calculated. The MAE represents the average absolute difference between the measured values from the PurpleAir instruments and the true values, and is an important indicator of an instrument's accuracy. Instruments with high accuracy will exhibit a high R^2 and low MAE. A low R^2 and low MAE suggests that the concentration range is too narrow to assess the accuracy of the sensor. On the other hand, a high R^2 and high MAE suggest that the sensor may require calibration. Finally, a low R^2 and high MAE indicates that the sensor is likely inaccurate.

4.2.4 Instrument validation – bias

Bias refers to a systematic error or difference between the measured values of an instrument and the true value. The normalised mean bias (NMB) was calculated for each instrument using Equation 4.2 (Giordano *et al.*, 2021). This was calculated separately for each instrument using 2-minute resolution data. The NMB values were used to assess the bias of each instrument relative to the true value.

$$NMB = \frac{\sum_{i=1}^{n}(measured\ concentration_i - true\ concentration_i)}{\sum_{i=1}^{n} true\ concentration_i} \qquad \textbf{Eq. 4.2}$$

4.2.5 Instrument validation – precision

Bias-corrected precision was calculated using Equation 4.3 (Wallace et al. 2011), where A' is the bias-corrected value for the instrument, and T the 'true' value.

$$Bias - corrected\ precision = \frac{Abs(A' - T)}{T} \qquad \textbf{Eq. 4.3}$$

Together, metrics of accuracy, bias and precision were used as model evaluation tools, not as data correction tools. Data correction was performed using calibration curves as detailed in section *4.2.2 Instrument validation – co-location*.

4.2.6 Personal exposure monitoring

Each participant monitored their personal exposure to fine particulate matter (particulate matter with an aerodynamic diameter ≤2.5μm ($PM_{2.5}$)) using a PurpleAir attached to a customised backpack (Figure 4.2). To standardise monitoring, participants were provided with a detailed 'Participant Guide' and access to two YouTube tutorials explaining how to use the monitoring equipment (see Supplementary Material D). Data collection took place over one-week per person to capture typical weekly variation in ambient $PM_{2.5}$ and to capture participants' weekly routines. Statistical analyses were conducted on participant-hour natural log transformed $PM_{2.5}$ exposure data to counter skewedness. Exposure variables examined included mean, maximum, within-hour range and within-hour increase (defined as the within-hour range calculated only where minimum timestamp precedes maximum timestamp) (Table 4.1). Hourly average $PM_{2.5}$ ambient air quality data were obtained from fixed-site monitoring station closest to the participant's residential address for the sampling week. Data were obtained from the Air Quality in Scotland website (https://www.scottishairquality.scot).

Table 4.1. Personal exposure metrics. Calculations are based on calendar hour (i.e., between 18:00-19:00).

Personal exposure metric	Description
Hour mean	Mean value for each hour
Hour max	Maximum value for each hour
Within-hour range	Maximum value minus minimum value calculated for each hour
Within-hour increase	Maximum value minus minimum value calculated only where minimum timestamp precedes maximum timestamp

Figure 4.2. PurpleAir attached to customised backpack and powered by battery pack (inside). The PurpleAir was secured in place with Velcro to minimise agitating fibre particles and to keep the sensor as close as feasibly possible to 'breathing zone' height. When stationary for long periods, the participant was permitted to remove the PurpleAir from the backpack and keep it close-by.

Alongside personal exposure monitoring, participants were asked to complete a time-activity diary (see Supplementary Material E) to support the pairing of $PM_{2.5}$ mass concentrations with activities and microenvironments. Time-activity diary templates were set at one-hour time intervals, with activity being a free-text response since it would not be possible to capture the entire range of possible activities. Microenvironment details were captured by check box, based on categories from previous studies (e.g., Steinle *et al.*, 2015). These encompassed broad, general categories such as 'transport' and 'public building', as well as more precise environments within the home (e.g., 'kitchen', 'bedroom', 'living room'). An 'other' option was provided for cases where required.

4.2.7 Asthma-related health

Participants were asked to keep a record of their asthma-related health for the duration of the monitoring week via a time-activity diary. Self-reported asthma symptoms were recorded hourly. This was designed as a free-text response to allow participants to describe their asthma symptoms in their own terms. These were reviewed by the researcher and subsequently grouped into broader terms (e.g., short of breath, out of breath, struggling to catch my breath were grouped as breathless). Inhaler and other asthma medication use was recorded at hourly intervals with check box options (nil, preventer, reliever, other) and, where applicable, a space for time administered. To distinguish between routine or prescribed use of medication and when medication was used for the more immediate relief of asthma symptoms, participants were asked "If you used your inhaler or asthma medication, why?". Again, this was an open-text response to realise the entire range of possible reasons.

4.2.8 Baseline survey/ covariates

Participants were asked to complete a survey once during the baseline monitoring campaign. The survey was designed to capture contextual information as in previous work (e.g., Steinle *et al.*, 2015) including personal information (i.e., age, gender), information about their neighbourhood, their home environment and building characteristics, other householders and their typical behaviours within the home. These data were included in the model selection process as potential confounders/ candidate variables in adjusted models.

4.2.9 Statistical analyses

Symptom prevalence (coded as a binary variable) and non-routine or exercise-related inhaler use were modelled as a function of different metrics of $PM_{2.5}$ personal exposure (see section *4.2.6 Personal exposure monitoring*) using mixed-effects logistic models with random intercepts for ID to account for person-level clustering within the data and repeated-measures design. Similarly, to test the association between symptom prevalence and environmental factors (temperature and relative humidity) distinctly from $PM_{2.5}$, these were modelled as a function of same-hour, one-hour and two-hour lag average $PM_{2.5}$. Hourly aggregated $PM_{2.5}$ exposure data were also tested at one-hour and two-hour post exposure to measure the potential continued impact of exposure on participants self-reported health (Bancalari *et al.*, 1999; O'Byrne, 2009). Odds Ratios (OR), a statistic which quantifies the strength of associations, are presented per interquartile range (IQR) increase in $PM_{2.5}$ concentration. The same analyses were repeated substituting personal exposure data for data collected via fixed-site monitoring station. The correlation between both measures was tested using Spearman's correlation.

Model selection followed a stepwise selection approach, whereby variables were added and removed at different stages to achieve the best fitting model (Chowdhury and Turin, 2020). To assess model fit, the Akaike information criterion (AIC), second-order Akaike information criterion (AIC_c) and Bayesian information criterion (BIC) were considered. Final models included variables that were significant predictors and/or had a theoretical basis for their inclusion (Steyerberg and Vergouwe, 2014). All analyses were conducted using RStudio version 4.2.2 (R Core Team, 2022) using the packages lme4 (Bates *et al.*, 2015), sjPlot (Lüdecke, 2018) and ggplot2 (Wickham, 2016).

4.3 Results

4.3.1 Instrument validation results

Results from instrument validation are presented in Table 4.2. PurpleAir units used in this study had a low average deviation and high correlation with 'true' $PM_{2.5}$ concentrations. MAE ranged from 0.185 to 0.391, and R^2 ranged from 0.96 to 0.98 (Supplementary Material F). Taking both measurements together, these indicated that each individual unit was performing well and was reporting with an acceptable level of accuracy.

Across units, average NMB was 1%. The NMB values ranged from -12% to +20%, indicating a range of biases from slight underestimation (-12%) to moderate overestimation (+20%) across instruments. Since all sensors were within 20%, it was decided that no additional correction had to be performed. Bias-corrected precision had a mean value of 0.6% (range 0–3.86%) indicating that each PurpleAir unit was reporting consistent and reproducible measurements of $PM_{2.5}$ concentrations. Calibration equations are given in Supplementary Material F.

Table 4.2. Instrument validation results. Accuracy was assessed using Mean Absolute Error (MAE) and the coefficient of determination (R^2). Bias was assessed using normalised mean bias (NMB). Precision was assessed using bias-corrected precision.

	Accuracy		Bias	Precision
Sensor	**MAE**	**R^2**	**NMB (%)**	**Bias-corrected precision (%)**
S01	0.234	0.98	-11.77	-1.38
S02	0.185	0.98	0.00	0.00
S03	0.221	0.97	-4.81	-0.23
S04	0.200	0.98	1.59	-0.03
S05	0.208	0.98	-5.41	-0.29
S06	0.188	0.98	-4.72	-0.22
S07	0.202	0.98	-7.18	-0.52
S08	0.391	0.97	19.65	-3.86
S09	0.238	0.98	9.26	-0.86
S10	0.247	0.97	-1.42	-0.02
S11	0.201	0.96	2.35	-0.06
S12	0.200	0.98	0.53	0.00
S13	0.241	0.98	8.67	-0.75
S14	0.188	0.98	-3.55	-0.13
S15	0.211	0.98	5.50	-0.30
S3	0.229	0.98	6.96	-0.48

4.3.2 Participant descriptive characteristics

Twenty-eight participants were included in the final analyses with nine participants excluded owing to sensor malfunction (n=2), equipment nonreturn (n=1), incomplete/ illegible diary data (n=5) and respiratory illness during the monitoring campaign (n=1).

Demographic and descriptive characteristics are presented in Table 4.3. After data cleaning (averaging periods only where >75% data were available), 143 participant-days and 4032 participant-hours remained.

Table 4.3. Demographic and descriptive characteristics (n=28). Urban/rural classifications are based upon Scottish Government definitions (Scottish Government, 2020b). *n=27 due to nonresponse.

Participant characteristic	Statistic
Age (years, mean (range))	47.5 (24-74)*
Gender (n (%))	
Female	19 (67.9)
Male	9 (32.1)
Other respiratory condition (n (%))	
No	26 (92.9)
Yes	1 (3.6)
Missing	1 (3.6)
Pregnant (n (%))	
No	28 (100)
Yes	0 (0)
SIMD Decile (n (%))	
1	0 (0)
2	0 (0)
3	1 (3.6)
4	2 (7.1)
5	5 (17.9)
6	4 (14.3)
7	4 (14.3)
8	2 (7.1)
9	3 (10.7)
10	7 (25.0)
Type of dwelling (n (%))	
Apartment	10 (35.7)
Semi-detached house	4 (14.3)
Detached house	5 (17.9)
Detached bungalow	3 (10.7)
Detached cottage	2 (7.1)
Terraced house	3 (10.7)
Missing	1 (3.6)
Number of residents (n, mean, (range))	2.5 (1-5)

Live with pets (n (%))	
No	12 (42.9)
Yes	15 (53.6)
Missing	1 (3.6)
Live with smoker (n (%))	
No	27 (96.4)
Yes	0 (0)
Missing	1 (3.6)
Have a solid fuel burner (n (%))	
No	20 (71.4)
Yes	6 (21.4)
Missing	2 (7.1)
Type of hob (n (%))	
Gas	9 (32.1)
Other (electric, induction)	18 (64.3)
Missing	1 (3.6)
In employment (n (%))	
No	6 (21.4)
Yes	22 (78.6)
Urban-rural Classification (n (%))	
Large urban area	8 (28.6)
Other urban area	9 (32.1)
Accessible small town	1 (3.6)
Remote small town	2 (7.1)
Very remote small town	1 (3.6)
Accessible rural	5 (17.9)
Remote rural	0 (0)
Very remote rural	2 (7.1)
Distance of home address from fixed-site monitor (km)	
Max	125.0
Mean	20.6
Median	4.0
Min	0.1

$PM_{2.5}$ personal exposures varied highly both within and between participants, with seven-day averages ranging from 1.0±2.5 μg/m^3 to 26.2±93.1 μg/m^3 (Figure 4.3). This variability was also reflected in microenvironmental exposure statistics with greatest average microenvironmental exposure in the private residential microenvironment (11.5±48.6 μg/m^3) and lowest in work buildings (2.9±11.3 μg/m^3) (Figure 4.4). Participants spent over 90% of participant-hours in indoor microenvironments, of which, 80% of this time was spent in the home microenvironment (2904h collectively). Least time was spent in the outdoor microenvironment (including 'garden' and active travel) (145h collectively, 3.6% participant-hours). Microenvironmental data were unavailable for 3.5% of the total monitoring period. Fixed-site monitor concentration average was 5.0μg/m³ (0.2-42.8μ/m³) during the participant measurement weeks.

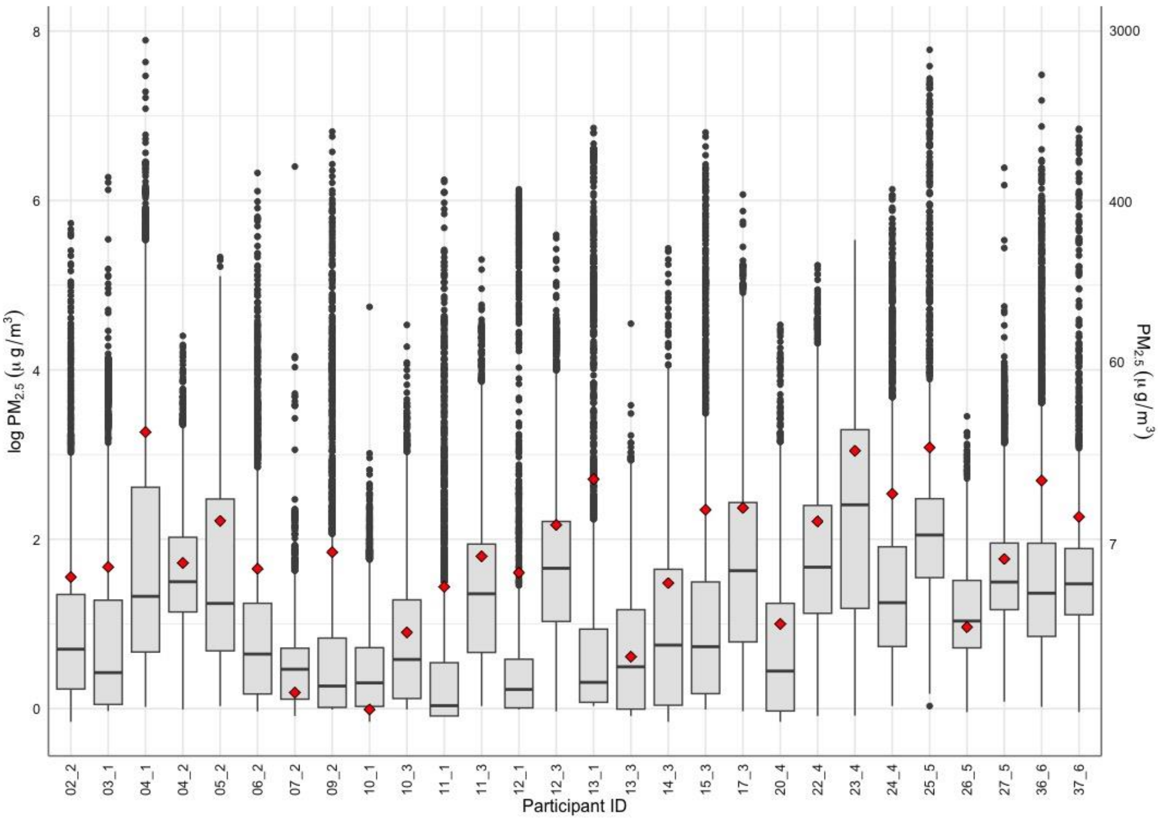

Figure 4.3. Natural log transformed $PM_{2.5}$ personal exposure collected via PurpleAirs over the monitoring week by participant. Whiskers extend to the minimum and maximum values. The lower end of the box represents Q1 (lower quartile) and upper end of the box Q3 (upper quartile). The median value is denoted by the black line inside the box and mean value denoted by the red diamond. Black dots represent outliers.

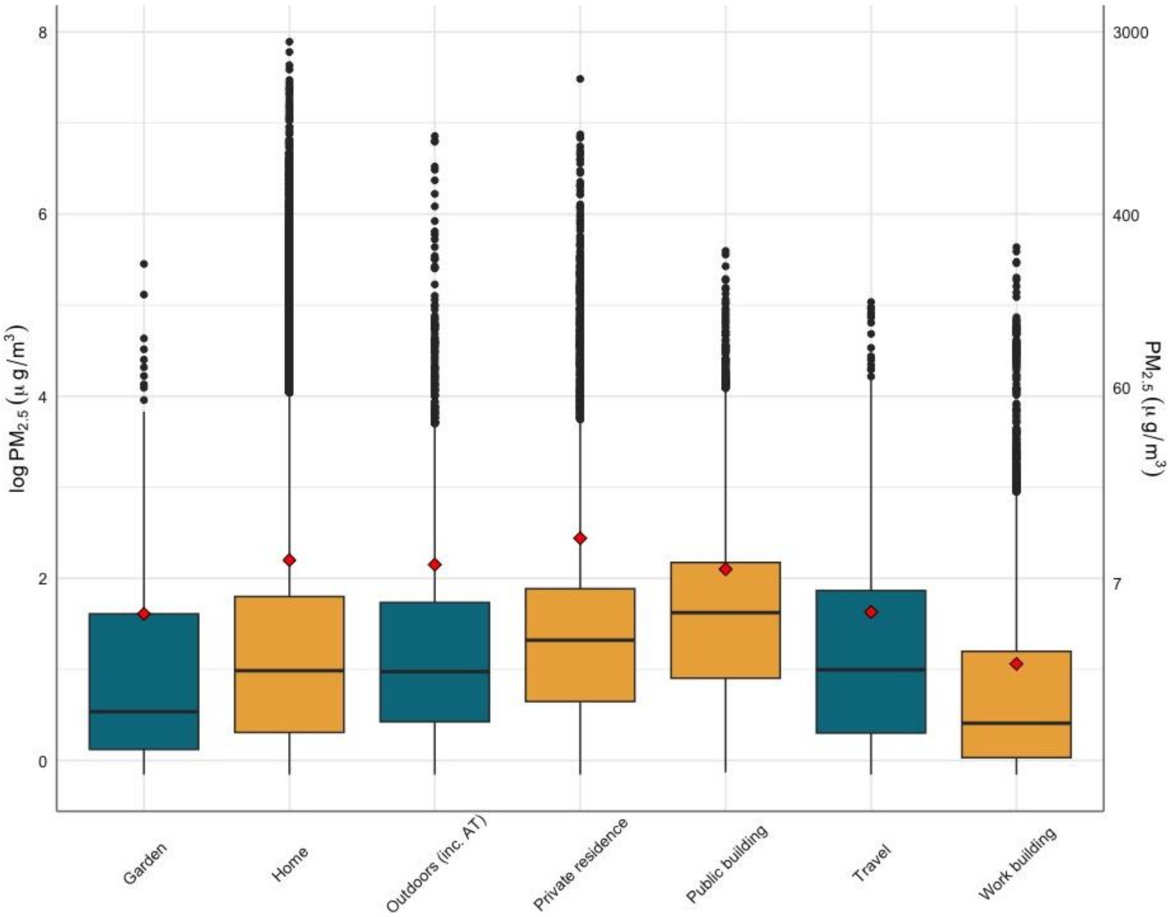

Figure 4.4. Natural log transformed $PM_{2.5}$ personal exposure by microenvironment. Whiskers extend to the minimum and maximum values. The lower end of the box represents Q1 (lower quartile) and upper end of the box Q3 (upper quartile). The median value is denoted by the black line inside the box and mean value denoted by the red diamond. Black dots represent outliers. Yellow boxes denote indoor environments and blue boxes denote outdoor environments. Outdoor includes active travel (AT). Mean values: Garden = 5.0μg/m^3; Home= 9.0μg/m^3; Outdoors = 8.6μg/m^3; Private residence = 11.5μg/m^3; Public building = 8.2μg/m^3; Travel = 5.1μg/m^3; Work building = 2.9μg/m^3.

Incidences of reliever inhaler use were low (n=67) and varied between participants, with twelve participants recording no uses and one participant recording fifteen uses over the monitoring week. Participants reported one or more symptoms on 451h during sampling (11% of participant-hours). This too was very variable between participants, with five participants experiencing/reporting no symptoms over the week and one participant reporting 151h with experience of symptoms.

4.3.3 Personal exposures and asthma-related health

The most frequently reported single asthma symptoms: wheeze, chest tightness and cough, were reported on 3.4%, 1.6% and 1.6% of participant-hours, respectively.

Symptom prevalence-exposure models included temperature and humidity as covariates with other variables dropped due to insignificance. Symptom prevalence odds ratios for hourly $PM_{2.5}$ exposure metrics are summarised in Table 4.4. Associations between $PM_{2.5}$ personal exposure and asthma symptom prevalence showed similar temporal trends for mean, maximum and range exposure metrics, with same-hour personal exposure associated with the greatest OR for symptom prevalence (Table 4.4; Figure 4.5). With a one-hour lag effect for the same exposure metrics, OR for symptom prevalence decreased but remained positively and significantly associated (Table 4.4). However, with a two-hour lag effect, no significant (albeit consistently positive) associations were observed. Discordantly, symptom prevalence was not found to be significantly associated with same-hour increase personal exposure but was found to be positively and significantly associated with a one-hour and two-hour lag effect. Testing the association between symptom prevalence and temperature and relative humidity revealed significant negative associations, with a one-unit increase in average temperature associated with a decrease of 0.03 in the log-odds of experiencing symptoms ($p<0.05$) and a one-unit increase in average humidity associated with a decrease of 0.03 in the log-odds of experiencing symptoms ($p<0.05$). Both symptom prevalence with a one-hour and two-hour lag was not significantly associated with average temperature and relative humidity.

Table 4.4. Odds Ratio and 95% CI for the associations between personal exposure to $PM_{2.5}$ and symptom prevalence. Statistically significant estimates ($p<0.05$) are highlighted in bold. Personal exposure adjusted model includes temperature and humidity and fixed-site adjusted model includes residential distance from monitoring station.

	Odds Ratio (95% CI) per IQR increase in $PM_{2.5}$ personal exposure					
	Adjusted			Unadjusted		
	Same-hour	1h lag	2h lag	Same-hour	1h lag	2h lag
Hour mean	**1.29 (1.07-1.54)**	**1.24 (1.04-1.49)**	1.09 (0.90-1.31)	**1.24 (1.04-1.48)**	**1.27 (1.06-1.51)**	1.12 (0.93-1.35)
Hour max	**1.32 (1.12-1.55)**	**1.28 (1.09-1.51)**	1.12 (0.95-1.32)	**1.30 (1.12-1.52)**	**1.31 (1.12-1.54)**	1.15 (0.98-1.36)

Within hour range	**1.12 (1.04-1.20)**	**1.12 (1.04-1.20)**	1.07 (0.99-1.14)	**1.12 (1.05-1.19)**	**1.13 (1.06-1.20)**	**1.08 (1.01-1.16)**
Within hour increase	1.06 (0.96-1.17)	**1.14 (1.04-1.26)**	**1.13 (1.02-1.24)**	1.05 (0.95-1.15)	**1.14 (1.04-1.26)**	**1.13 (1.02-1.24)**
Fixed-site $PM_{2.5}$ concentration	1.10 (0.89-1.34)	1.05 (0.86-1.29)	0.97 (0.79-1.20)	1.10 (0.89-1.34)	1.05 (0.86-1.29)	0.97 (0.79-1.20)

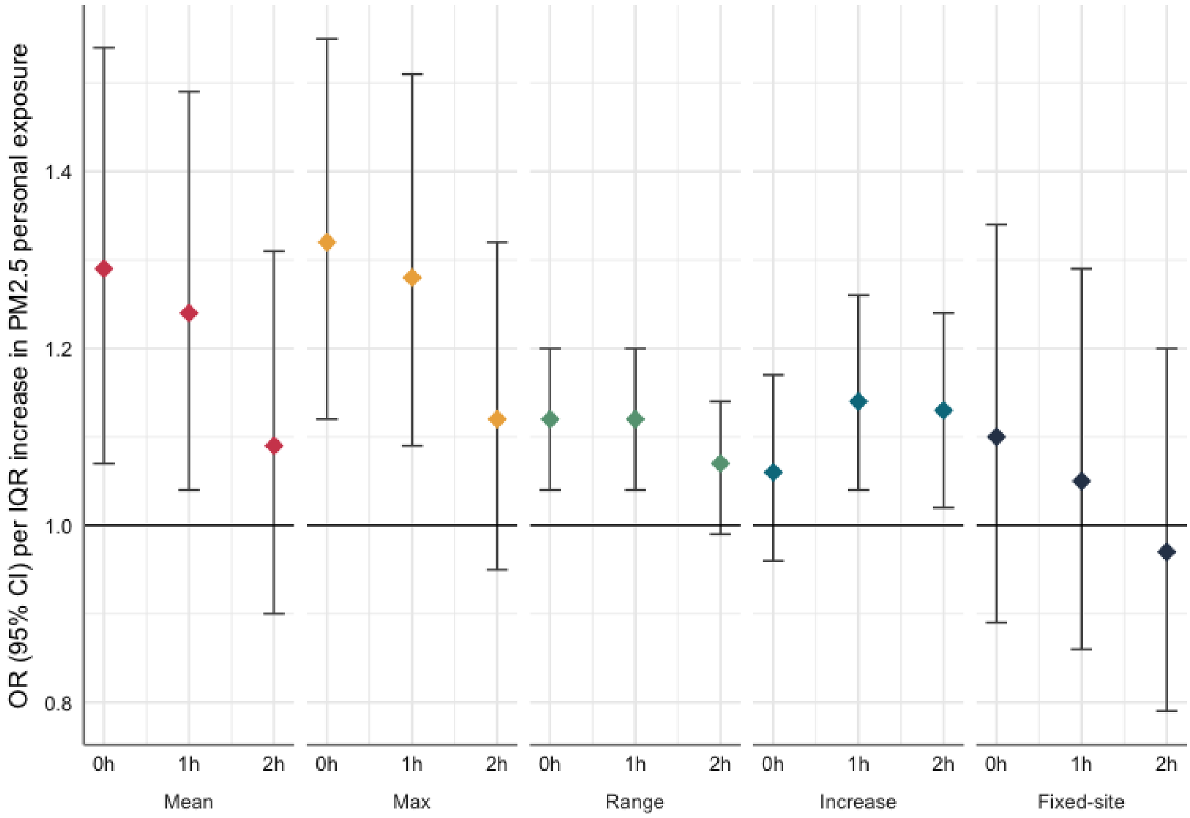

Figure 4.5. Odds Ratio and 95% CI for the associations between personal exposure to $PM_{2.5}$ and symptom prevalence for same-hour (0h), 1h and 2h lag.

Inhaler use exposure models also contained temperature and humidity as potential covariates within the model. Across $PM_{2.5}$ personal exposure metrics for same hour, positive but not statistically significant associations with reliever inhaler use were observed (Table 4.5; Figure 4.6). For hour mean, maximum and range metrics with a one-hour and two-hour lag effect, a negative but, again, not statistically significant association was observed (Table 4.5; Figure 4.6).

Table 4.5. Odds Ratio and 95% CI for the associations between personal exposure to $PM_{2.5}$ and reliever inhaler use. Statistically significant estimates ($p<0.05$) are highlighted in bold. Personal exposure adjusted model includes temperature and humidity and fixed-site adjusted model includes residential distance from monitoring station.

	Odds Ratio (95% CI) per IQR increase in $PM_{2.5}$ personal exposure					
	Adjusted			Unadjusted		
	Same-hour	1h lag	2h lag	Same-hour	1h lag	2h lag
Hour mean	1.02 (0.71-1.48)	0.81 (0.53-1.24)	0.76 (0.49-1.17)	1.03 (0.72-1.49)	0.83 (0.55-1.25)	0.78 (0.51-1.19)
Hour max	1.11 (0.81-1.53)	0.85 (0.58-1.23)	0.78 (0.53-1.15)	1.12 (0.82-1.52)	0.86 (0.60-1.23)	0.80 (0.55-1.16)
Within hour range	1.11 (0.98-1.27)	0.92 (0.76-1.12)	0.92 (0.76-1.11)	1.11 (0.97-1.26)	0.92 (0.76-1.11)	0.92 (0.76-1.11)
Within hour increase	1.00 (0.81-1.23)	1.08 (0.88-1.33)	1.00 (0.81-1.24)	1.00 (0.82-1.23)	1.08 (0.88-1.32)	1.00 (0.82-1.24)
Fixed-site $PM_{2.5}$ concentration	0.92 (0.61-1.38)	0.85 (0.56-1.29)	0.88 (0.58-1.34)	0.92 (0.61-1.39)	0.85 (0.56-1.29)	0.88 (0.58-1.34)

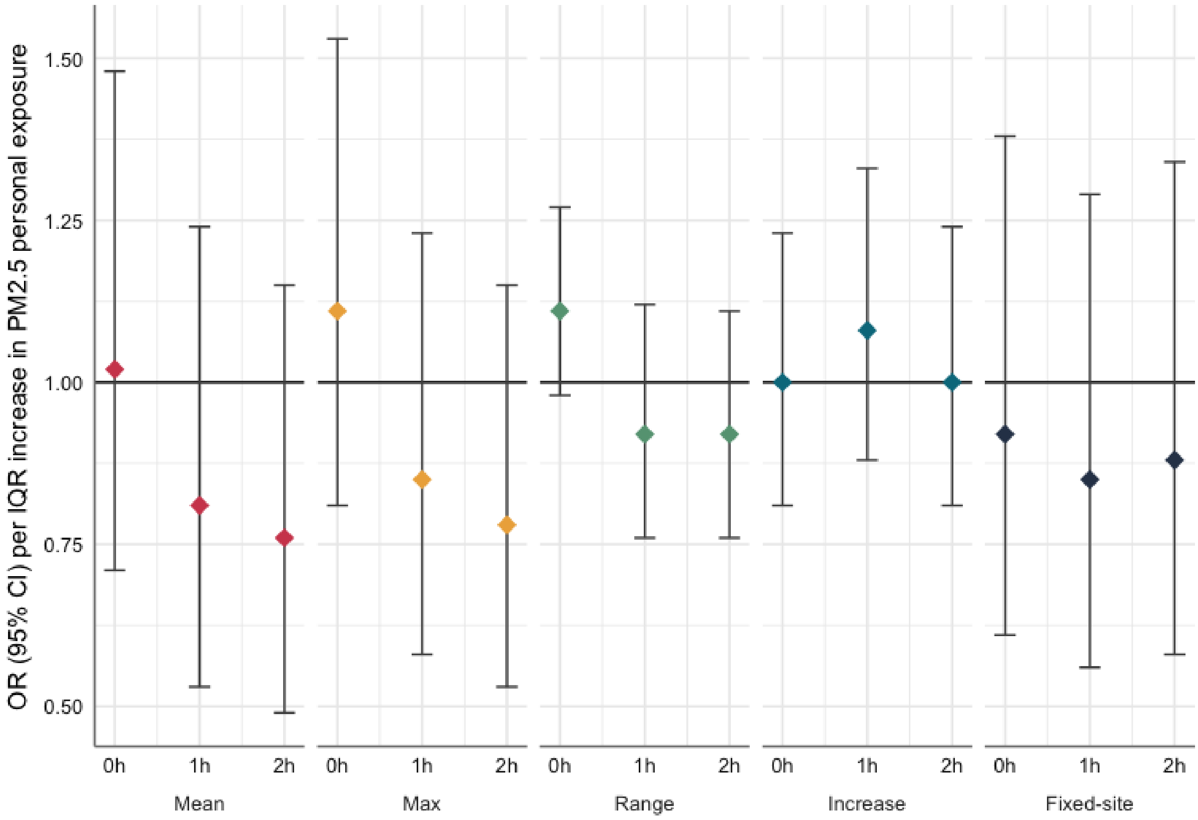

Figure 4.6. Odds Ratio and 95% CI for the associations between personal exposure to $PM_{2.5}$ and reliever inhaler use for same-hour (0h), 1h and 2h lag.

4.3.4 Fixed-site monitoring data and asthma-related health

Models using fixed-site air quality data included distance from closest fixed-site station as a control variable. Despite hourly averaged fixed-site and personal exposure $PM_{2.5}$ data being moderately correlated (Spearman r=0.44, $p<0.05$), there were no significant associations between asthma symptom prevalence and fixed-site ambient levels of $PM_{2.5}$ (Table 4.4; Figure 4.5). Neither a one-hour nor two-hour lag effect was found to be associated. Additionally, no significant associations were observed for reliever inhaler use and fixed-site ambient $PM_{2.5}$ (Table 4.5; Figure 4.6).

4.4 Discussion

Using directly measured hourly $PM_{2.5}$ personal exposure data paired with individual-level health data, this study has investigated the acute associations between personal exposure to $PM_{2.5}$ and self-reported asthma-related health.

The association between increased $PM_{2.5}$ exposure and increased asthma symptom prevalence has been relatively well demonstrated within the literature; however, these studies tend to examine temporally aggregated air quality data ranging from daily (e.g., Ścibor *et al.*, 2022) to biweekly (e.g., Mirabelli *et al.*, 2018) to annual exposure data (e.g., Doiron *et al.*, 2017). Adding to this previous work, findings from this study have revealed significant positive associations between same-hour and one-hour lag personal exposure to $PM_{2.5}$ and symptom prevalence. Results show that same-hour personal exposure to $PM_{2.5}$ was most strongly associated with symptom prevalence, decreasing with each hour lag. By two-hour lag, the association remained positive but was no longer statistically significant suggesting that short-term exposures play an important role in acute asthma symptom prevalence. Previous immunological work on allergen-induced asthma has shown that the release of inflammatory mediators resulting in bronchoconstriction occurs within 15 minutes of exposure and lasts between one and three hours (Bancalari *et al.*, 1999; O'Byrne, 2009). We have shown that personal exposure monitoring using high frequency sampling, paired with hourly-monitored health outcome data, can support detection of acute asthma symptom prevalence associated with personal exposure to $PM_{2.5}$. Such an approach, from an asthma-management perspective, could be a fundamental step in identifying activities and/or microenvironments associated with increased exposure thus has potential to inform decision-making and drive behaviour changes.

This study has demonstrated that high temporal resolution fixed-site monitoring data are unable to detect acute environmental changes inherent to personal exposures and its impacts on asthma-related health. Personal exposures have often been estimated based upon fixed-site monitoring or modelled data (e.g., Su *et al.*, 2017; Williams *et al.*, 2019). To compare the health effect estimates using both approaches, hourly averaged $PM_{2.5}$ data retrieved from the closest fixed-site monitoring station to the participants' home addresses were used as a surrogate for directly monitored personal exposure data collect via PurpleAir. Using this surrogate approach, no significant associations were found for same-hour, one-hour or two-hour lag. This contrasts with much of the literature which has found significant associations using fixed-site data (e.g., de Camargo Matos *et al.*, 2022; Phaswana *et al.*, 2022). This may be due to the acute (one week per participant) nature of this study since correlations between fixed-site monitoring data and personal exposure data have been shown to increase with time (Strand *et al.*, 2007; Hutcheon, Chiolero and Hanley, 2010). However, regardless of timeframe, fixed-site data cannot (and are not designed to) detect the inherent heterogeneity in personal exposures that arise from individual behaviours, particularly within indoor environments (i.e., cooking behaviours, second-hand tobacco smoke exposure, home heating behaviours) (McCarron *et al.*, 2022).

Fixed-site monitoring, by design, monitors ambient air quality predominantly influenced by outdoors sources, such as vehicle and industrial emissions. A subsidiary finding from this study arising from time-activity monitoring is the proportion of time participants, adults with a diagnosis of asthma, spent across different microenvironments, spending only 3.6% of their time in outdoor spaces and, as many other studies have found, more than 90% of their time indoors (e.g., Mazaheri *et al.*, 2018). Results from this study reveal that greatest exposure to $PM_{2.5}$ occurs in residential buildings (i.e., when visiting friends/relatives or in participants' own homes (which could also explain the null finding from the fixed-site data)). As such, using fixed-site data as a proxy for personal exposure may lead to exposure misclassification (De Hartog *et al.*, 2010). Evangelopoulos *et al.*, (2021) discuss that, in most cases, using ambient concentrations as a proxy for personal exposure will overestimate exposure since not all ambient pollution will ingress indoors where people spend most of their time. Though true, this downplays the importance of indoor exposure considering that indoor microenvironments contribute substantially to personal exposures due to prolonged duration and closer proximity to sources. Moreover, Habre *et al.*, (2014) found that indoor sources account for almost three-quarters of $PM_{2.5}$ mass within the home. This highlights the spatial inadequacies of using fixed-site data as a proxy for personal exposure and upon which to assess epidemiological impacts. Furthermore, current health-based guidance concerning exposure to air pollution is based upon data monitored and modelled using fixed-site data and primarily focusses on outdoor avoidance behaviours to reduce exposures to outdoor air pollution. While the avoidance of triggers is critical for asthma control (Papaioannou *et al.*, 2015), such advice ignores the significant contributions of highly variable indoors sources, as demonstrated in this study and, owing to the small proportion of time individuals spend in outdoor microenvironments, is unlikely to have a significant impact. Papaioannou *et al.*, (2015) suggest that personalised management is key to achieving asthma control. Research is needed to test the feasibility of personal exposure feedback as an asthma-management strategy.

As this and other studies have demonstrated, exposure to $PM_{2.5}$ can trigger the precipitation of asthma symptoms. Despite personal exposure to $PM_{2.5}$ being positively associated with symptom prevalence, the same results were not found for inhaler use. It was hypothesised that since reliever inhalers are the "first line of defence against asthma exacerbation” (Williams *et al.*, 2019, pg. 5250), an association may exist between inhaler use and $PM_{2.5}$ exposure. Conversely, results from this study suggest that there are no significant associations between hourly personal exposure and inhaler use for any metric of personal exposure and for any (analysed) lag effect. Our results conflict with similar works in this field (e.g., Williams *et al.*, 2019; Su *et al.*, 2022; Ścibor *et al.*, 2022) with suggestions for this disparity previously discussed. The null result is potentially fuelled by a relatively small sample size and a high number of inhaler use non-events within the sample, meaning our analysis may be underpowered to detect significant associations. 43% of participants did not report any use of their reliever inhaler during the study, which, in itself, is insightful. Non-adherence is a measured phenomenon, with Price *et al.*, (2013) reporting that between 40-60% of people with asthma are non-adherent to their medication and note that there are several multifaceted reasons for this. The invisible nature of air pollution, along with phenomena such as the home or neighbourhood ‘halo effect’ (Bickerstaff and Walker, 2001; Hofflinger, 2019), may influence how individuals appraise the threat (Rogers, 1983) that air pollution poses to their asthma-related health thus making them less likely to use their inhaler than when triggers are more perceivable (i.e., pet dander, cold weather). This indicates that a refocus of air pollution within clinical practice may be required, ensuring patients are aware of air pollution as an asthma trigger and subsequently promoting appropriate use of reliever inhalers to alleviate all asthma symptoms, not only those with obvious, visible triggers.

The monitoring methodology is both a strength and limitation of this study. While the use of low-cost sensors allows for the collection of air quality data across microenvironments giving a more accurate indication of personal exposure, reliability rests on correct use of the device (i.e., close to breathing zone height, always in the same environment as the participant). Though participants were trained on using the sensor (via a printed guidebook and online videos), there is no way to assess compliance during data collection. A few participants had missing air quality data for short periods of their monitoring campaign as a result of batteries running out of charge or power cables disconnecting. Simple alterations to the monitoring equipment, such as fixed cables, could overcome this simple issue and result in a more complete dataset. Additionally, time-activity diaries were used to collect data central to analysis within this study. While these were developed alongside a participant advisory group and considered to be the most ‘accessible’ format for recording information, issues with time-activity diaries have been discussed extensively in the literature. Inaccuracies, missing data, recall error, incompliance and the burdensome nature of data collection may hinder the reliability of data collected (Broderick *et al.*, 2003; Jordan, Jinks and Croft, 2006; Sternfeld *et al.*, 2012). Future research should examine agreement between diaries and ancillary environmental data collected via low-cost sensors to assess accuracy. Additionally, the generalizability of the result from this study are limited. Though care was taken to recruit a broadly representative sample, since this study relied on voluntary participation it will suffer from selection bias, with people more concerned or impacted by air pollution more likely to volunteer, and those with greater capacity (i.e., time, energy) more able to participate. We struggled to recruit people from Scottish Index of Multiple Deprivation (SIMD) deciles one and two, representing the most deprived areas, where there is likely different environmental susceptibility to air pollution (e.g., housing, access to healthcare, smoking behaviours, occupational exposures, modes of travel) (Royal College of Physicians, 2016). On a broader scale, ambient air quality in Scotland (which plays a role in personal exposure) is generally very good in comparison to other countries, and the underlying factors that influence household exposures are very different globally.

In conclusion, we have found compelling evidence which suggests that high-resolution data (both spatially and temporally) is required to detect the impact of $PM_{2.5}$ exposure on acute asthma-related health impacts. We have demonstrated that current monitoring practices are inadequate to assess these acute impacts and we suggest that personal exposure data can be better used both in asthma self-management and clinical practice as an effective asthma-management strategy.

Chapter 5 | Piloting co-developed behaviour change interventions to reduce exposure to air pollution and improve self-reported asthma-related health

Research Question 3: Can co-developed interventions reduce $PM_{2.5}$ exposures for people with asthma in Scotland?

> Objective 3a) Co-develop personalised interventions with each intervention group participant with the aim of reducing their exposure to $PM_{2.5}$.
>
> Objective 3b) Test the efficacy of interventions to 1) reduce $PM_{2.5}$ personal exposure and 2) improve asthma symptom management at follow-up campaigns 1-month post-baseline.

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Abstract

Background

Exposure to air pollution can exacerbate asthma with immediate and long-term health consequences. Behaviour changes can reduce exposure to air pollution, yet its ‘invisible’ nature often leaves individuals unaware of their exposure, complicating the identification of appropriate behaviour modifications. Moreover, making health behaviour changes can be challenging, necessitating additional support from healthcare professionals.

Objective

This pilot study used personal exposure monitoring, data feedback, and co-developed behaviour change interventions with individuals with asthma, with the goal of reducing personal exposure to $PM_{2.5}$ and subsequently improving asthma-related health.

Methods

Twenty-eight participants conducted baseline exposure monitoring for one-week, simultaneously keeping asthma symptom and medication diaries (previously published in McCarron et al., 2023). Participants were then randomised into control (*n* = 8) or intervention (*n* = 9) groups. Intervention participants received $PM_{2.5}$ exposure feedback and worked with researchers to co-develop behaviour change interventions based on a health behaviour change programme which they implemented during the follow-up monitoring week. Control group participants received no feedback or intervention (either co-developed or prescribed) during the study.

Results

All interventions focused on the home environment. Intervention group participants reduced their at-home exposure by an average of 5.7 $\mu g/m^3$ over the monitoring week (-23.0 to +3.2 $\mu g/m^3$), whereas the control group had a reduction of 4.7 $\mu g/m^3$ (-15.6 to +0.4 $\mu g/m^3$). Furthermore, intervention group participants experienced a 4.6% decrease in participant-hours with reported asthma symptoms, while the control group saw a 0.5% increase. Similarly, the intervention group's asthma-related quality of life improved compared to the control group.

Significance

This study demonstrates the potential of combining data feedback (to identify air pollution exposure peaks) with action and coping planning techniques to generate

effective behaviour changes leading to reduced personal exposure to $PM_{2.5}$ and improved asthma-related health. It highlights the importance of indoor air quality, advocating the expansion of this method in future research.

5.1 Introduction

Exposure to air pollution poses a significant public health threat and, globally, is responsible for 7 million premature deaths every year (World Health Organisation, 2020b) owing to illnesses such as asthma, chronic obstructive pulmonary disease (COPD) and lung cancer (World Health Organisation, 2013). The health impacts of air pollution span the entire life course, with foetal exposure resulting in adverse birth outcomes such as low birth weight and pre-term birth; childhood and adolescent exposure linked with, among others, physical and psychological developmental issues; and exposure in adulthood and old age associated with cardiovascular and respiratory ill-health and premature death (Fuller, Friedman and Mudway, 2023). Additionally, air pollution is a known trigger which can exacerbate existing illnesses and has been associated with both acute asthma exacerbations and the longer-term deterioration of the condition (Tiotiu *et al.*, 2020). Fine particulate matter is a key pollutant from a respiratory health perspective since it can be deposited throughout the respiratory tract, particularly in small airways and alveoli (Guarnieri and Balmes, 2014). As such, people with pre-existing respiratory conditions such as asthma, COPD or bronchiectasis, are considered a ‘vulnerable’ group for whom exposure to air pollution should be minimised (Jiang, Mei and Feng, 2016).

Air quality-related policies focus on emission reductions rather than exposure prevention (Public Health England, 2019), and though can be effective for improving ambient air quality, are slow to implement and even slower to produce tangible effects (Carnell *et al.*, 2019). Additionally, as they are designed to benefit entire communities, a policy approach tends to be a broad brush, one-size-fits-all approach (e.g., low emission zones), and does not provide those most vulnerable with targeted solutions to reduce their personal vulnerability. It has been argued that individual behaviours and behavioural patterns can have a more significant role in influencing personal exposure than ambient pollution levels (Ma *et al.*, 2021). Further, such behavioural changes can be easier to implement, can give people autonomy over their personal exposures and have a more immediate health impact (McCarron *et al.*, 2022) (though the burden of responsibility should not solely be with the individual (Laumbach and Cromar, 2022)). Behaviour changes can also be better targeted for the individual, recognising the nuances in personal exposure and allowing individuals to take protective and proactive control over their exposure-related health. Behavioural changes are therefore potentially very beneficial for supporting the non-pharmacological self-management of pre-existing respiratory conditions such as asthma (Janjua *et al.*, 2021; Ainsworth *et al.*, 2022). Individual-level behaviour change, alongside policy changes, could therefore have a key role to play in reducing the health impacts associated with exposure to air pollution (Allen and Barn, 2020), particularly for vulnerable groups (Public Health England, 2019).

Common resources aimed at encouraging individual-level behaviour change (e.g., the UK's Daily Air Quality Index (DAQI) and the U.S.'s Air Quality Activity Guide) recommend exposure-minimising behaviours such as reducing or avoiding outdoor activities. It has been argued however, that these, focusing on avoidance and reduction behaviours, do not empower change and are therefore unlikely to significantly impact behaviour change because of factors including the lack of personalisation of air quality data and lack of individual participation in developing feasible behaviour changes (McCarron *et al.*, 2022). Moreover, engagement with such resources tends to be stratified, with some groups of people more likely to access these data and information than others and interaction does not necessarily translate into action (Schulte and Hudson, 2023). Howard (2023) and others have called for information on the health impacts of air pollution to become more integrated into clinical practice, yet how this is implemented in a way that both personalises the air quality information and engages individuals in developing behaviour changes is still to be investigated. Progress is being made in this regard. For example, a recent initiative in London, UK led by Great Ormond Street Hospital and Imperial College London, reports annual average pollution levels for patients' postcodes on their medical records as a way of 'personalising' the risk of air pollution and initiating conversations (Andersson, Wilson and Hayden, 2022). However, this falls short of providing practical, personalised advice as to how to reduce personal exposures via behavioural modifications.

Accessing more personalised air quality data can motivate protective health behaviours by targeting an individual's threat appraisal (how one perceives the threat of air pollution to their own health) and coping appraisal (how one perceives their ability to overcome the threat of air pollution) (Rogers, 1983; McCarron *et al.*, 2022). However, motivation alone is insufficient to initiate behaviour change (Norman and Conner, 2017). Instead, it represents the initial stage of a multi-step process

(McCarron *et al.*, 2022). The next step, moving beyond motivation and initiating action, requires the development of action and coping plans (Schwarzer, 1992). Action planning involves developing a specific and detailed plan outlining the steps the individual will take to initiate a health-related behaviour change, detailing, for example, when and where the behaviour change will take place (for example as a hypothetical illustration, “I will open a window when I am frying food in the kitchen”). Coping planning focuses on overcoming barriers to initiating or maintaining the behaviour change by identifying potential setbacks and planning solutions. For example, “I will leave a jumper in the kitchen so that if it is too cold with the window open, I can put it on”. Health behaviour change can be challenging, but the process can be facilitated with help and support from a healthcare professional (Bailey, 2019).

The ‘MAP (Motivation, Action and Prompts) of health behaviour change’ (NHS Education for Scotland, 2023) is a tool developed by the National Health Service (NHS) in Scotland, UK, to guide individual behaviour change practice for improved health (Dixon and Johnston, 2020). Its function is to aid health and care staff to support service users to make sustainable behaviour changes to positively influence their physical health, mental health and general wellbeing, recognising that for a sustainable behaviour change to occur, individuals must be **m**otivated to make the change, take **a**ction to alter their behaviour(s) and have awareness of the **p**rompts and cues which can both support and hinder the behaviour change. It provides a simple and accessible, yet theoretically informed guide to identify the most appropriate behaviour change techniques to employ to achieve the desired outcome. A critical benefit of the ‘MAP of health behaviour change’ is its accessibility to the non-specialist user (e.g., asthma nurses) while being theoretically situated, without requiring input from behavioural scientists, which would command significant time and resource for intervention development (O’Cathain *et al.*, 2019). Therefore, it could be an efficient and effective tool to develop tailored behaviour changes for personal exposure reduction. To date, to the authors’ knowledge, the ‘MAP of health behaviour change’ has only been applied to the typical priorities of the NHS in Scotland, such as to provide support for smoking cessation or exercise uptake behaviour change (NHS Education for Scotland, 2023).

This study therefore had two main aims. The first, to test the method of using wearable sensors for personal exposure monitoring, data feedback, and co-developing behaviour change interventions structured around the ‘MAP of health behaviours change’. The second aim was to assess the efficacy of the method as a whole to reduce personal $PM_{2.5}$ exposure, with the hypothesis that this may subsequently improve self-reported asthma-related health.

5.2 Methods

5.2.1 Study design and participants

Between February 2021 and July 2021, 37 participants were recruited from across Scotland to take part in the study (see section 3.2.2). To be eligible to participate, participants had to have received an asthma diagnosis from a healthcare professional, be aged 18 or older, be a non-smoker, and live in Scotland. Participants were enrolled as part of a larger study in which they were interviewed about their lived experience of asthma in relation to air pollution (McCarron *et al.,* 2024b), before measuring their personal exposure to air pollution (hereafter called the baseline campaign) (McCarron *et al.*, 2023), and then taking part in the study presented here. Participants were divided into 6 cohorts who participated sequentially over the course of 1 year between September 2021 and September 2022. Overall, each participant took part in the study for (approximately) one month. A participant advisory group comprised of five individuals meeting the same eligibility criteria helped refine the project design and test the methodology during a pre-pilot phase (detailed in McCarron *et al.*, (2023)). This study followed a parallel group randomised control trial design, with all participants who conducted baseline monitoring allocated at random to either the control or intervention study arm, and subsequently conducted follow-up monitoring (Figure 5.1). Due to the mixed methods approach of the study, focusing on achieving a specific target sample size was not feasible or appropriate. Power calculations for the intervention work indicated that a sample of 110 would be necessary for adequate statistical power. However, due to constraints such as time limitations inherent in conducting this research as part of a PhD, as well as the inclusion of qualitative components, achieving this sample size was deemed unrealistic. We acknowledge that this is a limitation which has impacted the depth of analyses performed and the conclusions drawn from the study. Ethical approval for this study was provided by the University of Stirling's General University Ethics Panel [GUEP 2021 2506 1892].

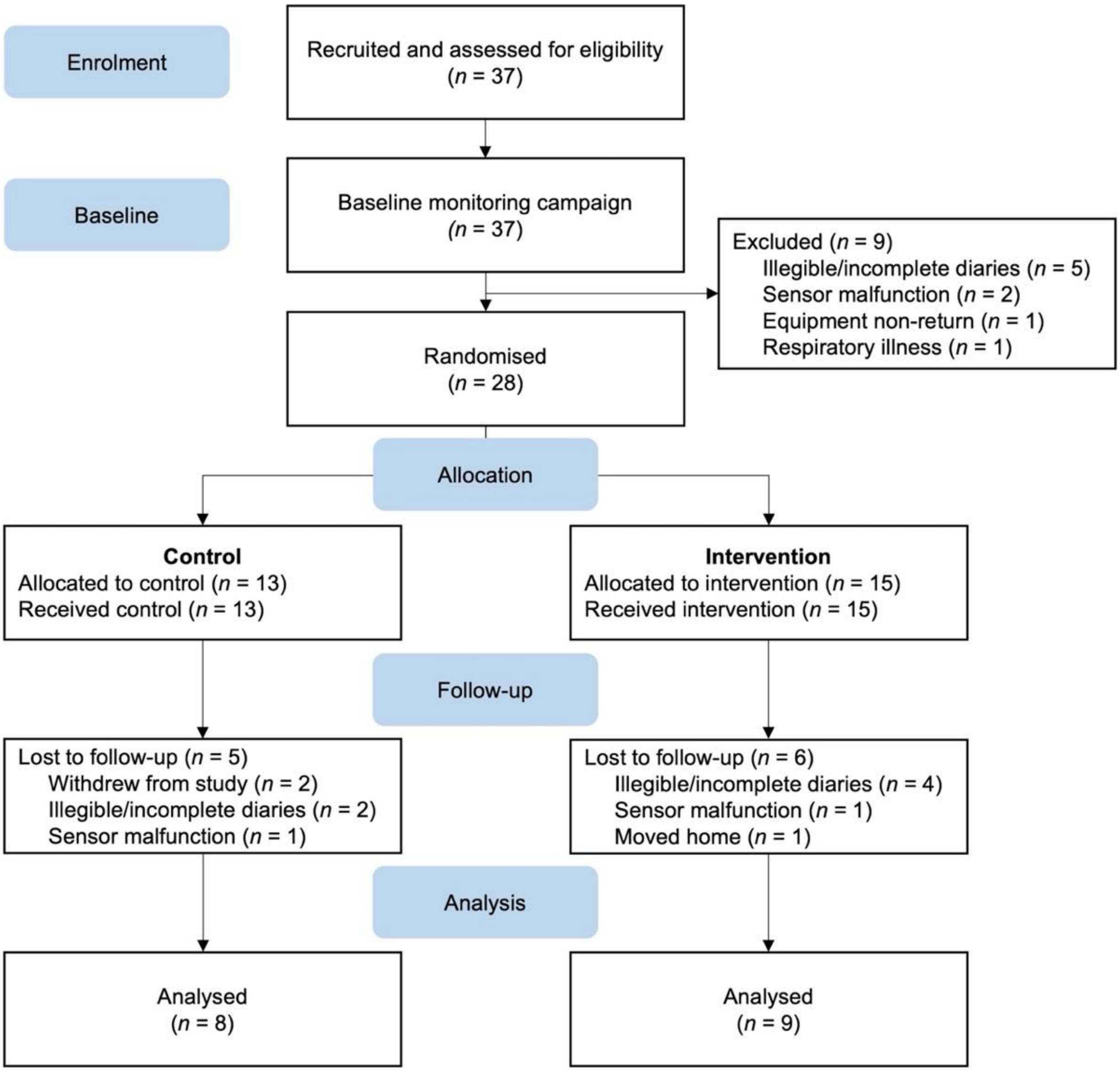

Figure 5.1. CONSORT-style flow diagram illustrating the flow of participants from recruitment through baseline and follow-up campaigns. Results from the baseline campaign are published in McCarron et al. (2023).

5.2.2 Personal exposure monitoring and self-reported asthma-related health

Full details of the personal exposure monitoring methodology and baseline campaign are detailed in McCarron *et al.*, (2023) and summarised here.

Personal exposure to fine particulate matter (particulate matter with an aerodynamic diameter ≤2.5μm ($PM_{2.5}$)), was individually monitored by each participant using a custom-designed backpack carrying a PurpleAir PA-II-SD air quality sensor (hereafter referred to as PurpleAir) (Figure 5.2). To standardise monitoring, participants were provided with a detailed ‘Participant Guide’ and access to two YouTube tutorials explaining how to use the monitoring equipment (see Supplementary Material D). To capture participants' weekly routines and typical weekly variations in ambient $PM_{2.5}$ concentrations, data collection took place over one week at baseline and, approximately 1-month later, over one week at follow-up. The PurpleAir uses Plantower PMS 5003 air quality sensors in addition to measuring relative humidity, temperature, and barometric pressure (Bosch, Reutlingen, Germany). Laser counters record readings every five seconds, with 120-second averages stored on an SD card.

Figure 5.2. PurpleAir attached to customised backpack and powered by battery pack (inside). The PurpleAir was secured in place with Velcro to minimise agitating fibre particles and to keep the sensor as close as feasibly possible to 'breathing zone' height. When stationary for long periods, the participant was permitted to remove the PurpleAir from the backpack and keep it close-by (as in McCarron et al. 2023).

Before data collection commenced, all sixteen PurpleAir devices used in this study were co-located for one week to ensure inter-unit comparability (Giordano *et al.*, 2021). Given that co-location with a reference-grade monitor was not possible owing to fieldwork restrictions during the COVID-19 pandemic, the median value across all sixteen sensors was accepted as the 'true' value (Wallace *et al.*, 2011). Individual sensor outputs were then plotted against this 'true' value, and subsequent data adjustments were made using the derived equations.

In addition to personal exposure monitoring, participants were asked to complete a time-activity diary (see Supplementary Material E) to allow $PM_{2.5}$ concentrations to be matched with the associated activity and microenvironment. The time-activity diary templates were structured in one-hour intervals, with participants providing a written description of their activities due to the diverse range of possibilities. Details about the microenvironment were gathered via checkboxes based on categories established by previous studies (e.g., Steinle *et al.*, 2015). These categories encompassed more general labels such as 'transport' and 'public building', as well as more specific settings within the home (e.g., 'kitchen', 'bedroom', 'living room'). An 'other' checkbox was provided for instances where required.

Approximately 1-month post-baseline campaign and following a randomised control trial design, participants were split into two groups (control and intervention) in an approximate one-to-one ratio (Figure 5.1). The control group (n = 13) conducted the second week of monitoring as they had the first, going about their usual day-to-day behaviours neither implementing co-developed nor prescribed interventions. Intervention arm participants (n = 15) received the intervention (see section *5.2.3 Intervention planning*).

At the end of each monitoring week, all participants completed a researcher administered MiniAsthma Quality of Life Questionnaire (mAQLQ; (Juniper *et al.*, 1999)). The mAQLQ is designed to measure various aspects of asthma-related health and wellbeing across four domains, namely physical symptoms, activity limitation, emotional function and environmental stimuli. It contains fifteen questions and uses a seven-point scale with one indicating the most impairment and seven the least.

5.2.3 Intervention planning

Data feedback and intervention planning conversations took place with fifteen participants individually via Zoom. These were structured around the ‘MAP of health behaviour change’, hereafter referred to as MAP, as detailed below.

5.2.3.1 Motivation

To first target participants' motivation to alter their behaviours to reduce their personal exposure, the intervention drew upon three behaviour change techniques; *5.1 Information about health consequences*, *9.1 Credible source* and *2.2 Feedback on behaviour* (Michie *et al.*, 2013). Using information readily available from Asthma + Lung UK (as a credible source), information about the health consequences was presented onscreen to each participant. This included information on air pollution as a potential asthma trigger, the links between air pollution exposure and asthma onset, acute asthma exacerbations as well as the impact of air pollution on the longer-term deterioration on respiratory health (Figure 5.3a). In addition, an overview of Asthma + Lung UK's recommended behaviour advice for managing asthma in relation to air pollution was presented to each participant (Figure 5.3b). Following this, participants were presented with personalised exposure information from the previous monitoring week whereby the researcher guided the participant through the data highlighting peaks in exposure and the associated microenvironments and activities (taken from time-activity diary information), comparison with the WHO guideline for 24-hour exposure to $PM_{2.5}$ and summarised average exposures across microenvironments (Figure 5.3c & 5.3d). Regardless of study arm, if participants' results showed excessive exposure levels, we were ethically obligated to inform them and suggest exposure reduction strategies. Likewise, if participants' diaries indicated that their asthma was poorly controlled based upon overreliance on their reliever inhaler, we would have recommended they contacted their healthcare professional. Such interventions were not required.

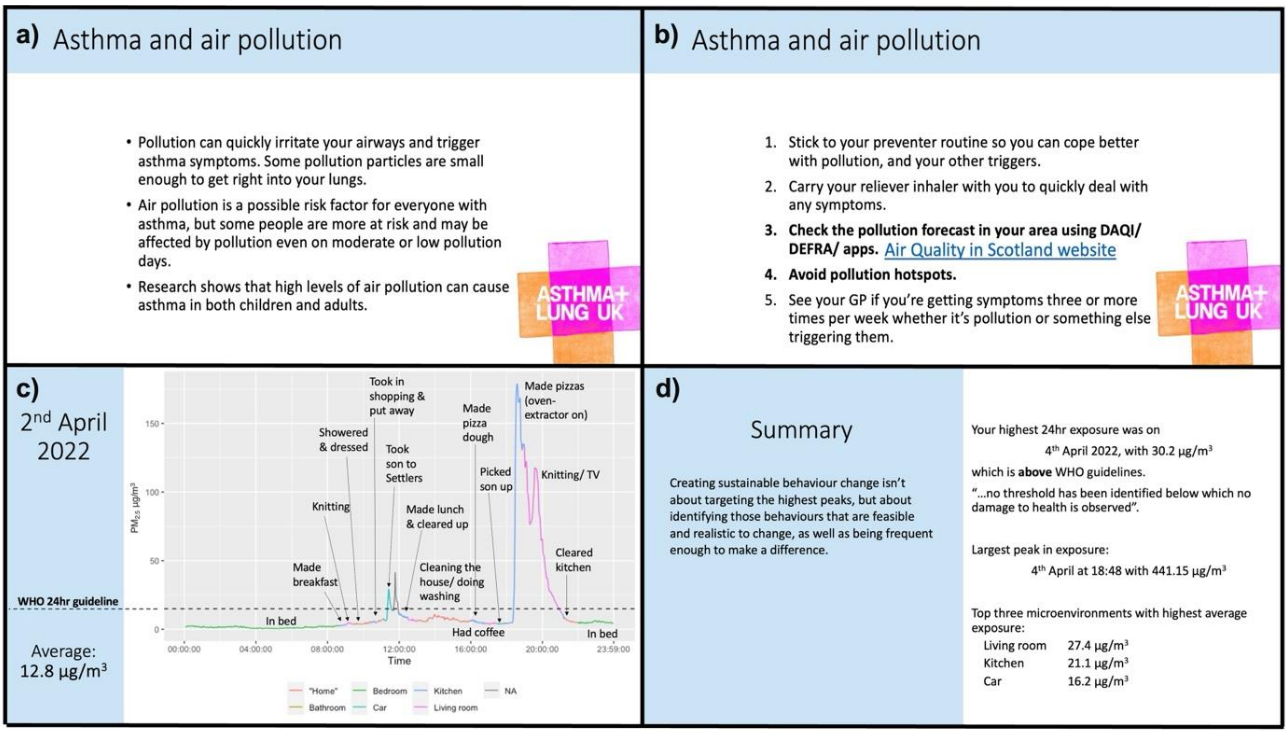

Figure 5.3. Slides shared with participants to target the motivation and action route to behaviour change. a & b) Bullet points outlining what is known about the links between asthma and air pollution (5.1 Information about health consequences; Michie et al. 2013) and recommended actions as detailed on the Asthma + Lung UK website in 2021 (9.1 Credible source; Michie et al. 2013). c) Personal exposure profile for one day of the baseline monitoring campaign. d) Summary slide.

5.2.3.2 Action

To target the action regulation route for behaviour change, participants and researchers co-developed the behaviour change intervention. This allowed the participant to plan (action and coping plans), implement, and self-regulate towards the intervention behaviour, with potential to be more effective in translating the intention into action (Weinstein *et al.*, 1998). These conversations were structured following the MAP template (Supplementary Material G) adapted from NHS educational materials and was shared onscreen and completed collaboratively. The role of the researcher was to facilitate this conversation and provide suggestions as needed, but the power and decision-making in choice of action was with the participant.

The outcome goal was to reduce personal exposure to $PM_{2.5}$, however participants were able to add their own outcome goal(s) if desired. Participants then decided how they were going to achieve the outcome and set their behavioural goal reflecting on the air quality data feedback they had just received. This behaviour was then broken down in detail in the 'action planning' section of the template, with participants detailing when, where, how, the frequency and (if appropriate) with whom they would enact the behaviour change. Participants were then asked to identify barriers or challenges that could prevent them from successfully conducting the behaviour change before developing coping plans to help overcome these barriers. Behavioural changes were not specified or restricted to particular behaviours or microenvironments.

5.2.3.3 Prompts

The MAP planning conversation concluded with participants identifying the prompts and cues that could help them successfully enact the behaviour change. Since prompts and cues target the associative pathway (i.e., they don't require deliberate thought or motivation to be necessary at the time of acting), again this was participant-led since it would be vital for the development of sustainable behaviour change interventions based upon their own assessment of their personal context and the stimuli most likely to elicit their behavioural response.

5.2.4 Analysis

5.2.4.1 Behaviour change interventions

Analysis was conducted on all co-developed interventions (*n* = 15; Figure 5.1). The analysis focused on the behavioural goals that participants set and the prompts they drew upon to help them achieve the behaviour change and involved the coding of individuals' main behaviour change interventions according to Michie *et al.'s* (2013) behaviour change taxonomy.

5.2.4.2 Personal exposure

Descriptive statistics were calculated for each participant's $PM_{2.5}$ baseline and follow-up personal exposure data across three different averaging periods; total exposure (the entire duration of the monitoring campaign), at-home exposure (exposure when the participants indicated they were within the home microenvironment), and intervention target behaviour (only calculated for intervention arm participants; exposure during the behaviour that the intervention was ultimately designed to target).

Where pre-post data were available (*n* = 17 across the control and intervention arms; Figure 5.1), average differences were calculated.

5.2.4.3 Self-reported health

Symptom occurrence for each hour was coded as a binary variable (symptoms experienced/ no symptoms experienced) and paired with hour-averaged exposure data. Symptom prevalence was calculated for the duration of each monitoring campaign as a percentage of hours within the monitoring campaign with an experience of symptoms.

Since mAQLQ questions are equally weighted, participants' mAQLQ scores were calculated using an individual's mean score across the questions. Within-individual differences were calculated by subtracting the follow-up score from the baseline score and group medians calculated. Juniper (1994) established that the Minimal Important Difference (MID), that is "the smallest difference in score which patients perceive as beneficial and would mandate, in the absence of troublesome side effects and excessive cost, a change in the patient's management" (Jaeschke, Singer and Guyatt, 1989, pg. 408), is approximately 0.5. A score greater than 0.5 indicates a clinically meaningful improvement, less than -0.5 indicates a clinically meaningful deterioration, with values between considered clinically unchanged. However, when assessing the efficacy of an intervention across a group, such as in clinical trials, they suggest that simply comparing mean/median differences between treatment arms is not always suitable and does not account for the heterogeneity in responses. As such, an additional metric, the Number-Needed-to-Treat (NNT), was analysed to determine the number of patients who would need to receive the treatment for one individual to experience a clinically meaningful improvement in their asthma quality of life. This was calculated following the methodology proposed in Guyatt *et al.*, (1998) with tables used for these calculations included in Supplementary Material H.

5.3 Results

5.3.1 Participant characteristics

Of the 37 people enrolled in the study, baseline data were collected for 28, with data excluded for nine, owing to ill-health, sensor malfunction and diary-related issues

(Figure 5.1; McCarron *et al.*, 2023). Of the fifteen participants assigned to the intervention arm, all co-developed interventions. However, follow-up data were only collected/ analysed for nine, encountering similar issues as the baseline campaign. There was a similar data loss rate for the control arm whereby pre-post data were collected/analysed for eight of thirteen participants (Figure 5.1).

Seventeen participants had pre-post exposure data available and were included in the final quantitative exposure analysis. Most participants were female (65%) and had an average age of 46.8 years (range: 24 - 74). Detailed demographic statistics for the sample as a whole and for the intervention arm participants who co-developed behaviour changes can be found in Supplementary Material I. The intervention group was representative of the overall study population.

5.3.2 Tailored intervention behaviours

The predetermined outcome goal was to reduce personal exposure to $PM_{2.5}$, though some participants chose to add an additional outcome goal (*n* = 6). These were pertaining to improved asthma symptoms (*n* = 2), the creation of new habits (*n* = 1), better asthma management (*n* = 2) and greater awareness of air pollution (*n* = 1).

All fifteen co-developed interventions were based within the home microenvironment (*n* = 15) and included largely positive action (e.g., “increasing ventilation” or “change cooking method”; *n* = 14). We identified three behaviour change techniques that participants drew upon as behavioural goals: *8.2 Behaviour substitution*; *12.1 Restructuring the physical environment* and *12.5 Adding objects to the environment*. The most frequent, *12.1 Restructuring the physical environment* (*n* = 10), included, for example, increasing or changing the current ventilation routine within the home. Three people set a behavioural goal of adding objects such as air purifiers or filters to a specific room within their home (*12.5 Adding objects to the environment*), with the remaining two substituting frequent cooking behaviours for alternative behaviours (e.g., opting to use a slow cooker instead of a gas hob; *8.2 Behaviour substitution*).

To support planned behaviour changes and to remind themselves to enact the intervention behaviour, participants drew upon three behaviour change techniques. Most frequently participants used prompts and cues as stimuli to remind them to enact the behaviour (*n* = 10; *7.1 Prompts and cues)*. Most frequently this manifested as visual prompts, such as placing stickers or sticky notes on or near to the object of interest (e.g., windows, extractor fans) to prompt the behaviour change (*n* = 8). This also included the use of alarms and phone alerts (as audio stimuli) as reminders to conduct the intervention behaviour (*n* = 2). Five participants used *7.8 Associative learning* which refers to the process of forming associations between a stimulus and a response. This included, for example, associating the action of starting to cook (specific stimulus) with turning on the extractor fan or opening a window (desired behaviour). Finally, two participants called upon reminders from co-habitees as a prompt to enact the behaviour (*3.1 Social support (unspecified)*).

5.3.3 Impact of interventions on personal exposures

In McCarron *et al.*, (2023), we presented the week-long baseline $PM_{2.5}$ data across all 28 participants. Here, we break this down for those in the control arm and intervention arm.

At baseline, average exposure across the week for intervention arm participants was 10.9 $\mu g/m^3$ (range: 2.7 – 26.2 $\mu g/m^3$), which was higher than the average for control arm participants (7.5 $\mu g/m^3$ (range: 1.0 – 21.8 $\mu g/m^3$)). Intervention arm participants also had greater at-home personal exposure to $PM_{2.5}$; their at-home exposure was 12.7 $\mu g/m^3$ (17% higher than their baseline week-average), whereas control arm participants' at-home exposure was 8.0 $\mu g/m^3$ (6% higher than their baseline week-average).

Examining only the intervention-targeting behaviour (i.e., the behaviour participants identified in their action plans) for intervention arm participants (*n* = 9), average baseline personal exposure was 72.7 $\mu g/m^3$ (range: 4.6 – 342.3 $\mu g/m^3$). The average change across the intervention arm pre- and post-intervention was -43.9 $\mu g/m^3$, ranging from -271.9 $\mu g/m^3$ to -2.6 $\mu g/m^3$. A reduction in personal exposure was observed across all participant intervention target behaviours (Table 5.1).

Both the control and intervention arm reduced their at-home personal exposure to $PM_{2.5}$ from baseline to follow-up campaigns. Within the home microenvironment, average difference in personal exposure was greater for intervention arm participants at -5.7$\mu g/m^3$ (range: -23.0 - +3.2$\mu g/m^3$; Table 5.1) compared to the difference in at-home exposure for control arm participants of -4.7$\mu g/m^3$ (range: -15.6 - + 0.4$\mu g/m^3$; Table 5.1). Examining differences in exposure across the two sampling weeks as a whole, the control arm had a greater change in average total exposure of -4.0μg/m^3 (ranging -15.1 to +1.3μg/m^3; Table 5.1). Comparatively, the intervention arm had a smaller average change of -3.2μg/m^3 (ranging -11.2 to +4.5μg/m^3; Table 5.1).

Table 5.1. Participants' change in personal exposures from the baseline week to the follow-up week. Coded behaviour changes (8.2 Behaviour substitution; 12.1 Restructuring the physical environment; 12.5 Adding objects to the environment) are included for intervention arm participants.

		Behaviour	**Total exposure**		**At-home exposure**		**Intervention exposure**	
	Partici-pant ID	Michie et al.'s BCT	Average difference (μg/m^3)	% change	Average difference (μg/m^3)	% change	Average difference (μg/m^3)	% change
Intervention	I_1	*8.2*	-8.8	-34%	-23.0	-68%	-271.9	-79%
	I_3	*8.2*	2.0	44%	-3.6	-79%	-8.2	-43%
	I_2	*12.1*	2.3	44%	3.2	47%	-10.7	-21%
	I_4	*12.1*	-3.7	-62%	-3.5	-62%	-3.0	-22%
	I_5	*12.1*	-6.3	-30%	-5.1	-21%	-13.8	-48%
	I_7	*12.1*	4.5	72%	0.4	5%	-36.3	-46%
	I_8	*12.1*	-5.2	-49%	-5.3	-51%	-5.8	-37%
	I_9	*12.1*	-11.2	-74%	-12.8	-73%	-43.2	-43%
	I_6	*12.5*	-2.3	-85%	-1.7	-81%	-2.6	-56%
Control	C_1	NA	0.7	66%	0.4	38%	NA	NA
	C_2	NA	-8.9	-85%	-8.4	-87%	NA	NA
	C_3	NA	-15.1	-69%	-15.6	-70%	NA	NA
	C_4	NA	-1.5	-56%	-1.6	-75%	NA	NA
	C_5	NA	-4.3	-86%	-4.8	-88%	NA	NA
	C_6	NA	-0.7	-15%	0.2	4%	NA	NA
	C_7	NA	-3.8	-64%	-3.4	-63%	NA	NA
	C_8	NA	1.3	15%	-4.2	-32%	NA	NA

5.3.4 Impact of interventions on self-reported asthma-related health

The greatest change in AQLQ scores was observed in the intervention arm, who had a change in their asthma quality of life score by a median of +0.3 compared to the control group's change of -0.10 (Table 5.2). These scores, being within -0.5 and 0.5 (with a positive change indicating an improvement and negative change a deterioration) are not considered to be clinically significant for the groups overall (Juniper, 1994). For most intervention arm participants (*n* = 8), there was an improvement in AQLQ score, with one of the eight experiencing a clinically meaningful improvement (i.e., over 0.5). The control group experienced a smaller proportion of participants improving their scores (n = 3), and a greater proportion (n = 4) of participants experiencing a deterioration in their score (Figure 5.4).

Table 5.2. Participants' change in self-reported asthma-related health outcomes from the baseline week to the follow-up week. Coded behaviour changes (8.2 Behaviour substitution; 12.1 Restructuring the physical environment; 12.5 Adding objects to the environment) are included for intervention arm participants.

		Behaviour change	**AQLQ score**			**% participant hours with symptom**			**% participant hours with inhaler use**		
	Partici-pant ID	Michie et al.'s BCT	Pre	Post	Difference	Pre	Post	Difference	Pre	Post	Difference
Intervention	I_1	*8.2*	6.7	6.8	0.1	0.6	1.3	0.7	0.0	0.0	0.0
	I_3	*8.2*	5.9	6.3	0.3	1.3	0.6	-0.7	0.0	0.0	0.0
	I_2	*12.1*	6.6	6.8	0.2	9.8	7.4	-2.4	7.7	2.0	-5.7
	I_4	*12.1*	6.5	6.8	0.3	2.5	0.6	-1.9	0.0	0.0	0.0
	I_5	*12.1*	6.2	6.7	**0.5**	8.6	1.1	-7.5	0.0	0.0	0.0
	I_7	*12.1*	5.7	6.1	0.3	9.7	7.7	-2.0	1.3	3.6	2.3
	I_8	*12.1*	6.7	6.5	-0.1	19.4	7.9	-11.5	1.3	0.5	-0.8
	I_9	*12.1*	6.0	6.4	0.4	6.8	3.1	-3.7	3.1	2.5	-0.6
	I_6	*12.5*	6.1	6.2	0.1	26.3	14.1	-12.2	0.6	1.2	0.6
Control	C_1	NA	4.9	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	C_2	NA	6.4	5.1	**-1.3**	0.0	0.0	0.0	0.0	0.0	0.0
	C_3	NA	6.3	6.1	-0.2	13.7	15.0	1.3	3.6	1.9	-1.7
	C_4	NA	6.0	5.4	**-0.6**	3.4	4.1	0.7	0.0	0.0	0.0
	C_5	NA	3.6	5.7	**2.1**	93.8	99.4	5.6	9.3	8.1	-1.2
	C_6	NA	5.3	6.5	**1.3**	3.4	0.7	-2.7	2.5	0.7	-1.9
	C_7	NA	6.4	6.9	0.5	2.7	0.6	-2.1	2.2	0.6	-1.6
	C_8	NA	6.0	5.1	**-0.9**	31.6	32.7	1.1	0.7	1.9	1.2

Examining change in the asthma quality of life domains, the greatest change in both groups was observed for symptoms, with a median improvement of 0.4 reported in the intervention group compared with a median deterioration of 0.3 in the control group. We observed no median change in activity limitation or environmental stimuli in the intervention group whereas a median improvement of 0.1 and 0.2, respectively, for the control group. The intervention group reported a median improvement of 0.3 for emotional function compared to no median change in the control group (Supplementary Material J).

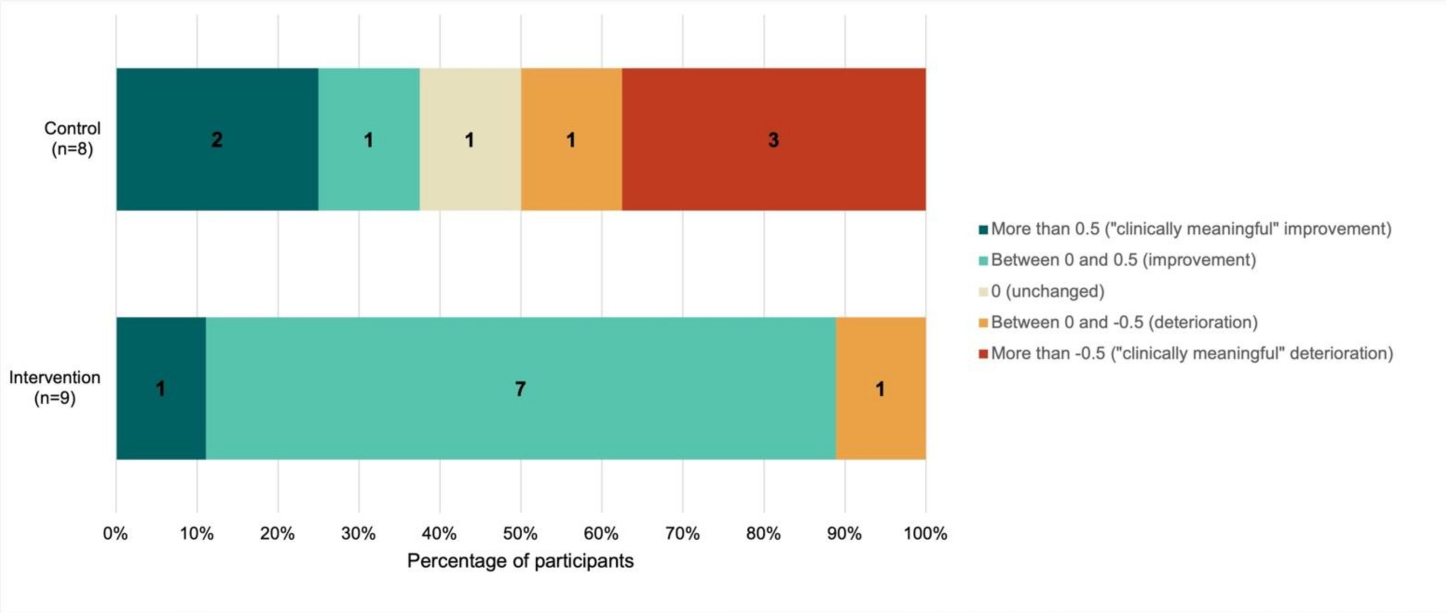

Figure 5.4. Participant individual differences in AQLQ score.

Based on the NNT, it was estimated that five patients would need to receive the intervention for one to experience a clinically meaningful improvement in asthma quality of life. In terms of resource efficiency, the symptoms domain can be most efficiently treated via this intervention, requiring three participants to receive treatment for one to experience a clinically meaningful improvement (Table 5.3).

Table 5.3. Number-needed-to-Treat (NNT) overall and across each of the AQLQ domains.

	Intervention mean difference mAQLQ score	Control mean difference mAQLQ score	Estimated proportion better on intervention	Estimated proportion better on control	Proportion benefitting from intervention	NNT
Overall	0.23	0.09	0.42	0.22	0.2	**5.1**
Symptoms	0.4	0.08	0.54	0.25	0.29	**3.4**
Activity limitation	0.03	0.19	0.38	0.25	0.13	**7.7**
Emotional function	0.22	0.04	0.42	0.28	0.14	**7.1**
Environmental stimuli	0.22	0.04	0.39	0.22	0.17	**5.9**

Asthma symptom prevalence, the percentage of hours where an asthma symptom was recorded across the monitoring week, was examined. Between baseline and follow-up, the intervention arm reported an average difference of -4.6%, with all but one participant reporting a decrease in the proportion of time they reported an asthma symptom (Table 5.2). In comparison, control arm participants reported an average increase in symptom prevalence of 0.5%, with six of eight participants either experiencing no change or an increase in symptom prevalence (Table 5.2).

5.4 Discussion

This pilot study has tested the viability of co-developing tailored interventions with people with asthma to reduce their personal exposure to $PM_{2.5}$ and, subsequently, improve their self-reported asthma-related health. Using data feedback and structured intervention conversations following the NHS 'MAP of health behaviour change' (NHS Education for Scotland, 2023) as the basis of intervention development, which to our knowledge has not previously been applied for reducing exposure to air pollution, we explore and discuss our findings below.

Personal exposure to air pollution is unique to an individual (Liang *et al.*, 2019). Though some factors that influence personal exposure are difficult - if not impossible - to control (e.g., where a person lives), personal exposure to air pollution can, to a degree, be modified by behaviour changes (Janjua *et al.*, 2021). Recent research has emphasised the significance of personalisation of air quality data, suggesting that involving individuals in the process can enhance their engagement with air quality information (McCarron *et al.*, 2022). Further, it has been suggested that personal exposure monitoring could be a useful step in the development of behaviour changes to support the management of cardiovascular and respiratory illnesses (Hadley, Baumgartner and Vedanthan, 2018; McCarron *et al.*, 2023). We tested this in practice, and evidence from our pilot work with a small sample of participants shows that such an approach can work to firstly identify peaks in personal exposure and, secondly, target these using tailored behaviour change interventions to successfully reduce personal exposure.

Many studies have reported the ability of low-cost air quality monitors to effectively communicate personalised information and raise participant awareness of air quality, identify peaks in exposure and potential exacerbation risks (e.g., Su *et al.*, 2015; Dons *et al.*, 2017; Becker *et al.*, 2021; Ródenas García *et al.*, 2022). Consistent with prior research, our study has demonstrated that data feedback can effectively be used to identify specific activities or microenvironments where participants encounter elevated personal exposure levels. Notably, participants in our study directed their interventions towards behaviours that, at baseline, had exposure levels, on average, 17% higher than their average exposure across the baseline monitoring campaign. However, our study advances beyond the identification of exposure peaks; it has illustrated that individuals can translate their intentions into meaningful actions, finding that all participants assigned to the intervention arm of the study reduced their personal exposure to $PM_{2.5}$ whilst enacting the intervention behaviour. While Park *et al.*, (2023) report that personal exposure monitoring can modify attitudes, perceptions, and behavioural intentions, our research supports and demonstrates the efficacy of this approach to not only shape behavioural intentions but also to create effective targeted actions.

Though our results demonstrated efficacy on targeted personal exposures, our results yielded mixed results for participants' at-home exposures. While, on average, the intervention arm experienced a greater reduction compared to the control arm, an increase in at-home exposure was observed for a small proportion of participants (two of nine) indicating non-universal impacts over longer durations. Furthermore, the control arm reduced their personal exposure to $PM_{2.5}$ from baseline to follow-up campaigns (averaged across the week-long sampling period) to a greater degree than the intervention arm. This therefore suggests that personal exposure monitoring alone may enhance individuals' awareness of their personal exposures, resulting in them, either consciously or subconsciously, altering their behaviours and therefore could be responsible for the reduction in total exposure in both arms. Previously published work has shown the added value of personalised air quality data feedback over generic information (e.g., Abdel Sater *et al.*, 2021). This study highlights the added value of data feedback and structured behaviour change planning on targeted and tailored exposure reduction. This demonstrates the ability of employing personal exposure monitoring and feedback, paired with structured behaviour change planning, as a method to identify peaks in personal exposure, reduce personal exposure and therefore, potentially, reduce the burden of air pollution on asthma symptom prevalence/control (McCarron *et al.*, 2023).

Asthma exacerbations caused by exposure to air pollution are a potentially preventable health risk (Kelly, Mudway and Fussell, 2021). Acute exposures are responsible for negative health consequences (Zhou *et al.*, 2017) since exposure to $PM_{2.5}$ can induce an immediate physiological response characterised by inflammation of the airway, excess mucus secretion and tightening of the smooth muscle (Guarnieri and Balmes, 2014), resulting in common asthma symptoms such as wheeze and cough. Previous research on the same sample of participants as in this study has shown a positive association between acute $PM_{2.5}$ personal exposure and symptom prevalence (McCarron *et al.*, 2023). Therefore, reducing air pollution-related exposure events can yield immediate benefits for asthma-related health. Results from this study showed an average reduction in symptom prevalence within the intervention group (-4.6%), in contrast to the control group (+0.5%). Eight out of nine individuals in the intervention group reported experiencing fewer symptoms, while six out of eight in the control group reported no change or an increase in symptom prevalence. These findings, while for a small sample size, underscore the discernible immediate impact of the intervention on health outcomes, supporting the use of personalised management strategies for asthma control (Papaioannou *et al.*, 2015; Kelly, Mudway and Fussell, 2021; Xie *et al.*, 2021).

Asthma symptoms are tangible indicators of an individual's asthma control and overall health status (Bime, Nguyen and Wise, 2012). However, solely focusing on clinical measures, such as peak expiratory flow (PEF), forced expiratory volume in one second (FEV_1), or even symptom prevalence, overlooks the broader impact of the illness on overall wellbeing, which is an important component of asthma status in its own right (Gonzalez-Barcala *et al.*, 2012). Asthma quality of life offers a holistic measure of asthma-related health and wellbeing which can more clearly reflect the condition’s impact on a patient’s day-to-day life (Juniper *et al.*, 1996). We hypothesised that reducing personal exposure to air pollution would result in improved AQLQ scores, reflecting better asthma control (Yung *et al.*, 2019), increased activity capabilities, and improved emotional wellbeing (Ścibor *et al.*, 2021) for individuals in the intervention group. Conversely, we expected scores in the control group to remain relatively stable. Our study revealed the most significant change in AQLQ scores occurred in the intervention group, with a median improvement of 0.3, compared to a median deterioration of 0.1 in the control group (Supplementary Material J). Consistent with symptom prevalence findings, the intervention arm improved their symptoms domain score by 0.40, while the control arm deteriorated by -0.30, providing convincing evidence as to the potential health benefits provided by the intervention. This also supports that the implementation of individual-level interventions aimed at reducing the health effects of air pollution can lead to prompt and significant improvement in health (Kelly, Mudway and Fussell, 2021). Not only does this study point to the viability of intervention co-development for exposure reduction and improved asthma-related health, but our results indicate that, for symptom improvement in particular, this could be an efficient intervention. In comparison to other non-pharmacological asthma interventions such as practising mindfulness (e.g., Ainsworth *et al.*, 2022; NNT = 7), the NNT for this intervention was comparatively more efficient, with five patients needed to treat for one to experience an overall improvement in asthma quality of life and three needed to treat for symptom improvement. The roll out of an intervention, co-developed between healthcare professionals and service users in a targeted manner (e.g., those unable to identify their triggers), utilising low-cost sensor technology and established behaviour change tools, could, therefore be a feasible solution to improve asthma management and control. This approach could also reduce healthcare utilisation in a cost-effective manner, with prevention being favourable over treatment (Pinnock *et al.*, 2017).

While symptom prevalence and environmental stimuli can be objectively measured, activity limitation and emotional function are more nuanced and subjective. These domains rely more on individuals' self-perceptions, emotional states, and personal interpretations of how asthma affects their daily lives. This subjectivity forms a crucial and novel element in our approach and the essence of co-developing tailored interventions for individual-level behaviour change. There have been several arguments made against individual-level behaviour changes to reduce exposure versus emission reduction strategies, such as the burden of responsibility they place on the individual and their potential to widen existing disparities (Laumbach and Cromar, 2022). However, findings from this study suggest that individual-level interventions can be empowering for susceptible groups, enabling them to regain control over their exposure and health while maximising personal choices (Rajagopalan *et al.*, 2020). This is evident in our findings, as the intervention arm experienced no median change in activity limitation indicating the implementation of an individual-level intervention as no more burdensome than inaction. Further, the median improvement in emotional function (with these questions within the mAQLQ pertaining to feelings of frustration, feeling afraid and feeling concerned) suggested that co-developed interventions may offer broader benefits beyond exposure reduction and improved symptom prevalence, but also work to the lessen feelings of anxiety surrounding their asthma and empower them to reduce their personal exposures (Wong-Parodi, Dias and Taylor, 2018). Stanescu *et al.*, (2019) report that anxiety in individuals with asthma is frequently linked with activity limitation and a perceived lack of control over their capabilities. This perception of control has been recognised as a key factor associated with quality of life (Katz *et al.*, 2002) by instilling individuals' confidence in managing their condition (Adams, 2004). Consequently, Adams (2004) argues that placing greater emphasis on perceived control appears justified as a central aspect of asthma management. As a means of improving overall quality of life for individuals with asthma, the co-development of behaviour change interventions based on data feedback provides them with an additional tool for taking charge of their health and mitigating their exposure to air pollution.

Control, in addition to lessening feelings of vulnerability, is a fundamental component in the development of coping strategies aimed at reducing people with asthma's exposure to air pollution (Kim and Kim, 2021). Perceived lack of control, on the other hand, can hinder the development of behaviour change (McCarron *et al.*, 2022) and has been found as a main factor in non-adherence to the behavioural advice communicated as part of top-down air quality communications, for example, from the UK's DAQI or Canada's Air Quality Health Index (Radisic *et al.*, 2016; D'Antoni *et al.*, 2017). Generally, people do not have control over their wider outdoor environment; they cannot (majorly) influence ambient air quality, in most cases they cannot avoid leaving their home to go to work and, for some, they cannot avoid physical activity outdoors (e.g., walking to work or school). Yet the behavioural advice communicated as part of the dissemination of air quality information is focused on avoidance behaviours in the outdoor environment. Though previous studies have found that people with asthma, owing to greater awareness of their personal vulnerability, are more likely to engage in avoidance behaviour (Lissåker *et al.*, 2016; Mirabelli *et al.*, 2018), this is not consistent with our findings. Individuals have little control (Laumbach and Cromar, 2022), and little perceived behavioural control (McCarron *et al*., 2024b) in the outdoor environment, evidenced by no participants developing behaviour change interventions for the outdoor microenvironment. Rather than participants co-developing avoidance behaviours when faced with the ability to choose the behaviour change to implement, participants opted for positive (i.e., "increasing ventilation") actions within the home, an obvious contrast with more traditional reduction and avoidance advice (e.g., "remain indoors and keep activity levels low", "reduce physical exertion, particularly outdoors…"). Ultimately, participants chose to change behaviours that they felt they could control, increasing their sense of self-efficacy. Thus, reframing how air quality related behavioural advice is communicated, putting more emphasis on the behaviours or environments where people feel that they have control, and framing these as more positive actions (Riley *et al.*, 2021), could be a more effective strategy for the sustained uptake of protective actions and reduce the burden of air pollution-related asthma exacerbations.

Effective and sustainable behaviour change interventions require tailoring to both reflective and automatic processes (Weinstein *et al.*, 1998). Reflective processes are deliberate and require thought, consideration and cognitive effort to perform the intended behaviour action whereas automatic processes are non-conscious, instead prompted or cued by environmental, social, cognitive or psychological stimuli which signal an automatic associated behavioural response (Dixon and Johnston, 2020). Participants self-implemented their behaviour change by opting for visual or audio prompts in their environment or social stimuli to remind them to take action, targeting behaviour change via the automatic and associative pathway (Strack and Deutsch, 2004), which, since the automatic process is less cognitively demanding, could be beneficial for sustainable behaviour change. Additionally, participants choice of visual and audio prompts signifies an adaptive response to air pollution as a largely imperceptible problem (Van Der Zee, Fischer and Hoek, 2016). This emphasises the critical role of data feedback to highlight exposure to air pollution in the home which previously would have been unperceivable (McCarron *et al*., 2024b) and highlights the potential of this approach to co-develop sustainable behaviour change interventions.

5.5 Limitations and recommendations for future work

Owing to the nature of a pilot study, this study was not powered to assess the differences in personal exposure or health measures between study arms. Our findings consistently demonstrated the viability of this method for exposure identification and effective intervention co-development for reduced personal exposure to $PM_{2.5}$ and improved self-reported asthma-related health. This paper creates an opportunity for future work to adopt this method and apply it to a larger sample size for more robust analysis.

The small sample in this study is due, at least in part, to preventable data loss for reasons such as illegible or incomplete diaries. We recommend that future studies should adopt alternative means of diary collection, for example in a digital format (e.g., Park *et al.*, 2023). Additionally, while we made efforts to recruit a generally representative sample, reliance on voluntary participation introduces a potential for selection bias, with it likely individuals who are more concerned or affected by air pollution more likely to volunteer, and those with greater resources, such as time and energy, may find it easier to participate.

Collecting subjective data from participants can pose significant challenges. In this study, although it was designed as a randomised controlled trial, it was conducted in a non-blinded manner, meaning that participants were aware of their assigned study arm. This awareness raises the possibility that the perceived benefits of the intervention may have been overstated in the intervention arm while understated in the control arm. For instance, holding other variables constant, not receiving the intervention should not have adversely affected control arm participants. However, we observed a decrease in AQLQ scores and an increase in symptom prevalence in this group. These findings may suggest reporting bias, given the inherently subjective nature of AQLQ responses, which rely on participant recall and self-assessment, especially in the context of a non-blinded study. For future studies and applications of this method, we recommend incorporating more objective health measures, such as spirometry tests (Turner *et al.*, 2021; Hao *et al.*, 2022) and, where possible, conducting this in a blinded manner.

With this said, participant burden must also be considered. Participants were invited to complete a brief evaluation questionnaire following the conclusion of the follow-up monitoring campaign. This questionnaire aimed to gather reflections on their study participation, providing valuable insights for informing the design of future studies. However, the response rates were disappointingly low (n = 2), indicating that participants may have felt overburdened towards the end of the monitoring campaigns. To address this issue, designing evaluation questionnaires to feature Likert scale or multiple-choice questions instead of open-text responses could reduce this participant burden.

It should also be noted that ambient air quality in Scotland, which influences personal exposure, is generally much better compared to other countries. Conducting similar research in countries or cities with higher levels of ambient air pollution would be beneficial.

Finally, future studies should consider different asthma phenotypes. Considering the array of phenotypes, for some individuals, air pollution will simply not be an asthma trigger and symptomology and clinical features will differ between individuals. Focussing on a particular phenotypic subgroup, or more broadly patients with poorly controlled asthma, presenting frequently at their GP or A&E department and who are unsure of their triggers, may be more beneficial, insightful and cost-effective.

Additionally, exploring the application of the method to different respiratory conditions such as COPD and bronchiectasis would also be worthwhile.

5.6 Conclusions

This study set out to test the ability of data feedback and structured intervention co-development to create tailored behaviour changes and reduce individual exposure to $PM_{2.5}$ and improve self-reported asthma-related health. We have demonstrated that: 1) personalised data feedback can help individuals with asthma to identify peaks in their personal exposure to air pollution; 2) these can be targeted with co-developed behaviour change interventions; 3) co-developed interventions can reduce personal exposure to $PM_{2.5}$ during the targeted behaviour; and 4) co-developed interventions can improve self-reported asthma-related health. These pilot findings demonstrate that such an approach warrants further feasibility testing with a larger group of participants. Further feasibility testing should also test this approach for other respiratory conditions potentially exacerbated by air pollution, for example, COPD and bronchiectasis.

As well as demonstrating the efficacy of the co-developed interventions, we have shown that this is potentially an efficient approach (based upon NNT), which, if applied in a targeted manner (i.e., with patients with poorly controlled asthma), could represent a high value and low-cost intervention. As such there is potential to integrate aspects of the approach into existing practices, such as asthma review appointments in healthcare settings, however this would need further testing around feasibility, acceptability and cost-effectiveness.

While this study focused on individual-level behaviour changes, this needs to be considered within the context of the suite of measures needed to reduce air pollution exposures encompassing top-down policies and bottom-up behaviour changes, such as explored in this study. This intervention gives those most vulnerable to the health effects of air pollution exposure an additional ‘tool’, allowing them to take control over their personal exposure to air pollution and help them to improve their asthma-related health.

Chapter 6 | Public engagement with air quality data to mobilise air quality conscious rural communities

Research Question 4: How do we increase community engagement with air quality data and mobilise air quality conscious communities?

> Objective 4a) Apply a novel framework for increasing community engagement with air quality data and information via community workshops.
>
> Objective 4b) Investigate air quality priorities and the potential for sustainable behaviour change in five Stirlingshire communities.
>
> Objective 4c) Develop an online resource to disseminate local air quality information.
>
> Objective 4d) Understand how users perceive a co-developed air quality resource using think-aloud testing.
>
> Objective 4e) Compare the useability and usefulness of various publicly available air quality resources using interviews and think-aloud testing.

McCarron, A., Barlow, J., Gillespie, C., Semple, S., Braban, C., Swanson, V., & Price, H.

Author contributions: **AMcC**: Conceptualisation, formal analysis, data curation, writing-original draft, visualisation. JB: visualisation, writing -original draft (*methods: Part 2 – Creating a digital 'data stories' resource*). CG: Conceptualisation, writing- review & editing. SS: Conceptualisation, writing- review & editing. CB: Conceptualisation, writing- review & editing. VS: Conceptualisation, writing- review & editing. HP: Conceptualisation, writing- review & editing

Abstract

Ambient air pollution causes around 4.2 million premature deaths annually, with 99% of people residing in areas surpassing WHO air quality guidelines. An understanding of the levels of air pollution experienced by an individual is a useful first step to reducing their exposure and improving health. However, particularly in rural areas, localised air quality data are lacking. Existing air quality data, even when available, may not effectively support individual-level behaviour change since the advice is generic. This study aimed to raise awareness of air pollution and mobilise air quality-conscious rural communities using an 'expanded approach' to engagement (reported in McCarron et al., 2022), by both increasing data relevance to rural people ('localising' data collection) and increasing public participation in data collection and analysis. Inputs from participatory activities were used as the basis to develop an online air quality data 'story' resource which was tested in terms of its usability within the context of people's preferences for air quality information communication.

Twelve workshops were hosted across five rural Stirlingshire villages which aimed to achieve three goals: 1) co-develop village-specific air quality monitoring campaigns; 2) interpret air quality data using local experiential knowledge; and 3) initiate discussions on behaviour change for improved local air quality. Workshop inputs were used to create an online air quality resource featuring locally relevant data. Subsequently, the resource was tested with four participants using the 'think aloud' method.

We found that, for rural communities, the main air quality priorities at the start of the project were related to emissions from traffic. However, our data-based engagement approach shifted community perceptions, highlighting domestic burning's contribution to local air pollution. Despite this, workshop participants did not contribute to activities regarding what behaviours they could change to improve local air quality. We found that locally relevant data are key to engagement but these need to be easily interpretable to be useful. Workshops help to 'pull' people in and encourage engagement and are useful as part of a suite of mechanisms to engage communities, but these need to be tailored for the community.

6.1 Introduction

Breathing ambient air pollution causes an estimated 4.2 million premature deaths globally each year as a result of illnesses such as heart disease, stroke and lung cancer (World Health Organisation, 2022b). Ninety-nine percent of the global population are living in areas where World Health Organisation guidelines are exceeded (World Health Organisation, 2022a), yet people are generally unaware of the quality of the air that they are breathing in their local surroundings (Delmas and Kohli, 2020), with recent findings from Europe indicating that 60% of people do not feel informed enough about the quality of the air that they breathe (European Commission, 2022). Awareness of air quality has been argued to be a prerequisite for empowering people to proactively take measures to reduce their exposure and, consequently, mitigate adverse associated health impacts (Carlsten et al., 2020; McCarron et al., 2022).

Sources of ambient air pollution are numerous and include emissions from the transport sector, industrial emissions, waste incineration, power generation, agriculture and residential energy usage (World Health Organisation, 2022b). Ambient air pollution is present in both cities and in rural areas, though the sources (and concentrations) will vary. While globally there is only very limited monitoring of air pollution, this is even more so the case when considering rural areas (e.g., Karambelas et al., 2018). In the UK context, air quality monitoring is conducted by government and institutions at a national scale to comply with national air quality regulations. The largest of the UK national networks, the Automatic Urban and Rural Network (AURN), as of 2023, consisted of c.170 sites nationwide, representing poor spatial resolution (Heimann *et al.*, 2015) and as such many people lack access to representative air pollution exposure information. Consequently, significant portions of the population remain unaware about the quality of their local air (Miranda *et al.*, 2011; Chen *et al.*, 2017) and unable to use it to inform their decision-making.

The lack of localised data (i.e., lack of relevant data) can limit engagement (e.g., Delmas and Kohli, 2020). Engagement is also often limited through the lack of public participation in the process of data collection (e.g., Brunt et al., 2016). The typical system to encourage public engagement with air quality data, typified by the top-down one-way flow of information from governments and institutions to the public, has tended to rely on the public passively receiving this information and assumes engagement and understanding (Riley *et al.*, 2021; McCarron *et al.*, 2022). Recognising the limitation of this model to successfully engage the public and support them to understand the information they are receiving, there have been calls for two-way communication between communities and ‘experts’ (e.g., Hubbell et al., 2018; McCarron et al., 2022). Ward et al. (2022) suggested that collaboration between stakeholders (i.e., communities, researchers) is needed to effectively engage communities in addressing air quality, and this collaboration must offer opportunities to draw on and incorporate experiential knowledge, perceptions and lived experiences of local air quality-related issues. Community-engaged research, defined by Davis and Ramírez-Andreotta (2021) as involving researchers working in collaboration with stakeholders affiliated by factors such as location or interest, is fundamental to identifying local environment and health issues and appropriate solutions (O'Fallon and Dearry, 2002; Ablah *et al.*, 2016). Building on this past work, McCarron et al. (2022) proposed that more effective engagement with air quality data and information required 1) increasing the personal relevance of the data along with 2) greater public involvement in the process (the 'expanded approach'). The value of community engagement in tackling local air quality issues has been recognised in urban settings (e.g*., The Community Air Quality Project* in Barking and Dagenham). This work set out to test this approach in a rural UK community setting.

Lower cost air quality sensors have been criticised for their poorer data quality compared with reference grade monitoring stations (Saini, Dutta and Marques, 2021). However, this can be addressed with proper calibration (Giordano et al., 2021) and is offset by the advantages they bring to this type of study; 1) the lower cost means that more sensors can be deployed (Mahajan, Gabrys and Armitage, 2021), 2) data are more relevant to people because of the enhanced spatial and temporal resolution (i.e., more localised) (Mason *et al.*, 2016; Giordano *et al.*, 2021), and 3) lower cost sensors offer the opportunity to engage communities in conversations about local air quality (Morawska *et al.*, 2018) by creating discussion around sensor placement or allowing citizens to collect data for themselves (e.g., Oltra et al., 2017; Raheja et al., 2022). Lower cost sensors therefore can play a key role in engaging communities in a collaborative way (Mahajan, Chung, *et al.*, 2022), promote better understanding of the issue, and encourage the development of solutions, as demonstrated in urban areas by the *Breathe London* project, for example (Varaden, Leidland and Barratt, 2019). This study aimed to assess the effectiveness of this approach within rural communities.

The aim of this exploratory study was to test an 'expanded approach' (McCarron *et al.*, 2022) to engage rural communities with air quality data and information, increasing both the local representativeness of data and increasing participation and involvement in the process. By focusing on rural areas in Scotland, UK, where air quality monitoring was not yet established, we were liberated from the constraints of typical air quality monitoring and data communication, allowing us to reflect community preferences and priorities in the deployment of sensors and test how to present these data and information for the communities in a more meaningful way. To achieve the main aim of this project – to increase community engagement with air quality data and information – we adopted a collaborative and participatory community-engaged research approach mirroring the approach proposed by McCarron et al. (2022) which recommended both increasing the personalisation of air quality data and increasing public involvement with the process from monitoring to dissemination.

6.2 Methods

The study was separated into three sequential parts; community-based workshops, the development of an online 'data stories' resource and think-aloud testing of the online resource (Figure 6.1), each with varying degrees of participation. Each 'part' is described in detail below. Ethical approval for this study was granted by the University of Stirling's General University Ethics Panel [GUEP 2022 4795 5302].

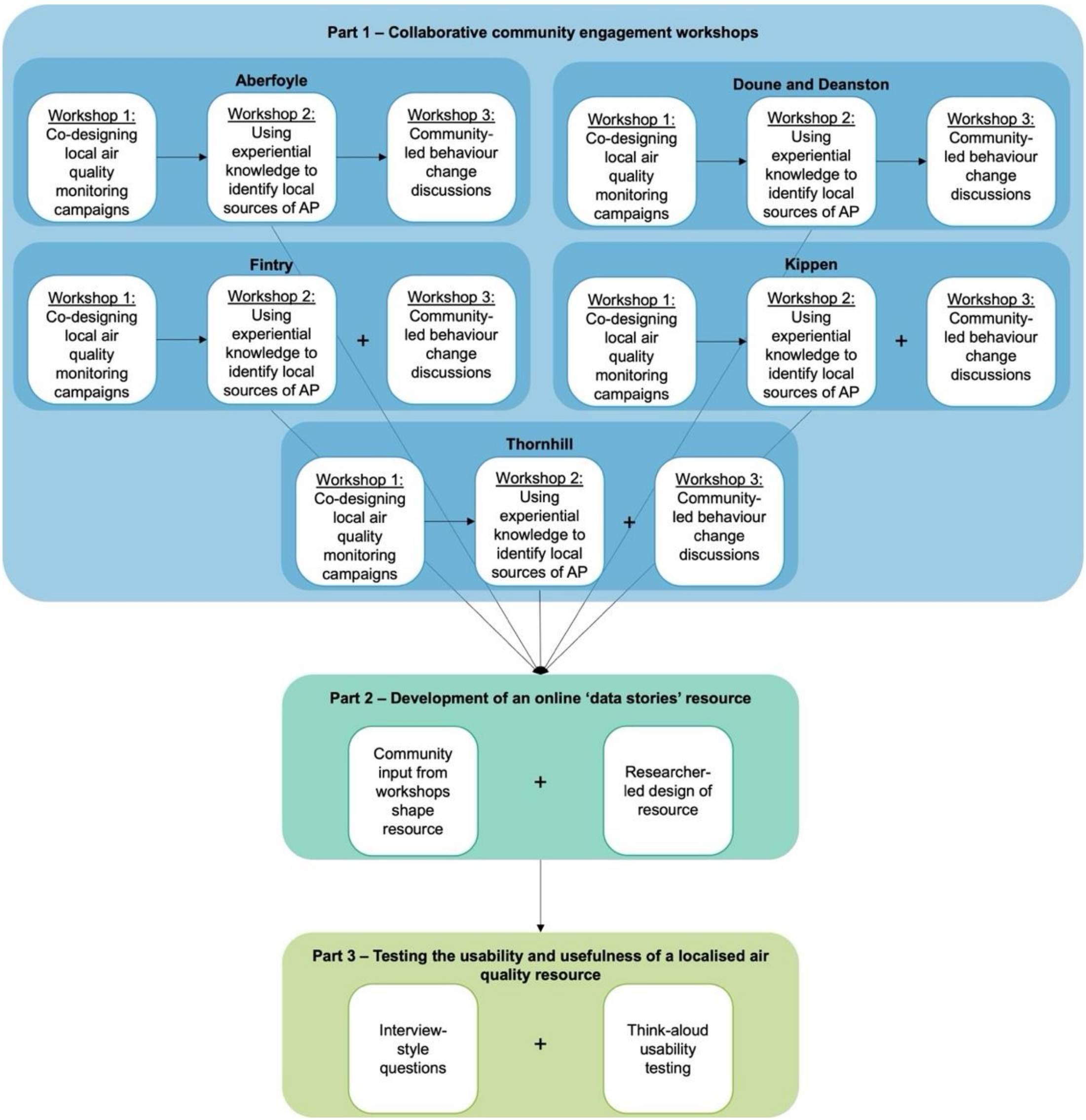

Figure 6.1. Overview of the project. Part 1: Workshops took place in five communities across Stirlingshire. Part 2: Community inputs from the workshops were feed into the design of the digital Stirlingshire resource. Part 3: The digital Stirlingshire resource was tested and evaluated using the think-aloud method and interviews.

6.2.1 Part 1 – Collaborative community engagement workshops

Community engagement workshops took place in five communities across Stirlingshire, UK including Aberfoyle, Doune and Deanston, Fintry, Kippen and Thornhill (Figure 6.2). Workshops took place iteratively and each community was targeted in turn. The first workshop took place in Aberfoyle in October 2022 and the final workshop in Kippen in May 2023. Workshops were run as drop-in sessions which took place in prominent public spaces in each village, such as in the village hall, sports centre or post office. The approach to advertising the events was tailored for each village based on guidance from key community representatives (such as Community Development Officers or Community Councils/Trusts) and included a mixture of social media advertising, leafleting and posters. Participants were anyone (adults and supervised children) who used the community in any way and who were familiar with the area. Workshops lasted between one and a half and three hours. In some cases, workshops coincided with other community events, such as Local Place Plan events or Christmas fayres, to maximise participation. Since the events were designed to be ‘drop in’, there was no incentive for participation and no target sample size set.

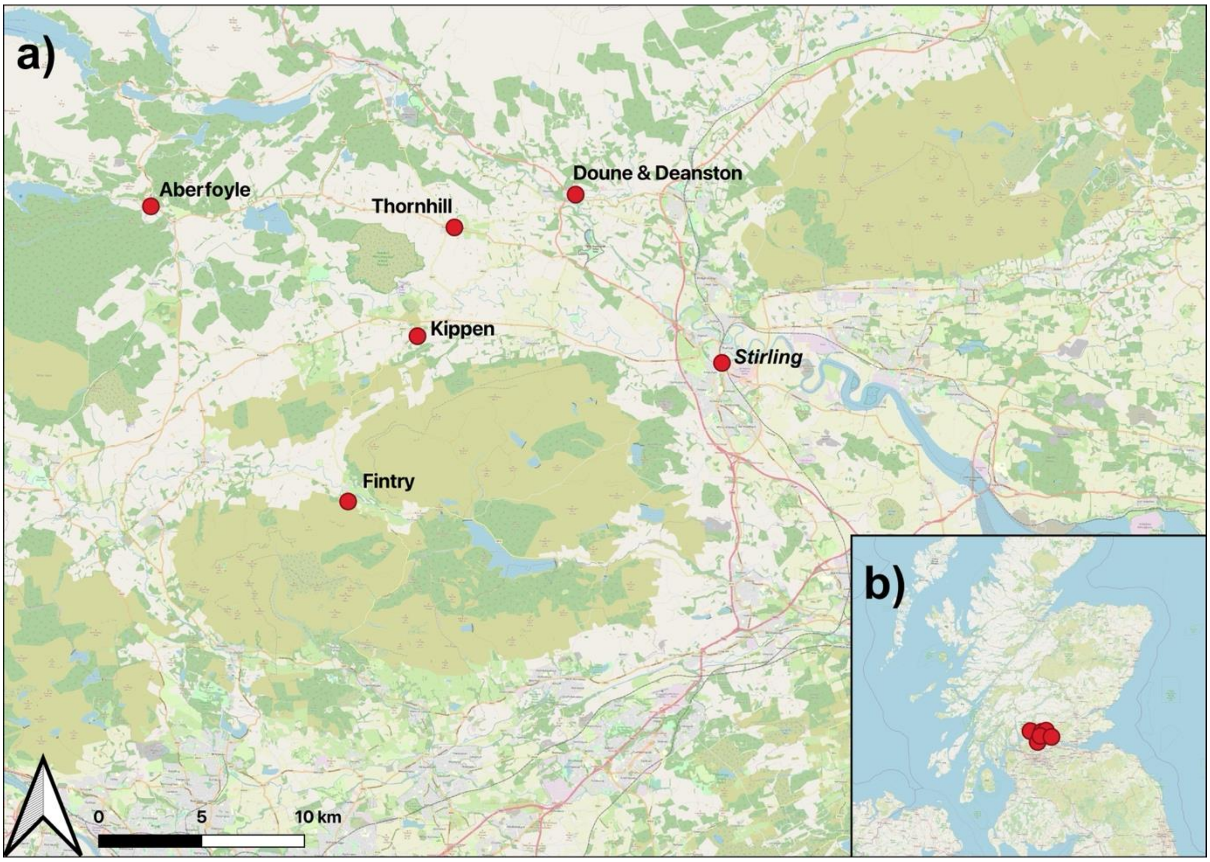

Figure 6.2. a) Workshops were hosted in five rural villages across Stirlingshire, UK (inset map b). Base map and data from OpenStreetMap and OpenStreetMap Foundation (CC-BY-SA). © https://www.openstreetmap.org and contributors.

6.2.1.1 Workshop 1

The aim of workshop one was to co-develop, with participants, a monitoring programme for their village. Based on a rapid appraisal participatory mapping approach (Cinderby 2010), the aim of this workshop was to gather as many people’s inputs as possible rather than gathering in-depth responses. As discussed by Cinderby (2010), such an approach is suitable for representative community engagement since it is less affected by barriers relating to literacy, minimises dominance bias, and the 'drop-in' nature of the workshops avoided the (sometimes off-putting) formality of a public meeting.

Drawing on locals' experiential knowledge, participatory mapping was used to engage participants and collect inputs (e.g., West et al., 2021). Workshop participants were asked to identify areas within their community they would like to see an air quality sensor installed and why. Physical A0 copies of the basemap were displayed (OpenStreetMap) and participants were encouraged to add as many contributions as they desired using sticky notes to identify the location and write or draw a brief explanation (Figure 6.3). We opted for sticky notes over dot stickers or flags to allow participants to specify why they wanted to see a sensor installed in a particular location at the expense of more precise placement. There was also an option to provide verbal contributions to be as inclusive and accessible to as many people as possible. While resources had been developed to capture participants' basic demographic information, we found this additional step discouraged many potential participants, therefore we decided to omit this to encourage greater participation.

Figure 6.3. Participatory mapping exercise used to identify areas around the community where participants would like an air quality sensor installed. The example shown is for Doune and Deanston.

Participants' contributions were digitised using QGIS version 3.32. Photographs of the physical maps were taken and georeferenced using the Freehand Raster Georeferencer plugin v. 0.8.3 (Vellut, 2021). Points were traced and a separate point shapefile layer generated for each village. Since exact locations were not possible to ascertain, points were positioned at the point closest to the feature of interest (i.e., if the participant had written traffic, then the point was positioned at the closest point to road). In some cases, directional arrows had been drawn by the participant which were then used to position the point.

Separately, sticky note written contributions were collated in an Excel file. Quantitative content coding was applied to sticky note responses to convert the unstructured data into structured, organised categories (Gibbs, 2007). These were categorised by source of air pollution and word count frequency analysis was conducted.

Following workshop one, air quality sensors were installed in the village for approximately one week to capture typical weekly trends in ambient pollutant concentrations. The sensors used for this project were PurpleAir PA-II-SD (PurpleAir, Draper, UT, USA) and/or Zephyr (EarthSense, Leicester, UK). Installation locations were guided by the participatory mapping activity (greatest density of stickers) and dictated by logistical factors such as access to an energy supply or direct sunlight (for Zephyr solar panels). In some villages, volunteers were recruited to host a sensor. A member of the research team supported installation at home addresses to ensure proper placement and set-up.

6.2.1.2 Workshop 2

The aim of the second workshop was to draw upon valuable local knowledge to interpret the air quality data collected via the co-developed monitoring campaign. Graphs illustrating particulate matter ($PM_{2.5}$ / PM_{10}) and nitrogen dioxide (NO_2) trends for the monitoring campaign were displayed at the workshop and participants were asked, in the same manner as in the participatory mapping exercise, to label the peaks, troughs and trends with what they thought was the source or cause of air pollution drawing on their experiential knowledge (Figure 6.4). A researcher was on-hand throughout to support this process. As these events were 'drop-in,' participation was voluntary, meaning the individuals who attended workshop one may not be the same individuals who participated in workshops two and three.

Again, sticky note written contributions were collated in an Excel file and content coding applied to responses. To allow comparison with responses collected during workshop one, these were categorised according to the source of pollution stated.

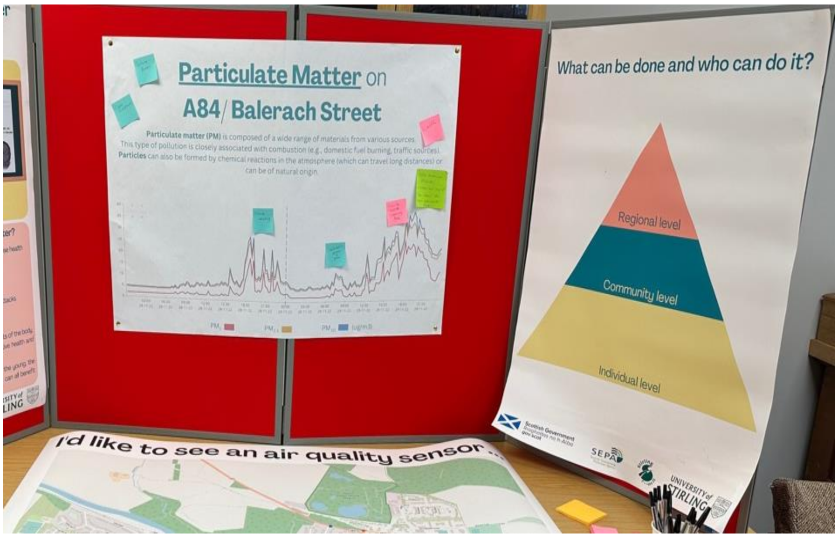

Figure 6.4. Data feedback from one sensor located in Doune. Participants populated the poster with sticky notes using their local knowledge to identify trends and possible sources.

6.2.1.3 Workshop 3

The aim of workshop three was to initiate behaviour change conversations within the community. Participants were asked to consider the sources of air pollution as determined by participants in workshop two and then to think about potential solutions. Participants were asked to think on multiple scales, giving regional, community and individual-level solutions (Figure 6.4). Due to a lack of response, data were not further analysed.

The design of the workshops evolved as they progressed based on the researchers' critical reflections, and therefore for three villages, workshops two and three were merged.

6.2.2 Part 2 – Creating a digital 'data stories' resource

JB was responsible for creating the digital resource while the contents were guided by workshop participants inputs. Air quality data collected via PurpleAirs and Zephyrs were imported into Spotfire (v, 1.17.0), an analytic and data visualisation tool. Participants' inputs gathered during workshop two (interpreting air quality data using their local knowledge) were reviewed alongside the data to ensure interpretations were accurate and, where so, were selected to be visualised within the resource. The digital resource was made up of several pages for each village, where each page focused on a single pollution event. For each event, there was a simple graph and description, with a map to show the location of the monitor where the pollutant was measured. The aim was to keep the user interface simple and to make the graphs and descriptions easy to understand, so that the resource was widely accessible.

The resource was hosted by Scotland's Environment Web, an online hub for environmental data and information managed and operated by the Scottish Environment Protection Agency (SEPA). The beta version of the resource has been publicly available since February 2023 and can be found at https://www.environment.gov.scot/our-environment/air/stirlingshire-villages-project/ (Figure 6.5).

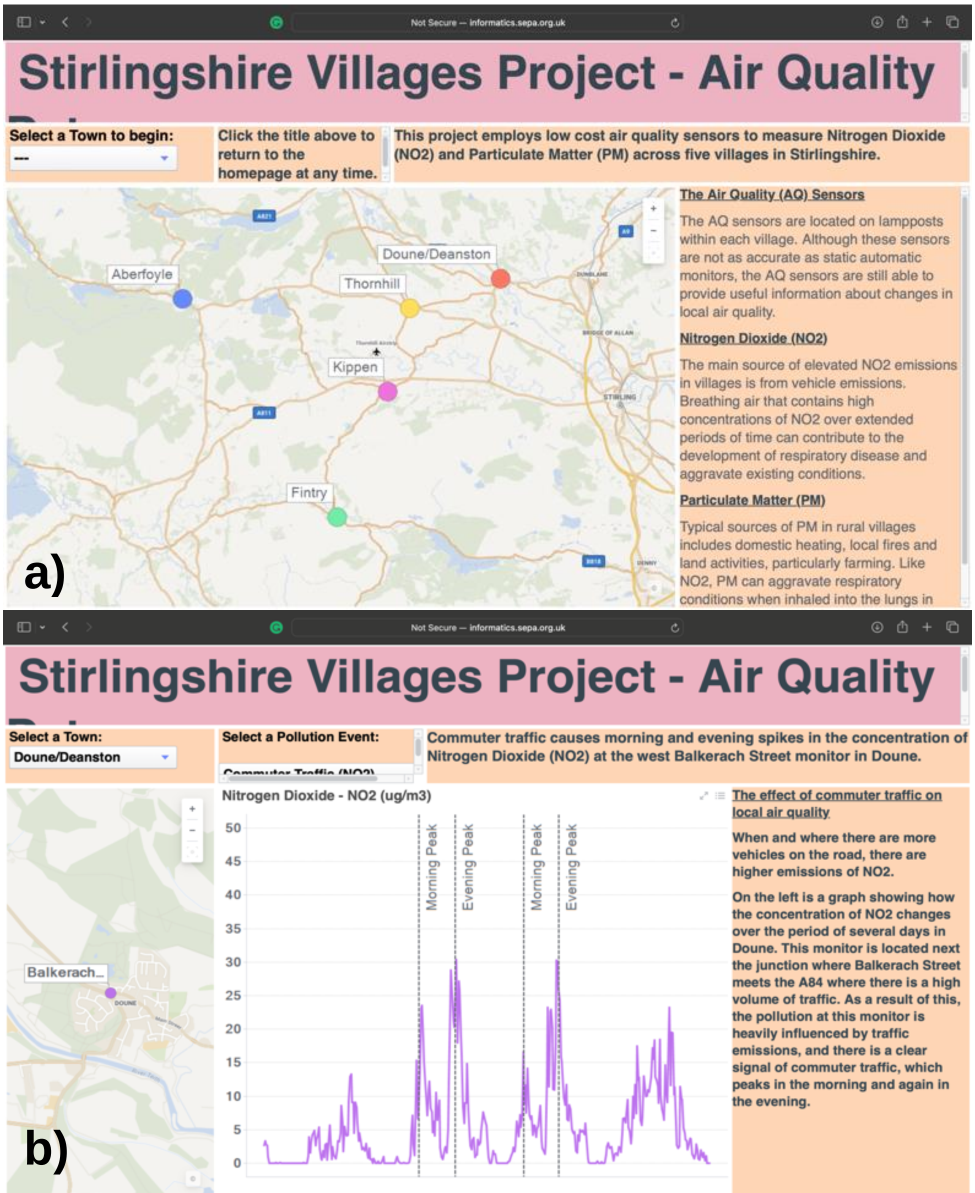

Figure 6.5. Screenshots from the digital Stirlingshire resource. a) Resource home screen. b) Commuter traffic pollution event recorded in Doune and Deanston. Available: http://informatics.sepa.org.uk/StrlingshireVillagesProject/.

6.2.3 Part 3 – Testing the usability and usefulness of an online air quality resource

The final phase of this study aimed to test the usability of the digital resource created in Part 2, by exploring community members' perspectives about the usefulness, usability and comprehensiveness of the resource, as well as how it compares to other online air quality resources. Using the concurrent think-aloud method (Eccles and Arsal, 2017), we asked participants to verbalise their thoughts as they performed various tasks set by the facilitator in real-time. Think-aloud scenarios were divided into three, with participants asked to use a different resource for each scenario. The first scenario used no set resource, while scenario 2 used the airqualityinscotland.co.uk resource (as Scotland's flagship air quality resource, hereafter referred to as the Air Quality in Scotland website) and scenario 3 the digital Stirlingshire resource (co-developed in Part 2). Participants narrated their thoughts as they completed the tasks, explaining what they were looking for, what they had found, what worked well and what could be improved. In addition, insights were gained more generally around how people navigate and use online air quality resources.

The session opened and closed with a semi-structured interview, with questions prior to the think-aloud session relating to the workshop sessions (see *Part 1 – Collaborative community engagement workshops*). The session finished with questions focused on particular aspects of the resources they had accessed during the session with an emphasis on their practical use and application in their day-to-day lives, as well as comparisons between them. A copy of the schedule can be found in Supplementary Material K.

Think-aloud testing/interviews were conducted by the lead author at the University of Stirling between September and October 2023. Think-aloud testing, going beyond usability testing by fostering more in-depth conversations, were then analysed along with interview data. The sessions were recorded using the in-built function within MS Teams before being transcribed verbatim. Transcripts were checked for accuracy against recordings and notes taken on screen use recorded before being uploaded to NVivo software v1.7.1. for analysis. Informed signed consent was obtained from all participants.

Inductive thematic analysis was conducted in accordance with the procedure outlined by Braun and Clarke (2022). Coding involved a systematic and iterative process, first generating initial themes which were then refined. Three final themes were developed from the data.

6.3 Results

6.3.1 Initial community air quality priorities

Community air quality priorities at the outset of the project were explored in terms of both the sources of air pollution and where they were experienced. Across all villages, traffic was the main air quality concern for participants in workshop one, ranging from 45% of sticky note responses in Kippen to 88% of sticky note responses in Aberfoyle (Figure 6.6). This was also observed with the placement of proposed sensor locations with these tending to be clustered along the main streets through the villages, at traffic junctions and at car parks/parking (Figure 6.7). Additionally, clustering was observed at traffic calming measures, such as at speed bumps (Aberfoyle, n = 3) and “slow down” signs (Doune, n = 6). Schools were also commonly identified as a hotspot for traffic-related air pollution, particularly in Aberfoyle (n = 4), Kippen (n = 5) and Thornhill (n = 3, with n = 1 pertaining to children as receptors).

Between two and three sensors were deployed per village (Figure 6.7). While these were guided by participants' inputs during workshop one, it was not always possible to install these in exact hotspots owing to limitations primarily around energy access.

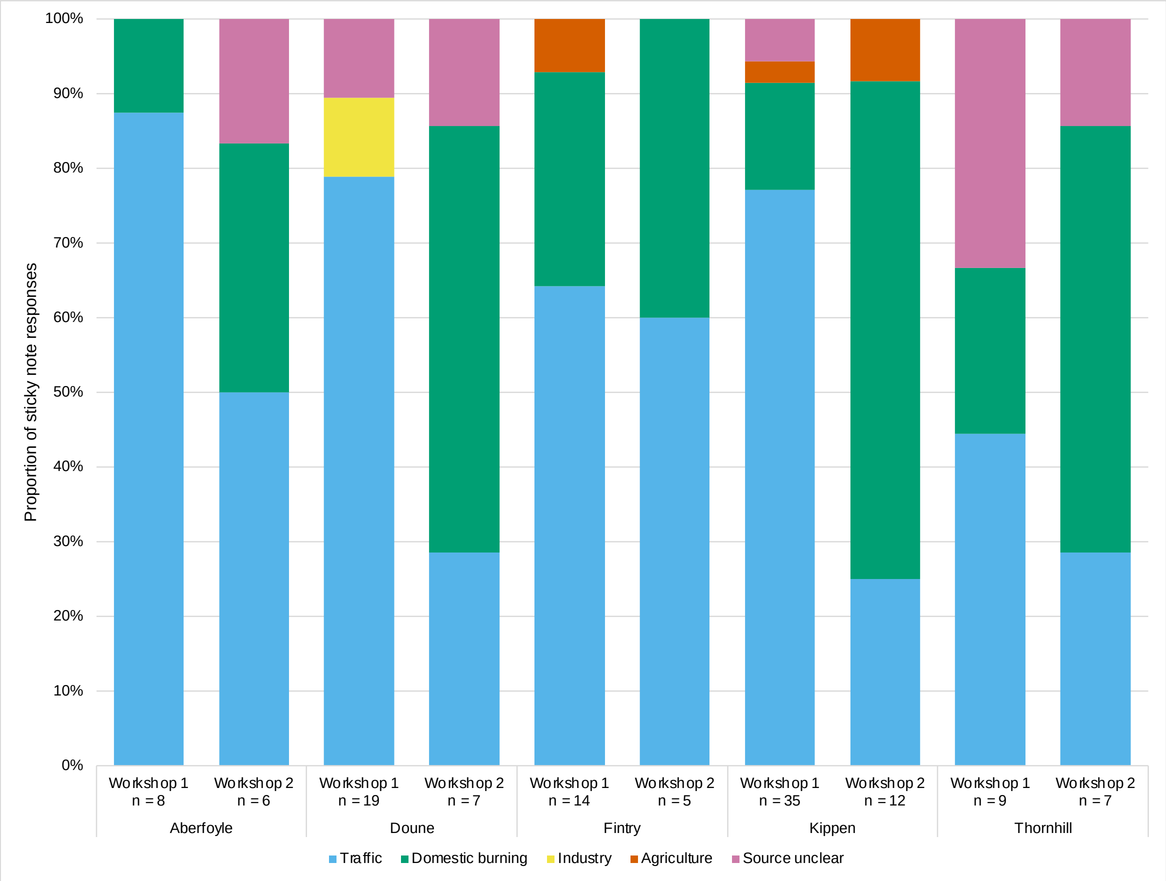

Figure 6.6. Proportion of stickly notes categorised to difference sources of air pollution during workshop one and then following data feedback and discussion during workshop two.

Figure 6.7. Digitised points for suggested install locations gathered during workshop one and install locations. a) Aberfoyle; b) Doune and Deanston; c) Fintry; d) Kippen; e) Thornhill.

6.3.2 Air quality priorities after data feedback

Traffic was the primary concern for participants at the outset of the project (workshop one) across all villages. However, following exploration of the collected air quality data in workshop two, there was a shift in perceived air quality sources (identified from sticky notes added to the graphs/maps) from traffic to domestic burning across all villages (Figure 6.6). In Aberfoyle and Doune, with data feedback, there was also an increase in 'source unidentified' sticky notes (i.e., the participant had made an observation about the data but not the particular source (e.g., "Mixed. Quieter than Saturday."). In Doune and Fintry, perceived issues identified during workshop one (industry and agriculture, respectively) did not resurface in workshop two after data feedback. Conversely, in Kippen, there was an increase in the proportion of sticky notes pertaining to agriculture after data feedback between workshop one and workshop two.

In all villages, workshop one was the most well attended and with the greatest participation with the workshop task (participatory mapping). Workshops two and three were generally less well attended and with fewer people participating with the tasks (data interpretation and behaviour change).

6.3.3 Testing the 'data stories' resource

The digital Stirlingshire resource (Figure 6.5) was tested to better understand its usability and usefulness. In total, four think-aloud interview sessions were conducted, lasting between 32 and 48 minutes. All villages were represented except for Fintry, and all participants had attended at least one of the workshops. Half of the participants were members of a Community Trust/Council and had some involvement in the organisation of the events such as space hire or advertising strategies but were not directly involved in the planning of the content of the workshops.

Based upon both data collected during the think-aloud sessions and from interview questions, we developed three themes: 'data relevance is critical for engagement', 'air quality should be easily interpretable' and 'air quality data, regardless of source, needs to be pushed'. We describe each of these in turn below.

6.3.3.1 Theme 1: Data relevance is critical for engagement

The theme ‘data relevance is critical for engagement’ was developed from the participants’ preference for local (rather than distant) air quality data. Local air quality data was deemed more relevant to people living in rural areas where they and their families spend most of their time.

> *Well I found out [from the Air Quality in Scotland website] information about the nearest site to where I live, which is actually about 10 miles away at a busy traffic junction. So although it's interesting, is it relevant to me and my family's exposure to air quality where we live and work? Not sure. (P1)*

There was a feeling of non-representation or exclusion in discussions about the sort of air quality data typically available (i.e., via the Air Quality in Scotland website), with participants expressing joy in being able to access non-urban data which was perceived to be more relevant to them:

> *I’m actually really pleased to get on to something which is the Stirlingshire villages rather than all the more urban places. So I'm now going to select a village which, here we go, Kippen is on it, which is great. (P2)*

Participants suggested that having access to localised and relevant air quality data can help to inform individual decision-making. Participants could recognise the value of, and need for, different types and sources of air quality data, such as the value of national scale data to inform policy or top-down decisions. But for their own personal and specific behaviours, locally relevant data were critical.

> *…the whole of Scotland is probably too general but yes, it's probably more important for top-down decisions… it doesn't do much for individual decisions. (P3)*

6.3.3.2 Theme 2: Air quality data should be easily interpretable

The theme ‘air quality data should be easily interpretable’ was developed based on the contrasts we identified in participants’ use and discussion of the Air Quality in Scotland website compared with their use and discussion of the new Stirlingshire resource.

Using the Air Quality in Scotland website, participants tended to describe the data, reading out loud what was displayed on their screens. Participants dwelled on specific metrics such as averages, maximums and exceedances. While this demonstrated their ability to access, view and read air quality statistics, it did not necessarily demonstrate understanding and comprehension of the data provided.

> *Okay so, annual hourly mean 6, maximum 87. So, I've got a maximum hourly mean, which basically is the one that I would probably be interested in, cause it's nice to know that it's low, relatively speaking, but there have been occasions where there have been high ones and I think I'd want to look at that and it's now telling me there are no defined exceedance criteria for this pollutant... (P2)*

Another challenge to comprehension arose from the use of banding or index values. Participants sought a clearer, more detailed and informative breakdown of the banding values and colouring system. There was a sense among participants that the burden for interpretation was being placed on them, with one participant describing the task as “overwhelming” (P4). The absence of detailed information left participants unable to determine the significance of the data. Moreover, a disconnect was identified between the way the data were presented and participants’ perceptions of the real-world variations in air quality across the country, cultivating a sense of scepticism. This underscored the importance of data transparency and interpretability for building trust.

> *For instance, today, if I look at this website, the whole country's green. Yeah. Does that mean that there's no pollution anywhere in Scotland? Probably not. And it's a darker shade of green everywhere. And there's nowhere in Scotland that appears to be the lighter shade of green. Even the remote islands where you would expect there is no pollution at all, or very little. So why is it all one colour? That's the first thing I would I'd say. (P1)*

In contrast, the Stirlingshire resource was regarded to be more user “friendly” (P4). Rather than participants simply describing the data and information they saw onscreen (as with the Air Quality in Scotland website), participants were able to interpret the data by connecting specific events (drawing on their experiential knowledge of living in the area) with trends in air quality data for their village.

> *Okay so that may well have been a specific event, either to do with farming or something, or more likely, somebody having a bonfire to be honest, which happens about the place. And there's, you quite often smell smoke, and you have no idea it's coming from, and we've had that quite a few times. (P2)*

In particular, the way in which the data were presented, providing a textual summary in addition to the graphs, was regarded as a particular strength of the resource and aided interpretation. This highlighted that while quantitative air quality data are important, for it to be engaging and interpretable by the public, the value lies in the story the data can tell. Presenting this in a meaningful and comprehensive manner was key.

> *The data is good. I think you've done something here that a lot of sites skip over and that's you've got the space to show the data and the description at the same time without clicking on the data, you're saying you're putting the importance right there, the important stuff right there on the screen in front of people ... (P4)*

6.3.3.3 Theme 3: Air quality data, regardless of source, needs to be pushed for inclusive engagement

Engagement with air quality data and information was not commonplace among participants. Air quality data were not generally regarded to be engaging and failed to encourage or entice participants to engage with it. Rather, participants recognised that for them to take notice of it would require external encouragement, motivation and support.

> *Yes, I do feel I would need, yeah, pushing in some respect. Yes, I'm not quite sure how. I think it's the sort of thing you can be aware of, but ignore almost… (P3)*

The 'push' that participants needed to think about and engage with air quality data and information varied between participants, but in all cases, involved some perceivable manifestation to serve as a prompt or cue to engage. For example, one participant suggested that social media alerts when air quality was poor would act as a prompt and engage many locals. Workshops on the other hand were regarded as more subtle cues to engagement and prevented participants from being able to “ignore” air quality information by creating a “physical presence” (P1) in the community.

> *…that's why the workshop was good. Yes, some kind of push. Periodic push or something, yeah. (P3)*

However, whether workshops acted as a push or a pull mechanism was undecided amongst participants. While some regarded their physical presence within the community as a ‘push’ to encourage engagement, particularly for those who would not typically interact with air quality data and information or those without prior knowledge or interest, others regarded these as pull mechanisms. Workshops, as pull mechanisms, were regarded to only encourage those people already actively engaged in their community or with prior knowledge and/or vested interest in air quality and therefore willing to input effort and engage.

> *But what you got that day was a whole range of people who have very diverse interests in a whole range of different things relating to the village. And therefore, you probably got the opportunity to speak to people that might not necessarily have known about air quality problems or regarded them as particularly important. (P1)*

> *… it also tended to be rather the older generation that was, that was focusing on it… People engage when something affects them directly and if they don't perceive there's a problem then…they're not going to show up for things like that. (P2)*

The appeal of air quality data, even when relevant to their local area communicated via the Stirlingshire resource, seemingly lay in its ability to validate participants experiences rather than using it proactively to inform their behaviours.

> *Well, what would be useful is if you had some event in the area where there was a fire and you could go on to a site like this and check out what effect it was having on you specifically, I think that was really useful to be able to do that...you could just nip on and go right, what happened yesterday? There was a fire. Um. Is that why I'm feeling rubbish today or you know…so I think it's very useful for that. (P2)*

6.4 Discussion

This study has explored the application of a novel approach, building on previous work, to encourage and enable community engagement with local air quality data and information, and investigated appropriate ways of conveying this information meaningfully to the public.

The participatory workshops themselves were considered a key factor in ‘pulling’ people in to engage with air quality data and information, particularly for those who would not usually engage, those who knew little about it, or those who tend to “ignore” or forget about it. To contrast with the traditional model of one-way dissemination to *inform* the public about air quality (e.g., via the UK’s Daily Air Quality Index), the workshops were, by design, *interactive* to promote two-way dialogue between facilitators and participants (McCarron *et al.*, 2022) and empower participants (Cinderby *et al.*, 2021) beyond just *consultative* or *functional* participation (Pretty, 1995; McCarron *et al.*, 2022). Information dissemination via newspapers, the internet or smartphone apps (Riley *et al.*, 2021) has demonstrated limited engagement from the general population (Riley *et al.*, 2021; McCarron *et al.*, 2022) and have failed to serve to the majority (Schulte and Hudson, 2023), with it frequently being those with a prior interest or considered to be at-risk (such as those with respiratory illness) more likely to engage (Lisståker *et al.*, 2016; Mirabelli *et al.*, 2018). *Informing* makes it easier for the general population to ignore. Conversely, workshops have been found to increase community knowledge about outdoor air quality (Dorevitch *et al.*, 2008) and increase environmental consciousness (Rickenbacker, Brown and Bilec, 2019). In this sense, workshops’ ability to reach the ‘difficult to reach’ or ‘usually disengaged’ people in some villages, as noted by the participants themselves, is a strength of this approach. Additionally, workshops were considered by some to be the “periodic push” that they needed to encourage them to think about or engage with air quality information. In this regard, workshops, as a visible and “physical presence” in the community, counter the invisible nature of air pollution (Kuchinskaya, 2018). In particular we found that workshops, when integrated with other community-based events, such as Place Plan workshops or Christmas fayres, encouraged increased participation. Leveraging community assets, be these community resources, infrastructure or existing programmes, have been found in past work to encourage and strengthen participation (Wong *et al.*, 2020). Workshops and community-based activities to encourage engagement with air quality data and information, however, have been subject to many criticisms, for example their resource intensity to host (i.e., human and financial capital)

(McCarron *et al.*, 2022), and for the capacity they require of community members to engage (i.e., time, effort) (Evans-Agnew and Eberhardt, 2019; Symanski *et al.*, 2020). It was also noted that in some villages it was those already active members of the community (such as the older generation), those with a prior interest, or those who were willing to travel who were ‘pulled’ to the events and had been the most engaged. This demonstrates the potential exclusionary nature of these events, such as geographical exclusion (e.g., where they are hosted), socioeconomic exclusion (e.g., cost to travel) or demographic exclusion (e.g., exclusion of younger people/families). Workshops therefore are one way of increasing community engagement with air quality data and information, but they are by no means the ‘silver bullet’ to engagement and cannot be the sole engagement mechanism (Ward *et al.*, 2022).

Risk perception is contextual (Renn, 2004) and location in particular plays an important role in the formation of perceptions about air quality (Brody, Peck and Highfield, 2004). At the outset of the project and in the initial phase of our workshops conducted in rural villages across Stirlingshire, it was evident that the predominant concern among the local population was traffic-related air pollution. Traffic, including privately owned vehicles, buses and heavy goods vehicles as examples, was perceived as a substantial contributor to local air pollution as evidenced by both spatial and qualitative analysis of the participatory mapping exercise. This observation aligns with findings from the Scottish Government’s report on public engagement with air quality in Scotland which found that the Scottish public regard the transport and traffic sector as a primary contributor to poor air quality (Scottish Government, 2023). Similarly, it supports with the findings of Maione et al., (2021), who, in a Europe-wide study, identified traffic and industrial activities to be the sectors perceived to be the largest contributors to local air pollution. Likewise, Liao et al. (2015) found that respondents' heightened visibility and contact with vehicles led to their perception of traffic as the primary source of poor air quality. Our study adds to this more urban/industrial setting-focused research, confirming this finding persists in rural areas, despite lower traffic levels. Though rural areas are often perceived to be less polluted than urban areas (Smallbone, 2012), traffic is a very visible manifestation of air pollution, incorporating issues like noise and congestion (e.g., Anciaes et al., 2017), making traffic a more palpable concern for residents.

The often invisible and imperceivable nature of air pollution presents a significant challenge to increasing public awareness of ambient air quality (Kuchinskaya, 2018) and, consequently, people's perceptions of their local air quality can often be misinformed (Schmitz *et al.*, 2018; Kim, Senick and Mainelis, 2019). To address the disparity between these (misinformed) perceptions and the actual objective risks associated with local air pollution, it has been suggested the implementation of a targeted communication strategy delivering tailored and relevant data and information can enhance public awareness and engagement (Schmitz *et al.*, 2018; Feenstra *et al.*, 2020). Localised data has the ability to connect with people and can influence their understanding of local sources of air pollution (Mason *et al.*, 2016; Radisic and Newbold, 2016), as was observed in this study, with data feedback demonstrating its ability to transform the perceptions of workshop participants regarding the local sources of air pollution. Most notably, there was a shift from attributing air quality issues primarily to traffic and transport in workshop one to recognising the impact of domestic fuel burning on local air quality in workshop two. Additionally, the relevance of data was considered a particular asset of the Stirlingshire resource, demonstrating the ability of local and relevant data to engage local people (Ramírez *et al.*, 2019; Riley *et al.*, 2021) and effectively raise awareness and change perceptions of ambient air quality (Xu, Taylor and Tien, 2022).

An individual's perception of an issue (i.e., their perception of the threat posed, their perception of the severity of the threat, and their perception of vulnerability to the threat) is a significant factor for behaviour change (Rogers, 1983), particularly since perceptions can be more influential to inform behaviours than objective data (Calvillo and Garnett, 2019). Therefore, changing perceptions is a critical first step for changing behaviours. Behaviour change is a complex and multistage process and it has been argued that providing relevant air quality data and information is an important first stage to inform and influence perceptions of the threat (McCarron *et al.*, 2022). This exploratory study has demonstrated the ability of the 'expanded approach', using more locally relevant air quality data whilst simultaneously increasing public participation, to alter individual's perceptions about the sources of local air pollution as discussed in the preceding paragraph. However, this failed to engage workshop participants in exploring behaviour changes to improve local air quality and ultimately bridge the motivation-behaviour gap. The discovery of domestic fuel burning being a significant contributor to local $PM_{2.5,}$ generated discussions around the limited choice people in rural locations have for heating their homes and suggested that burning solid fuels is considered a binary behaviour; you either do burn solid fuels or you don't. However, this ignores the small step changes that people can make to reduce the air quality impacts of solid fuel burning. For example, DEFRA's 'Burn Better, Breathe Better' campaign (DEFRA, 2023) suggests actions such as servicing stoves annually, ensuring wood is properly seasoned and clearing ash frequently as small changes to reduce the negative impact on air quality. Based upon these findings, these messages are not being received. Domestic burning is an interesting issue in itself. Though in rural locations there is a greater reliance on solid fuels as energy sources, more recently there has been a focus, for example, on the use of woodstoves in more urban areas where they are not relied upon as a heat source but rather because of their 'cosy' aesthetic and misconceptions of being 'environmentally friendly' and a cheaper source of heat (Heydon and Chakraborty, 2022). Such misconceptions can work against interventions to improve air quality (Boso, Ariztía and Fonseca, 2017; Boso *et al.*, 2018) and thus need to be addressed for effectively supporting behaviour change. This is an area requiring further research.

The presentation of air quality data can play a significant role in influencing user perceptions (Heydon and Chakraborty, 2022). Using the 'think-aloud' method we compared people's experiences of using our digital Stirlingshire resource with their experiences of other publicly available alternatives (i.e., the Air Quality in Scotland website). Participants' critiques of the publicly available air quality resources included its inaccessibility and limited understandability. In particular, this related to use of index values (unitless values typically ranging from one to ten, representing the best to worst air quality, respectively), bandings (i.e., describing air pollution as 'low', 'moderate', 'high', 'very high') and colour-scales (Bickerstaff and Walker, 2001; Shooter and Brimblecombe, 2009; Smallbone, 2012; Ramírez *et al.*, 2019). Additional criticisms included the (lack of) local relevance and representativeness of data via the traditional platforms (Yatkin *et al.*, 2020). In contrast, the digital Stirlingshire resource was regarded as a more "friendly" platform, with more relevant data, and requiring less effort to comprehend similarly complex information. Additionally, the Stirlingshire resource was observed to be more interpretable than the other available resources and seemed to encourage participants to understand and interpret the data, rather than just describing it. The visualisation of air quality data on public facing interfaces has a vital role to play in the intuitiveness and informativeness of the data, with unintuitive or difficult to use interfaces discouraging public engagement with the data (Feenstra *et al.*, 2020). Moreover, Heydon and Chakraborty (2022) report that when presented with difficult to interpret data (i.e., numerical data), people are more likely to rely upon their preconceptions (or misconceptions as described above) which may lead to individuals drawing inaccurate conclusions about air quality. Other lower cost sensor online platforms have tended to present data as tabular summaries, plotted timeseries or concentrations maps, as examples (e.g., AirSensor (Feenstra *et al.*, 2020)), to provide the public with a better understanding of the fundamentals of air quality and their local pollution levels (Sandhaus, Kaufmann and Ramirez-Andreotta, 2019). However, we found that participants indicated a preference for the textual descriptions or ‘stories’ over graphed summaries, and these were regarded as a key feature of the Stirlingshire resource, distinguishing it from the Air Quality in Scotland website. In the climate change context, presenting narratives (i.e., stories) instead of data and information has shown to play a significant role in shaping climate action (Chapman, Lickel and Markowitz, 2017; Fløttum and Gjerstad, 2017) since these can help people make better sense of events and phenomena (Van Der Leeuw, 2020) and guide action (Fløttum and Gjerstad, 2017). For air quality related behaviour change therefore, drawing on this and exploring more effective ways of presenting air quality data that are accessible, regardless of literacy, is needed.

Regardless of how air quality data are presented, the public need to be motivated to access and engage with it (Shaw and Hargittai, 2018). As with the publicly available resources, the Stirlingshire resource demonstrated limited potential to be able to ‘pull’ people in, despite containing more local, relatable and understandable data. Participants reflected on the need to ‘push’ the data, for example via social media or email alerts, however such alerts have demonstrated little effectiveness for behaviour change in the past (e.g., D’Antoni et al., 2017). Trialling the efficacy of this with more relevant and localised data is recommended. Moreover, participants reflected on the resource being useful as a validation tool, for example to see how their activities had impacted local air quality or whether local air quality had been responsible for how they were feeling, rather than as intended as a decision informing or behaviour change support tool. This supports the findings of McCarron *et al*., (2024b), who, in an interview study with people with asthma, similarly found that people engage with air quality data to validate their previous experiences. This suggests that more research is needed into how to encourage the proactive use of air quality data and information across the general population. In particular, ‘pushing’ air quality data and information via online resources, which may be more ‘hidden’ from less interested, motivated or digitally connected individuals (Schulte and Hudson, 2023) needs further investigation.

6.5 Limitations

This exploratory study set out to test a novel ‘expanded approach’ to engage rural communities with local air quality data and explore the presentation and communication of these data. Throughout the data collection process we critically reflected on our approach. This enabled us to adapt on the go, but also provides learning for future teams looking to undertake similar work.

Though we do not have exact numbers of participants who attended the workshops, based on the number of sticky note responses, it is clear that only a small number of people engaged with the workshop activities (though this does underestimate turnout as people who attended together would often share sticky notes). The villages we targeted were small, for example, Fintry, the smallest of our study villages, has a population of approximately 700 and Doune, with the largest population of our villages, has a population of approximately 2,000, so smaller turnout numbers were expected. However, offering a wider range of engagement possibilities, such as hosting activities on an online platform or perhaps a longer-term (e.g., one week) stall set up within the community (e.g., in a town hall, post office, local store) could remove some of the barriers to participation such as a lack of time and lack of confidence to participate (Cinderby, 2010).

Workshop three explored potential behaviour changes to improve local air quality but failed to encourage participation with a total of three sticky notes produced for the activity across the five villages. Upon reflection, the way that this activity was posed “what can be done and who can do it” was perhaps too direct and open-ended. In future to encourage greater participation with this activity, we would frame this differently, (e.g., “what behaviours could you *alter* to improve local air quality?”).

Finally, the development of the digital Stirlingshire resource itself was resource intensive, requiring researcher time to create the resource, pull the required air quality data from the sensors to upload to the site (also meaning that data were not real-time), and synthesise and upload workshop two inputs, which also limits its use beyond the scope of this study. Automating the data upload process and online participation would ease the resource burden and create a more robust end product.

6.6 Conclusions and recommendations for future work

This exploratory study aimed to test and apply the ‘expanded approach’ to engage rural communities with air quality data and information and subsequently explore how best to present such data to promote engagement.

Across twelve workshops in five rural villages in Stirlingshire, Scotland, we demonstrated that community-based events effectively engage locals in air quality discussions, particularly when facilitated by individuals with local expertise and when hosted in conjunction with other community events. While workshops serve as valuable tools for interactive, open and participatory engagement, they should be just one element in a wide-ranging toolkit for conducting public engagement work around air quality.

Our findings highlight the expanded approach's ability to engage communities and alter perceptions of local air quality over the typical approach, emphasising the importance of locally relevant data feedback for increased engagement. This suggests that, as an initial step, increasing data relevance could help lead to greater participation and engagement. While more local data were regarded as most relevant, considering where people spend most of their time (i.e., indoor environments), carrying out such an approach as detailed in this paper but with an indoor emphasis would be valuable. Increasing the localisation and relevance of air quality data (since the advent of lower cost sensors) is the easier element. Encouraging active and interactive engagement of the general public, on the other hand, is much more nuanced and challenging, requiring more research.

For the expanded approach to effectively instigate behaviour change, there is a need to empower the public, for example by generating greater awareness regarding the variety of behaviours that can be (slightly) modified to improve air quality. Given that there is no safe level of exposure to air pollution, even small, incremental behavioural changes can play a crucial role in reducing exposure and are vital for improved public health.

Chapter 7 | General discussion

The aim of this thesis was to co-develop strategies to promote awareness of air pollution and support exposure-minimising behaviour changes to reduce exposure to fine particulate matter ($PM_{2.5}$).

To fulfil this aim, this study aimed to answer four research questions (detailed in chapter one) which have been addressed in turn in each of the data chapters (Table 7.1). In this chapter, the original contributions of this work are outlined, findings across the chapters are synthesised, implications and practical applications are explored, the limitations of this study are addressed, and opportunities for future research outlined.

7.1 Key contributions

This thesis has made a series of original contributions. Chapter three explored how air pollution exposure impacts the lived experiences of people with asthma and influences management of the condition. Chapter four highlighted the usefulness of high-resolution data in health exposure assessment, and chapter five demonstrated the effectiveness of pairing data feedback with a health behaviour change programme for $PM_{2.5}$ exposure reduction and self-reported asthma-related health improvement. Additionally, a theoretical exploration of behaviour changes related to accessing air quality data and information was conducted (chapter two) and tested for two case studies (chapters five (people with asthma in Scotland case study) and six (Scottish rural communities case study)). Collectively, these contributions have deepened our understanding of the factors that influence air pollution exposure-minimising behaviour changes.

Table 7.1. Research question addressed in each data chapter.

Research Question	Case study	Chapter in which research question was addressed
What are the lived experiences of air pollution for people living with asthma in Scotland?	People with asthma in Scotland	Chapter 3
What is the level of exposure to $PM_{2.5}$ of people with asthma in Scotland and does this influence the short-term precipitation of asthma symptoms?	People with asthma in Scotland	Chapter 4

Can co-developed interventions reduce $PM_{2.5}$ exposures for people with asthma in Scotland?	People with asthma in Scotland	Chapter 5
How do we increase community engagement with air quality data and mobilise air quality conscious communities?	Scottish rural communities	Chapter 6

7.2 Discussion synthesis

7.2.1 Adopting the ‘expanded approach’ for engagement and behaviour change

The ‘expanded approach’ to engage the public with air quality data and information for health behaviour change (McCarron *et al.*, 2022 (chapter two)) centres around two key components: increased data relevance (i.e., the localisation of data) and increased public involvement. Individually, neither component is unique or novel. For example, several studies report on the application of lower cost air quality sensors for personal exposure monitoring (e.g., Steinle *et al.*, 2015), microenvironment monitoring (e.g., Shen *et al.*, 2021), ambulatory monitoring (e.g., Padilla *et al.*, 2022) and to build networks of sensors to monitor ambient air quality (e.g., Peters *et al.*, 2022), with their ability to provide data for areas previously unfeasible recognised as a valuable advantage (Morawska *et al.*, 2018). Similarly, increasing public participation with air quality data and information is itself not particularly novel, with DEFRA recognising its value and promoting the inclusion of experiential knowledge and engagement with communities to tackle air quality issues (DEFRA, 2017a), and several studies having done so (e.g., Gabrys, Pritchard and Barratt, 2016; Rickenbacker, Brown and Bilec, 2019). The originality of the ’expanded approach’ is the theoretical establishment of the need for simultaneously increasing representativeness and engagement to bridge the motivation-behaviour gap (i.e., the alignment of actions with intentions) for behaviour change, based on health behaviour theories.

Applying and testing the 'expanded approach' to bridge the motivation-behaviour gap in two distinct case studies (people with asthma and rural communities) yielded different outcomes for behaviour change and behavioural intention. It cannot universally be asserted that moving to an expanded approach, with increased involvement and data relevance, consistently supports exposure-minimising behaviour change in all cases.

In the individual-level asthma case study (chapter five), the application of the 'expanded approach' demonstrated that personalised exposure data and self-mobilisation effectively promoted behaviour change toward exposure reduction. In contrast, at the community-level in the Stirlingshire case study (chapter six), the use of locally relevant data and interactive participation did not result in exposure-minimising behavioural intention. However, it did alter community members' perceptions of local sources of air pollution, a crucial step for intervention acceptance and subsequent behaviour change (Heydon and Chakraborty, 2022).

As discussed in chapter five, personalised exposure data feedback allowed participants to clearly identify the influence of their individual activities and microenvironments on the air pollution they were exposed to, enabling targeted behaviour changes. Conversely, in chapter six, though it was found that more locally relevant air quality data feedback was more engaging than the more typical spatially sparse air quality data collected for regulatory purposes, community members felt they could not engage in activities focusing on emission or exposure-reducing behaviour changes. Despite data being more locally relevant, data were collected in outdoor environments and represented collective societal emissions (e.g., from domestic fuel burning) which are less easily influenced by an individual's actions (Air Quality Expert Group, 2022). This suggests that air quality data need to be relevant at the individual-level for effective behaviour change (Figure 7.1).

The typology of participation (Pretty, 1995) also differed between the two case studies. In the Stirlingshire communities project (chapter six), *interactive* participation involved workshop participants co-developing the monitoring campaign and jointly analysing the data. While workshops were beneficial for engagement, they fell short on instigating behaviour change since air quality-related behaviours were generally regarded by participants in binary terms (i.e., you either do burn solid fuels or you don't). An interesting comparison can be made with the language of the UK's Daily Air Quality Index (DAQI), in which the recommended actions and advice primarily focus on avoidance behaviours. This frames activities linked with increased air pollution exposure as behaviours that need to be stopped or avoided when air quality is poor – again, binary options. Participants felt that their only option was to stop or avoid solid fuel burning, which was not regarded as feasible and thus did not empower change.

Conversely, personal interventions (chapter five) applied a *self-mobilisation* approach (Pretty, 1995), empowering individuals to use their initiative and retain control over decisions but with support if required. This approach encouraged a wider range of positive behaviour changes, such as *increasing* ventilation or *changing* cooking methods.

7.2.1.1 Recommendations for future research

Generally speaking, the Scottish public are aware of and engaged with air quality issues (Barnes *et al.*, 2020), and as demonstrated in this study, this can be further enhanced by applying the ‘expanded approach’, simultaneously increasing the relevance of air quality data provided and adopting more participatory methods of engagement. Individual behaviour change, however, is more challenging to target - a finding supported by the recent Scottish Government report on public engagement with air quality (Scottish Government, 2023) – and it has been postulated why this may be the case with specific reference to the expanded approach. Research to better understand this and examining a range of methods within the expanded approach, evaluating different types of participation strategies and data feedback for engagement and behaviours change is required, with consideration for variations in local geographical contexts and preferences. Additionally, testing this in various contexts (e.g., with deprived communities, expectant mothers, urban communities) would enrich understanding.

Furthermore, there is a need for research to explore the motivations driving behaviour change. The two populations studied within this research are likely to have different levels of willingness to modify their behaviours to minimise their personal exposures to air pollution. Individuals with asthma are more likely to possess intrinsic motivation driven by their health protection as a 'vulnerable' group compared with the participants of the rural communities case study (more representative in terms of population health). By understanding motivation for behaviour change, messages and advice can be developed to effectively motivate behaviour change across diverse population sub-groups.

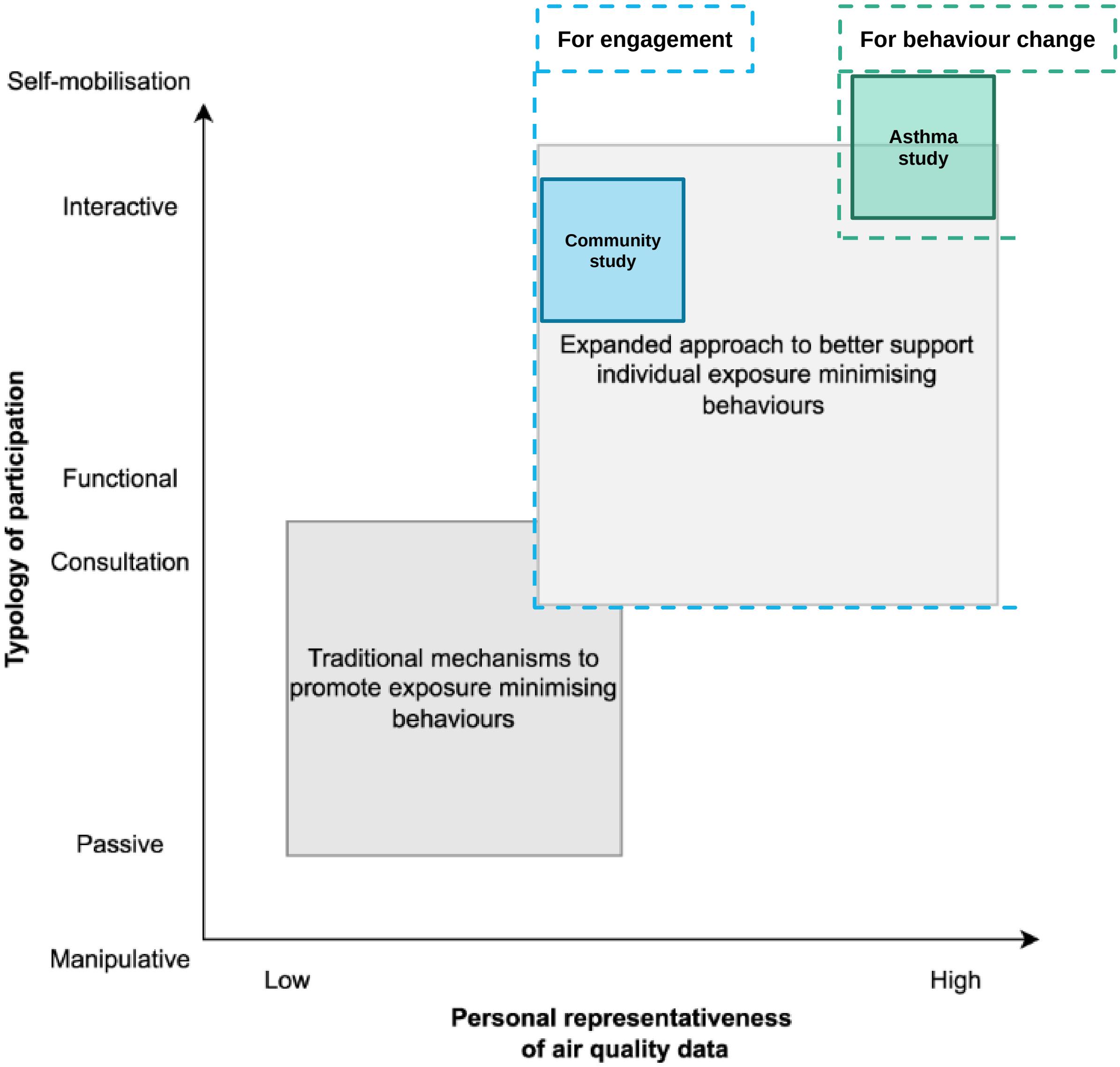

Figure 7.1. Two case studies were tested within the 'expanded approach'. Asthma and Air Pollution: Scotland Study (Asthma study) involved personally relevant data and self-mobilisation at the individual-level (Pretty, 1995), and conducted with people likely to be more intrinsically motivated (i.e., by their own health) to alter their behaviours to reduce their personal exposures. Mobilising Air Quality Conscious Communities in Stirlingshire (Community study) involved locally relevant data and interactive participation at the community-scale (Pretty, 1995). The expanded approach works for engagement (blue dashed line), but for behaviour change requires a more focused approach (green dashed line). It should be noted that the asthma study's measured outcome was behaviour change, while the community study's measured outcome was behavioural intention. Adapted from McCarron et al. (2022).

7.2.2 Control is the crucial construct for behaviour change

Empirical findings in this thesis, collectively, reinforce a key finding initially identified in chapter three: the critical role of (perceived behavioural) control on exposure-minimising behaviour change. With reference to the Theory of Planned Behaviour (Ajzen, 1991), the enabling and limiting constructs contributing to behaviour change intention and subsequent behaviour change were explored, finding the constructs of attitude and perceived behavioural control to be most limiting, supporting previous literature (e.g., Sun, Kahn and Zheng, 2017; Tomsho *et al.*, 2022).

Further bolstering the key role of control for behaviour change and exploring this beyond self-reported behaviour change explored in chapter three, the significance of control in the development of behaviour change interventions was demonstrated in chapter five, with all participants developing interventions based within the home microenvironment.

While it is not possible to ascertain the motivation and reasoning for developing interventions within the home microenvironment, two potential reasons for this are offered. Firstly, within chapter three, the theme “the home is a safe space” was developed to describe the need and ability to protect and preserve the air quality within the home. With reference to this, it is proposed that interventions were developed within the home because “the home is a <u>controllable</u> space”, whereby individuals can freely and effectively take measures to protect and preserve the quality of the air within their home. Furthermore, as illustrated in chapter six, a perceived lack of control can hinder the development of exposure and emissions reduction strategies, with a perceived lack of control over ambient air quality and collective societal emissions a barrier to behavioural intention.

The second potential reason proposed for participants developing interventions within their home is that air quality data feedback emphasised the fact that “the home is <u>not always</u> a safe space”. Though air quality within the home may be perceived to be very good (McCarron *et al.,* 2024b (chapter 3)), this is often not the case (Vardoulakis et al., 2020). As demonstrated in chapter four, some of the highest concentrations of fine particulate matter were found within the home microenvironment (McCarron *et al.*, 2023), supporting numerous studies which have found indoor air quality to be worse than outdoors (e.g., Vardoulakis *et al.*, 2020; González-Martín *et al.*, 2021; Stratigou *et al.*, 2022). Additionally, it was identified that personalised data feedback allowed individuals to specifically target peaks in their personal exposure (chapter five). The efficacy of air quality data feedback to support behaviour change has been demonstrated, for example, in the smoking cessation literature (e.g., Hughes *et al.*, 2018; Ratschen *et al.*, 2018; Semple *et al.*, 2018), and is itself a recognised behaviour change technique (Michie *et al.*, 2013). It has too been demonstrated in this study in relation to the development of exposure-minimising behavioural changes.

7.2.2.1 Recommendations for future research

As discussed throughout this thesis, lower cost sensors have a role to play in increasing data availability and relevance, thus data feedback as an intervention strategy is relatively straightforward to implement. However, to increase sense of control over air quality and perceived behavioural control over actions to reduce exposure to air pollution is much more challenging, with air pollution often thought of as a "distant" and "impersonal" problem (van den Elshout, 2007; McCarron *et al.*, 2022). Investigating how to increase sense of control with regards to air pollution is needed to promote individual-level behaviour change more effectively. Initially, an in-depth exploration of perceptions of air quality specifically within the home environment (as a controllable microenvironment) may be beneficial to better understand the psychological, social, and contextual factors influencing feelings of control in relation to air quality. Findings from this could be used to enhance the effectiveness of communicated advice aimed at encouraging behaviour change.

7.2.3 Targeting indoor microenvironments for exposure-minimising behaviour changes requires changing perceptions

Considering that outdoor air quality is more heavily influenced by collective societal emissions, it can be challenging to directly impact it through individual-level behaviour changes (Air Quality Expert Group, 2022). Further, as people typically spend the majority of their time in indoor microenvironments (Klepeis *et al.*, 2001; McCarron *et al.*, 2023 (chapter four)), and these indoor spaces are often more polluted than outdoor microenvironments (Vardoulakis *et al.*, 2020; McCarron *et al.*, 2023 (chapter four)), coupled with the observation that perceived behavioural control is higher indoors than outdoors (McCarron *et al.,* 2024b (chapter three)), it is suggested that targeting exposure-minimising behaviour changes in indoor microenvironments is more feasible and potentially impactful than in outdoor microenvironments.

However, the successful implementation of, and adherence to, behaviour change interventions in indoor settings depends on the extent to which an individual perceives indoor air quality to be an issue (Kim, Senick and Mainelis, 2019). There is a common misconception that outdoor environments are more polluted than indoor environments (Hofflinger, 2019; Kim, Senick and Mainelis, 2019), which was also a collective finding of this body of work. In chapter three, it was found that the indoor environment was regarded as a “safe space”, with air pollution being something believed to exist outdoors, and which was inflicted upon the home and the individual from the outdoor environment. Similarly, in chapter six, it was found that, prior to receiving data feedback, emissions from traffic and transport (as ‘classic’ outdoor sources) were perceived to be the main contributor to poor air quality across the Stirlingshire villages. Hence, a necessary step in promoting indoor exposure-minimising behaviour change is to modify these perceptions (McCarron *et al.*, 2022 (chapter two)).

A significant finding of this body of work is the ability of data feedback to reshape perceptions. For example, the efficacy of data feedback in reshaping perceptions was evident in chapter six, where, following data feedback, community members' opinions shifted from traffic-related emissions being the major air quality problem to identifying domestic burning as the main concern in most cases, and allowing them to more accurately appraise the threat posed (McCarron et al. 2022). Since misconceptions can work against the effective implementation of air quality-related policies (Heydon and Chakraborty, 2022), altering public perception of air quality issues is required.

Policy plays a complementary role alongside behaviour change initiatives in addressing indoor air quality issues. While enforcing concentration standards or regulations in indoor environments presents challenges, policy interventions can assist individuals in making better-informed decisions. For instance, the implementation of warning labels on wood burning logs and cleaning products, akin to those found on cigarette packets, is just one example of a policy approach aimed at facilitating individual behaviour change. Future research should explore the effectiveness of such policy measures in informing behaviour change for the improvement of indoor air quality.

7.2.3.1 Recommendations for future research

While the expanded approach as a bottom-up strategy for altering perceptions of air quality issues has been demonstrated, it can be argued that these perceptions have first been shaped by external and strategic influences, be it anti-idling campaigns, the introduction of low emissions zones, or emphasis on the outdoor environment within the DAQI, signalling that air pollution is generated and exists outdoors. Recent and pending legislation, such as the Clean Air (Human Rights) Bill (Ella's Law)[2] and the Social Housing (Regulation) Act (Awaab's Law)[3], both of which (either fully or partially) acknowledge the importance of indoor air quality, could act to increase awareness of indoor air quality. Research investigating the role that such legislation plays in altering social norms around indoor air quality could prove insightful. For example, the introduction of legislation aimed at smoking cessation in public and semi-public spaces in Scotland has altered social norms and denormalised smoking behaviours (Brown, Moodie and Hastings, 2009; Ritchie, Amos and Martin, 2010). A similar shift for indoor air quality more generally is now required and legislating indoor air quality in public spaces could be one such way, however research into the feasibility of implementation and acceptability of the public is needed.

7.2.4 Awareness raising and promoting exposure-minimising behaviour change is a justice issue

Environmental injustice, whereby ethnic minorities, indigenous communities and low-income communities face a higher burden of environmental pollution, is well established (Mohai, Pellow and Roberts, 2009). Air pollution is a known environmental injustice (Mitchell and Dorling, 2003; Barnes, Chatterton and Longhurst, 2019) since it disproportionately affects the most marginalised and vulnerable communities, leading to inequitable environmental and health outcomes (Cook, Argenio and Lovinsky-Desir, 2021; Mathiarasan and Hüls, 2021). The most socioeconomically deprived communities frequently live in areas with poorer air quality due to their closer proximity to sources, such as traffic and industry (Ferguson *et al.*, 2023). In turn, this this can exacerbate existing health disparities with rates of respiratory illness and cardiovascular diseases (known to be onset/aggravated by air pollution exposure), higher in more disadvantaged areas (Wang *et al.*, 2023). Coupled with more limited access to/of healthcare services, this exacerbates existing socioeconomic inequalities further.

A significant factor contributing to environmental and health injustices related to air pollution is economic inequality (European Environment Agency, 2023). Individuals or communities with lower income levels often lack the financial means to relocate away from areas with poorer air quality; to introduce exposure-minimising mitigation

[2] https://bills.parliament.uk/bills/3161
[3] https://bills.parliament.uk/bills/3177

strategies (e.g., purchasing air filters); or the ability to implement advised behaviour changes (e.g., unable to reduce physical exertion outdoors if their only option is to walk to work). This emphasises a justice issue related to managing and reducing personal exposures to air pollution among disadvantaged and vulnerable populations.

In this regard, this body of work exposes this exposure management justice issue. Throughout this thesis we have advocated for (chapters four, five and six) and demonstrated (chapter five) the use of lower costs air quality sensors to raise awareness of personal/local exposure to air pollution and for the ability of these to help shape individual- and community-level behaviour change. However, this overlooks a critical aspect – the financial accessibility of lower cost sensors. While research institutions and government agencies may perceive such air quality sensors as 'lower cost' - amounting to hundreds of pounds instead of tens of thousands - this remains a substantial barrier for economically deprived individuals. As such, ‘lower cost’ air quality sensors remain inaccessible, leaving the most vulnerable uninformed and unaware of their personal exposures, and unable to make informed decisions, potentially exacerbating socioeconomic, environmental and health disparities further. Even with access to sensors, self-management of health conditions (as proposed in chapter five) has been found to be challenging for people experiencing socioeconomic deprivation due, in part, to a lack of financial resource (e.g., purchasing an air purifier), but additionally due to lower levels of health literacy (i.e., less able to understand, appraise, and apply health information to make health-related decisions (Sørensen *et al.*, 2012)) (Woodward *et al.*, 2023), compounding these injustices. While ultimately the roots of environmental injustice lie in systematic decision-making (i.e., transport planning and land use) (Docherty and Mackie, 2010; Barnes, Chatterton and Longhurst, 2019), the promotion of lower cost sensors as a management strategy could exacerbate these further.

Further, this work has highlighted the inaccessibility of participation. Within the asthma study (chapters three to five), we failed to recruit participants from Scottish Index of Multiple Deprivation (SIMD) deciles one or two (representing the most deprived areas). Similarly, the inaccessibility of attending workshops was directly addressed in the Stirlingshire project (chapter six), with participants recognising that event attendance could be limited owing to related factors. Participation and citizen engagement has been found to be fundamental in creating more resilient individuals and communities (Mahajan, Hausladen, *et al.*, 2022), that is, individuals and communities who are able to respond, adapt and cope with threats and hazards associated with, amongst other things, environmental issues such as air pollution (Cinderby *et al.*, 2016). Moreover, participation in research can assist the transfer of knowledge, foster a sense of empowerment and control by building individual self-esteem and capability (Titterton and Smart, 2008), and motivate actions (Hammond *et al.*, 2018; Cinderby *et al.*, 2021). Hence participation is a fundamental component of the ‘expanded approach’ (McCarron *et al.*, 2022 (chapter two)). Yet socioeconomic exclusion in health research is frequent (e.g., Clark *et al.*, 2019; Williams *et al.*, 2021).

7.2.4.1 Recommendations for future research

Engaging individuals in deprived communities on the issue of air quality and promoting behaviour change is particularly challenging owing to multiple significant barriers, such as a lack of time to engage and competing priorities (Barnes *et al.*, 2020). While the expanded approach to enhance engagement and behaviour change is advocated, it is acknowledged that a one-size-fits-all approach is insufficient. Understanding the specific barriers of the expanded approach preventing inclusive participation and exploring ways to reduce these barriers is needed. This involves understanding the specific needs of the most vulnerable and deprived communities, tailoring the expanded approach to overcome participation obstacles, and investigating methods to encourage and support engagement and behaviour change. More generally, more research is required to increase participation of the most deprived communities in health research (NHS Health Research Authority, 2023).

There is a need to explore strategies to ensure equitable access to relevant air quality data and resources. This may involve investigating the feasibility and acceptability of subsidies to make lower cost sensors accessible to economically deprived communities or implementing personal exposure monitoring through health and care services, as examples. Moreover, research to investigate alternative means of air quality data communication, ensuring that data are accessible and interpretable by all, is needed. Addressing these issues could contribute to mitigating the outlined exposure management injustices.

7.3 Implications and practical applications

7.3.1 Implications for the Daily Air Quality Index

The last major update of the DAQI occurred in 2011 following a review by the Committee on the Medical Effects of Air Pollutants (COMEAP), prompted by advancements in air pollution regulation and in the presentation of air quality information (COMEAP, 2011). In the report, the 2011 proposals to update the air quality index were described as “a real advance in helping the public deal with the impact of polluted air” (COMEAP, 2011, pg. iii). However, given the evolving nature of the air pollution issue and the emergence of new evidence, this is again being reviewed to better the support the public in dealing exposure to air pollution (DEFRA, 2021).

A review of the UK’s air quality information systems, including the DAQI and other channels delivering air quality messages, is currently in progress and is expected to be reported imminently at the time of writing. The Steering Group reviewing the DAQI have several functions including to 1) provide a view of whether the existing systems of alerts and advice could be improved and 2) recommend approaches to providing information and advice that will most effectively reduce the harm caused by air pollution (DEFRA, 2021).

Based on the collective findings of this body of work, it is suggested that the alerts and advice as part of the DAQI could be more effectively communicated. It has been demonstrated why, from a theoretical standpoint, the current system does not work to induce individual behaviour change (McCarron *et al.*, 2022; chapter 2). Additionally, we have demonstrated alternative means and methods of communication that have proven effective for engagement and to support the behaviour change needed to reduce the harm caused by air pollution (chapter five). To this end, and based upon the finding of this thesis, the following recommendations are made:

1) The advice communicated as part of the DAQI needs to be reframed to increase perceived control and empower individuals to modify their behaviours. As an initial step, revising the language used, transitioning from negatively framed avoidance towards promoting positive behaviour change could be beneficial (Riley *et al.*, 2021). For instance, instead of suggesting a reduction in outdoor physical activity, the guidance could be reframed as 'consider taking less congested routes when outdoors today,' placing greater emphasis on the impact of nuanced and incremental behaviour changes.

2) At 'low' pollution levels (index values 1-3), the DAQI guidance suggests that everyone can enjoy their usual outdoor activities. However, this overlooks the indoor environment, where people typically spend the majority of their time (Klepeis *et al.*, 2001), and which can be more polluted (Vardoulakis *et al.*, 2020). Consequently, as discussed previously, this could be contributing to the misconception that indoor spaces are safe from air pollution. Greater emphasis on the indoor environment (even if falling short of specific advice since this is context dependent), would be beneficial to raise awareness of indoor air quality (e.g., 'Enjoy your usual outdoor activities. Be aware of activities indoors that may be negatively impacting indoor air quality'). Work is being done by charities (i.e., Global Action Plan and Asthma + Lung UK) to raise awareness of indoor air quality for example by promoting opening windows or using extractor fans while cooking, however this should be communicated at a more strategic level via the DAQI.

It should be noted that the air quality information used for the DAQI is also limited by the fact it is based on modelled data and specific index values (and the associated advice) are therefore representative of background modelled levels covering wide areas. However, given that air quality is spatially and temporally heterogeneous (He, Schäfer and Beck, 2022), index values based on modelled data may not be accurate for everywhere within the area they are reported for. This caused scepticism among participants in chapter six. As such, recommending specific behaviours to improve indoor air quality based on the ambient DAQI value (such as opening or closing windows) is not possible. This would require monitoring and modelling with greater spatial and temporal resolution and supplemented by indoor air quality data.

7.3.2 Implications for the Cleaner Air For Scotland strategy

The Cleaner Air For Scotland (CAFS) strategy is a Scottish Government initiative aimed at addressing air quality issues in Scotland and sets out the Government's mission for having "the best air quality in Europe" (Scottish Government, 2021, pg. 6). Currently in its second iteration, CAFS2 is structured around ten themes, aligning with recommendations from the review of the original CAFS strategy. Of particular relevance to this thesis is theme 5, Public Engagement and Behaviour Change. This theme was developed in recognition of the need for further research to better understand the knowledge and attitudes of the Scottish public regarding air pollution and their receptiveness to behaviour change (Scottish Government, 2021). Throughout this thesis, these aspects have been thoroughly explored.

Within theme 5, recommendations were outlined for future engagement on air quality issues and the development of a public engagement strategy on air quality in Scotland (Scottish Government, 2021, pg. 46). Building upon the insights gained from this thesis, additional recommendations for consideration within the next iteration of the CAFS strategy (expected in 2026) include:

- Work alongside members of the public/communities to interpret air quality data, recognising the value of different types of knowledge (i.e., scientific knowledge and experiential/local knowledge).
- Adopt a suite of participatory approaches (e.g., workshops, community stalls) to ensure diverse and inclusive participation, understanding that this requires a nuanced understanding of the specific barriers to engagement within the targeted community/group/population.
- Co-develop monitoring campaigns/networks with the public using lower cost sensors and based on locals' priorities for more personally relevant air quality data.
- Adopt an 'expanded approach' (McCarron *et al.*, 2022), simultaneously increasing air quality data relevance (and accessibility) and the participatory mechanisms employed to engage the public, noting that to encourage behaviour changes, a more targeted and individualised approach is required.
- Explore, with members of the public, a narrative approach to communicating air quality information and the potential value this can add.
- Integrate air quality messaging into health and care communications to emphasise it more effectively as a human health issue and the need for individual-level behaviour changes.

7.3.3 Application within health and care

Air pollution is a public health emergency (Holgate, 2022) and as such needs to be addressed as a public health issue. As discussed throughout this thesis, health and care providers can play a vital role in promoting and supporting exposure-minimising behaviour changes (Howard, 2023).

Health and care providers are equipped with resources (e.g., "All Our Health" by the Office for Health Improvement and Disparities) and training (e.g., "Clean Air

Knowledge Hub" by Global Action Plan) to facilitate discussions and actions aimed at mitigating the health impacts of air pollution exposure, however, these are not currently being delivered strategically (Omrani *et al.*, 2020). Additionally, while these resources promote conversations, there is a need for more practical measures to offer personalised and context-specific advice, with particular support for the most vulnerable groups, such as those with severe asthma or pregnant women. It is suggested that adopting an individualised strategy involving personal exposure monitoring, data feedback, and co-developed interventions (with efficacy demonstrated within this research) can enhance support in this regard.

As previously discussed, this approach could be implemented through health and care providers, including asthma nurses or General Practitioners. While a universal application would be inappropriate, directing such interventions toward patients with poorly controlled respiratory conditions who are unaware of their specific triggers could prove beneficial. As outlined in chapter five, further research is needed to explore this method (i.e., with a larger sample size and in different contexts), but also the feasibility of its application for rollout within the NHS.

7.4 Limitations

The limitations associated with each work package in this thesis have been presented within the relevant chapter. Here, the focus is on limitations that crosscut the study as a collective body of work.

Lower cost sensors have provided a low cost and portable solution to air quality monitoring, used for different applications within this study. While these have been shown to perform well compared with reference grade instruments (S. Park *et al.*, 2023), the quality of the data these can provide has previously been criticised (e.g., Castell *et al*. 2017; Giordano *et al*. 2021). To address some of these challenges, sensor validation and calibration was conducted to ensure data were as accurate and precise as possible to provide indicative air quality data. With reference to personal exposure monitoring, where sensors were used in a portable manner, moving across microenvironments will have meant that changes in temperature and relative humidity were possible across short time periods, and could have impacted air quality measurements. For example, water vapour condensing around a particle could lead to inaccurate measurements of particle size. This is a particular challenge faced by lower cost sensors, which lack the technology to overcome such issues by heating inlets, for example. The capabilities of the technology must be considered before they are used more widely for personal exposure monitoring, for example, as part of an intervention.

The ‘expanded approach’, the basis for and rationale behind the work undertaken within this thesis, is grounded in behavioural theory and based upon a theoretical exploration of the steps linking air quality data and information to exposure-minimising behaviour changes. Though grounded in behavioural psychology, behavioural theories are attempts to explain why humans act the way they do or why their behaviours change (Davis *et al.*, 2015). Health behaviour theories, such as Protection Motivation Theory (Rogers, 1983), the Health Action Process Approach (Schwarzer, 1992) and the Theory of Planned Behaviour (Ajzen, 1991), are well-established, and interventions based on such behavioural theories have been shown to be effective in changing health behaviours (Hagger and Weed, 2019). The ‘expanded approach’, breaking down the steps to exposure-minimising behaviour change, is reductionist in nature. While reductionism is regarded as a limitation by some (e.g., Ahn *et al.*, 2006; Mazzocchi, 2008), others argue that it can lead to new insights (Kandel, 2016; Hantula, 2018). In this case, it provides an insightful theoretical basis for this work.

Studying human behaviours is particularly challenging due to the numerous factors influencing behaviours that are neither easy to measure nor control (Sanbonmatsu, Cooley and Butner, 2021). In the context of the asthma study, where participants were recruited explicitly for research related to asthma and air pollution, and study arms were assigned in a non-blinded manner, the observed behaviours may not reflect the behaviour change that would have been observed outwith a research study setting. A particular challenge within behaviour change studies is deciphering whether observed behavioural changes are genuine or influenced by participant awareness of being observed (Landsberger, 1958). Key features of the personalised asthma intervention (therapist/researcher contact and exposure monitoring) will have made the participant explicitly aware that their behaviours were being studied. In contrast, there was no expectation or requirement that Stirlingshire community members had to make a behaviour change for the purpose of the research study. Therefore, making comparisons about the efficacy of the two interventions to promote behaviour change is not simple and straightforward. With that said, community members did not show behavioural intention, leading us to conclude that the community-level intervention would not have resulted in behavioural change. The complexity in deciphering genuine behaviour change could also have been reduced with sensor choice. Upon reflection, and in future studies, we would consider using a smaller and more portable device.

This choice would have made the device less conspicuous to participants and could potentially mitigate the Hawthorne effect, where participants may alter their behaviour due to the awareness of being monitored, rather than genuine behaviour change. In doing so, we would enhance the reliability and validity of our findings while minimising potential biases introduced by participant awareness of monitoring.

The two study populations are likely to have had different motivations for 1) taking part in the research study, and 2) changing their air quality-related behaviours. Both groups of participants took part voluntarily, suggesting prior motivation existed, with it likely that individuals who are more concerned about or directly affected by air pollution, more likely to volunteer. As such, participants perceptions, priorities and willingness to change their behaviours may not necessarily be representative of the general population. In addition, comparing between study populations, since people with asthma are more susceptible to the effects of air pollution and therefore may feel the impacts of pollution exposure more directly, it is likely that they will be more willing and more responsive to behaviour change interventions than the general population, motivated by their own health.

Finally, as addressed within the limitations of qualitative chapters (chapters four and five), in comparison to other countries, ambient air quality in Scotland is generally very good, which, as previously discussed, plays a role in personal exposure. In addition, the contrast in ambient air quality between Scotland and more polluted countries is likely to influence public perceptions and priorities regarding air pollution (Noël, Vanroelen and Gadeyne, 2021). Local environmental conditions play a crucial role in shaping individual perspectives, and these distinctions may impact the perceived importance of addressing air quality issues in Scotland. As such, the findings of this thesis are unlikely to be generalisable to broader contexts.

7.5 Conclusions

This thesis aimed to co-develop strategies to promote awareness of air pollution and support exposure-minimising behaviour changes to reduce exposure to fine particulate matter ($PM_{2.5}$). To achieve this goal and address the research questions posed, this thesis makes several contributions to the literature. This work provides a better understanding of how air pollution is experienced and how air quality-related behaviours are formed by ‘at-risk’ individuals with asthma. Additionally, by applying the ‘expanded approach’ (using a combination of personal exposure monitoring and personalised data feedback, underpinned by health behaviour theory, within a health behaviour programme), this strategy has demonstrated its efficacy not only in successfully promoting exposure-minimising behaviour change at the individual-level, but also in improving asthma-related health. Together, these findings can help inform a public health improvement programme aimed at reducing the health burden caused by air pollution exposure. This should next be applied and tested within a health and care setting.

Collectively, the findings of this thesis more broadly have demonstrated the ability of the ‘expanded approach’ to increase public engagement with air quality data and information by providing more personally relevant data and increasing the level of participation in the research process. Significantly, across two different case studies (people with asthma in Scotland and Scottish rural communities), this strategy was able to correct individuals’ misconceptions about air quality issues. However, the ‘expanded approach’ was unable to support behaviour change at the community-level in rural Stirlingshire. As highlighted throughout this thesis, exposure-minimising behaviour change is complex, dictated by internal factors such as perceived control and empowerment, and external factors such as access to and accessibility of air quality data.

As a whole, this body of work can inform future air quality public engagement strategies designed to encourage exposure-minimising behavioural change. Combined with more ambitious air quality policies and regulations, the development of such programmes can work to reduce the health burden caused by exposure to air pollution and improve public health, thereby contributing to the achievement of Sustainable Development Goal 3 and ensuring healthy lives and promoting wellbeing for all.

Chapter 8 | References

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Chapter 9 | Supplementary Material

Supplementary Material A – *Asthma and Air pollution: Scotland Study* interview topic guide

1) When I say the words ‘air pollution’ to you, what comes to mind and are you able to draw this for me?
   a) Can you describe what you’ve drawn to me?
   b) Why have you drawn it?

2) Have you noticed that air pollution can worsen your asthma or is this something you haven’t really noticed?

3) Are you aware of any potential connections between air pollution and asthma?

4) Are you able to remember any specific advice about how to manage your asthma relating to ait pollution?
   a) Where did the advice come from?
   b) How was it given to you?
   c) Do you follow this advice?
   d) Why/why not?

5) Is there anything you do that may not be ‘advice’ as such to limit your exposure to air pollution?

6) If you wanted to find out about air quality or air pollution, where would you get this information from?
   a) How do you know about this resource?
   b) Have you used it before?
   c) What for?

Supplementary Material B – Categories of behavioural action developed from participants' actions and standpoints in the context of the Theory of Planned Behaviour. This is discussed and expanded on further in the discussion.

Category	Description in relation to attitude and perceived behavioural control
Able	People within the able category access and use air quality information and/or have developed adaptive behaviours to minimise their exposure to air pollution. They demonstrate a more positive attitude ("I can") towards behaviour adaptions and (to a lesser extent) accessing air quality information. They also demonstrate greater perceived behavioural control ("I do"). They are not limited by any of the constructs and as such are able to take action to reduce their exposures.
Attempting	Attempting is characterised by people who try to engage with air quality information and/or try to adapt their behaviours to minimise their exposures but feel defeated. People within the attempting category intend to seek out information and/or act to reduce their exposures but barriers outwith their control prevent them from doing so. They are driven to intention by a positive attitude but are constrained by their perceived behavioural control and as such fail to successfully engage with information or act.
Conceding	The conceding group do not intend to engage with information or act to minimise their exposures. They are limited by their attitude ("nothing I can do") and demonstrate a lack of perceived behavioural control. As such they do not attempt to act.
Resisting	The resisting category do not act to engage with air quality information nor act to reduce their personal exposures. This is characterised by defiance. People in this category demonstrate a more negative attitude ("I don't need to") toward engaging with information and developing adaptive actions. They emanate a sense of perceived control over their (in)action.

Supplementary Material C – The Theory of Planned Behaviour (Ajzen 1991).

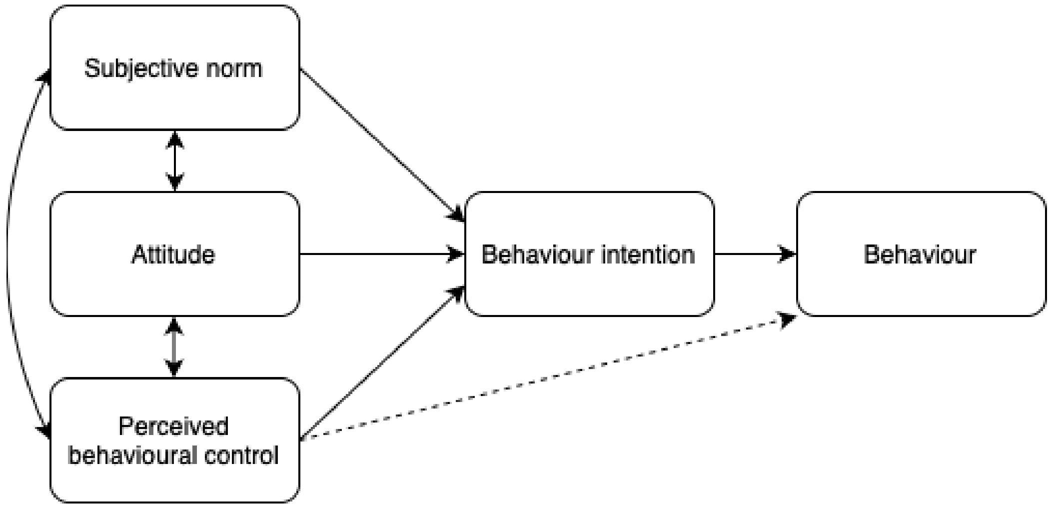
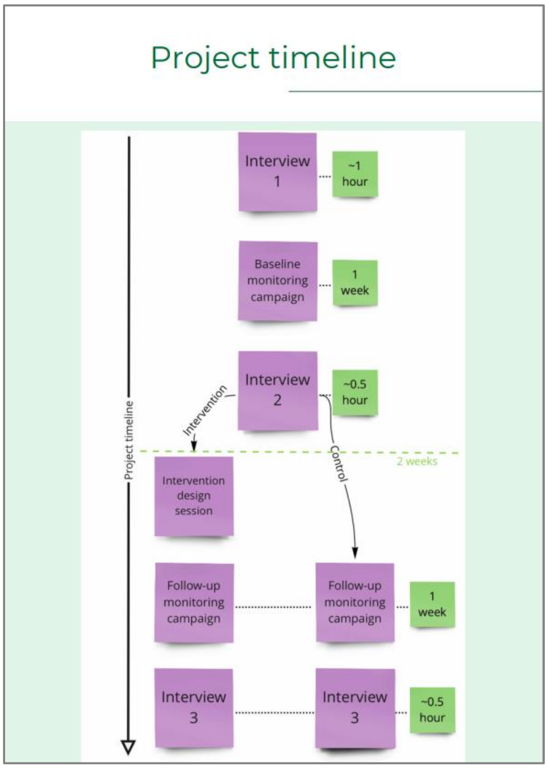


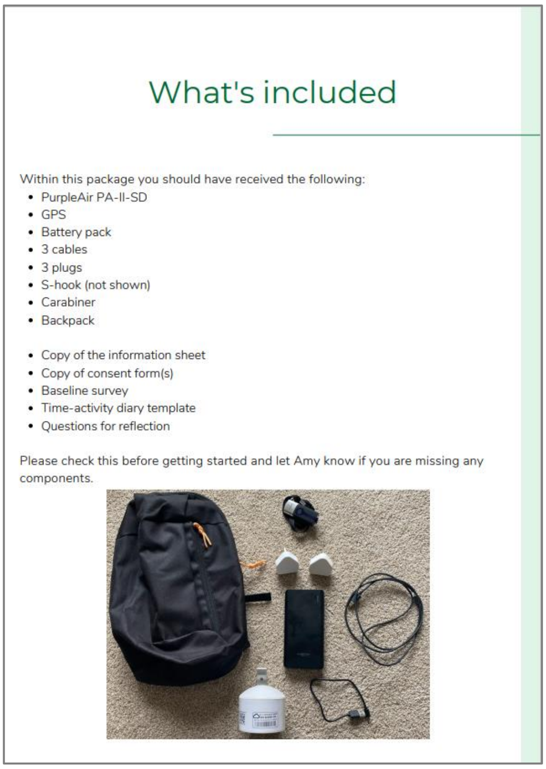
Figure S1. The Theory of Planned Behaviour (Ajzen 1991).

Supplementary Material D – Monitoring standardisation resources.

Switching on the PurpleAir: https://youtu.be/g0sojjJOH7E

Using the PurpleAir: https://youtu.be/WxGPi_8lCZU?si=7lFgpNQCZ6ooU_DJ





Getting started:
The PurpleAir continued…

Because the PurpleAir draws in air from its base, this needs to be exposed, so try and avoid sitting or placing the sensor in a way that obstructs this. Therefore, when moving around, we recommend hooking it to (**do not place inside**) the backpack or something it can hang off which leaves this unobstructed. You'll notice a strip of velcro on the backpack and on the PurpleAir- this is to ensure it doesn't move around too much and agitate fibres which could potentially cause spikes in your data. This also keeps the sensor close to breathing zone height (the area close to your nose and mouth) so it is most representative of the air you are breathing in. Because the quality of the air can vary in the vertical profile, it is important you keep the sensor as close to this height as possible (see figures below). When you are stationary in a room for a long period of time, you may wish to leave the sensor close by. In these circumstances, we ask that you keep this as close to you as reasonably possible, again at a height close to the same height as your breathing zone. This might be on a shelf or on the back of a chair if you are seated, for example. We ask that when sleeping, again, you keep this as close to you as reasonably possible, but at a minimum, in the same room as you are sleeping. It will likely be the case that you will have the PurpleAir connected to mains power overnight (see battery pack section). The closer this is to where you sleep, the better the data we collect. If you are seated on a train, bus or in a car etc. then you may wish to place the PurpleAir on the seat beside you, just remember to keep the base of the sensor unobstructed (the carabiner or S-hook should help with this)!

Getting started:
The battery pack

The battery pack allows you to use the PurpleAir as a mobile air quality monitor, allowing you to collect more representative data. The battery pack should last a couple of days from full charge, however this can vary depending on environmental factors, such as temperature. The battery pack has a power indication panel on the front, which consists of 4 blue lights. When the 4 LEDs are lit, there is between 75%-100% battery remaining, 3 lights indicate 50%-75%, 2 lights 25%-50% and a single light between 1% and 25%. You can check the battery life by pressing the button on the side. If there is no light illuminated, then the battery is completely discharged, and it needs to be connected to mains power.

To charge the battery pack, connect the micro-USB to the battery pack and the USB to mains power. We have provided you with USB plugs. Rather than let the battery pack completely drain, we recommend that you charge this overnight while the PurpleAir is connected to mains power to avoid the risk of losing data because of power loss.

To power the PurpleAir from the battery pack, simply connect the USB to the battery pack and micro-USB to the PurpleAir. This is the preferred power source when moving around (i.e., don't move from one socket to another when you are moving around your home) since we will lose data every time it is disconnected from power. The PurpleAir will power on as soon as it's connected to a power source. You can check it is on by looking for the red light within the unit (see image previous).

Getting started:
The GPS

The GPS is used to track your location while collecting air quality data. This allows us to look at the spatial variability of the PM2.5 you are exposed to. You'll find the on/off switch at the side of the device (the on position is closest to the solid dot). When it is in the 'on' position the blue light should be on (see picture over page). If the blue light is flashing slowly, then the GPS position is detected. A constant blue light indicates that the GPS position is not detected. The GPS will have been calibrated with GPS satellites before it has been sent to you, however, if you switch it on indoors, it is likely satellites will not be detected. Placing it on a windowsill or outdoors for a few minutes will calibrate it. You'll know it has found satellites when the light flashes slowly.

Remember to take the GPS with you (and turn it on) every time you leave your home, even if you are just nipping to the shop or doing the school run. There are certain times when you don't need to use the GPS, for example, if you're not going to be leaving your home. In such cases, your time-activity diary should capture enough detail to pair with your air quality data. If you are going to be remaining in one location for a longer period of time (i.e., more than 1 hour) then, again, your time-activity diary should provide sufficient detail and you can switch the GPS off; just remember to turn it back on again when you leave!!

Though it's not ideal if you forget to switch the GPS, don't worry if you forget on occasion. Just <u>make sure to note such issues</u>, for example, at the side of your time-activity diary and ensure your diary is as detailed as possible to pair with your air quality data.

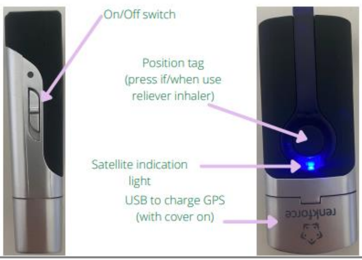
In addition to tracking your location, the GPS also allows us to monitor your asthma medication use so we can investigate whether there is a relationship between this and air quality. If you are using

Getting started:
The GPS continued…

the GPS to record your location and you need to use your reliever inhaler, then you should 'tag' the position using the GPS. All you need to do is press the centre button once and the time and location will be recorded. Remember to also note these occasions in your time-activity diary under the 'time administered' column! For this reason, we think it is easiest to wear the GPS using the lanyard provided. If this isn't appropriate, then keeping it in an accessible area on your bag or in a pocket should be fine, but try and tag the use of your inhaler as close as possible to the time you used it.

To switch off the GPS, slide the switch to the 'off' position. You'll know that it is off when no lights are illuminated.

The GPS should last up to 18 hours on full charge. As with the battery pack, we recommend that you charge this overnight to avoid the battery draining and losing important data. To charge the GPS, you just need to insert it into a USB plug socket. A computer/laptop should also do the trick. The indicator light will turn green when the battery is charging. The light will be red to indicate the battery is empty.



Getting started:
The time-activity diary

During the monitoring campaign, we ask you to keep a detailed record of your activities, locations, asthma-related symptoms and inhaler and/or medication use of the week. The reason we are interested in this information is so we can match this with your exposure data to better understand how the things that you do and places that you go influence your exposure. We have provided you with a template for this and have included a completed example in this pack.

The most useful time-activity diaries will be those that are most detailed. This means providing details of exact activities and, as close as possible, **exact** times of these activities. This includes, for example, considering who is in the room with you (and how what they are doing might influence the air quality); whether windows/doors are open in the room that you are in; what foods are you cooking, how you are cooking it and whether you are using fats/oils; if you travel by car then what mode of ventilation are you using, what is the fan speed and are there other passengers? Basically the more details you give us, the more accurate your exposure profile will be. We recommend that you complete your time-activity 'on the go' so you don't forget any potentially crucial bits of information, however, if this isn't possible, then taking a couple of minutes out every so often is another simple way of doing this. For ease, for example, if you are on the move, you can take voice notes or send text messages to yourself to make it easier to recall when you get around to completing your entries.

Getting started:
The baseline survey

The baseline survey is designed to gather contextual information that plays a role in your personal exposure. You only need to complete this once during the study and it should take around 10-15 minutes to complete. Sit down with a cup of tea/coffee and a biscuit (on us!) at some point during the first monitoring campaign to complete this.

Getting started:
The reflection diary

In this pack you'll also find 'questions for reflection'. These are a few short questions to find out about your experience in taking part in this study. We ask that you consider these questions near the end of the monitoring weeks and respond. You can complete this any way you like: write down your responses, take a voice note, take a video…it's up to you. I'll ask you to send me this document/file at the end of the monitoring campaign.

FAQs

? **Do I need to take the PurpleAir everywhere I go?**
Ideally, yes. We want to learn about the places that you go and things that you do and how these impact your exposure to PM2.5. If you strongly feel that there are times where using the monitoring equipment would be inappropriate then please make sure all equipment is switched off at this time and turn ot back on as soon as you can.

? **Can I use the monitoring equipment in the rain?**
Yes, but carefully. The PurpleAir is weatherproof and can be exposed to rain, however, you must ensure it remains the right way up (i.e., don't let rainwater into the sensors). The battery pack and GPS, however, are not waterproof, so you must ensure these remain covered in the backpack (or the GPS under your coat etc.).

? **What do I do with the monitoring equipment while I am using the bathroom?**
You don't need to take the sensor to the bathroom with you. Leave it outside the door (again, leaving the base unobstructed) and collect it when you're finished.

? **What do I do if the battery pack/GPS runs out of charge or I forget to switch something on?**
The best way to avoid running out of charge is to charge the devices overnight while the PurpleAir is connected to mains power, even if you think there is enough power to last another day. However, we understand that accidents can happen. If you discover that a device is out of power, please charge it at your earliest convenience and take a note of the disrupted time in your time-activity diary. If you realise you have forgotten to switch a device on, please turn it on as soon as possible. Again, note this in your time-activity diary. A detailed time-activity diary will minimise the disruption caused by the GPS running out of charge.

Contact details

If you have any issues at any time please contact Amy,
Email: amy.mccarron@stir.ac.uk
Phone/text/WhatsApp: 07825200048

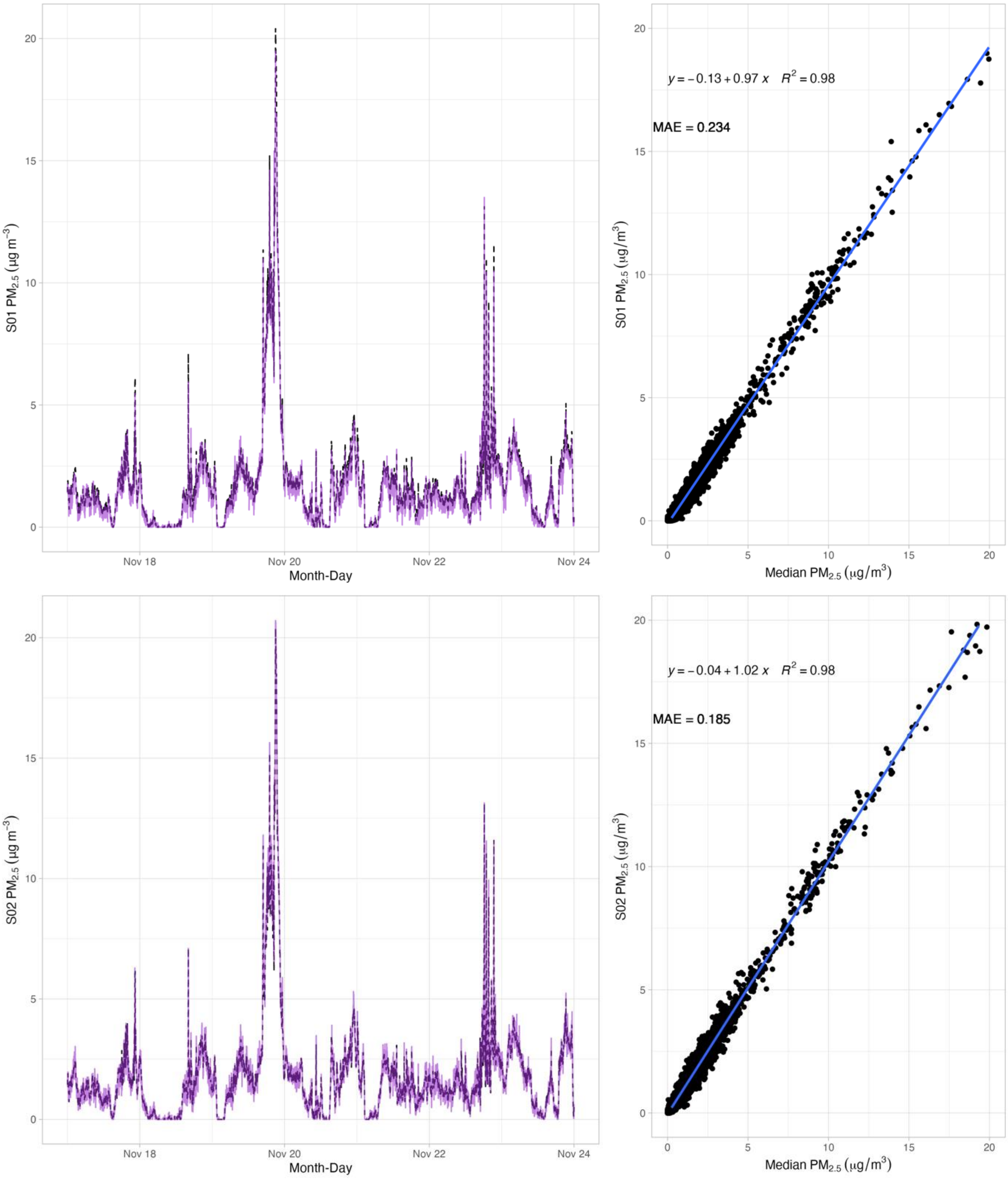
Should you have any issues and wish to speak to someone independent of this study you may email the Biological and Environmental Sciences office,
Email: sbes1@stir.ac.uk

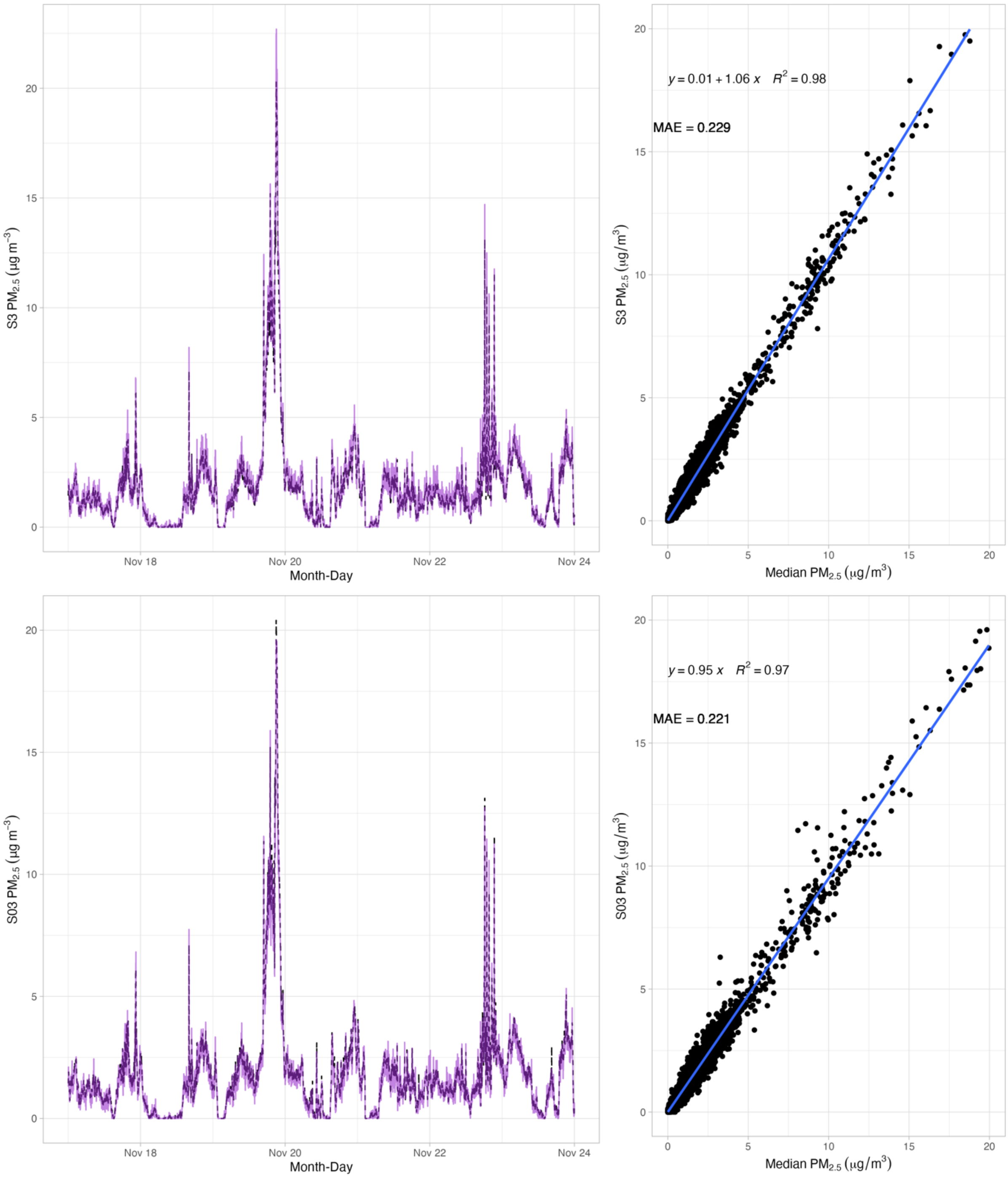
Supplementary Material E - Daily time-activity diary templates provided to participants in paper form.

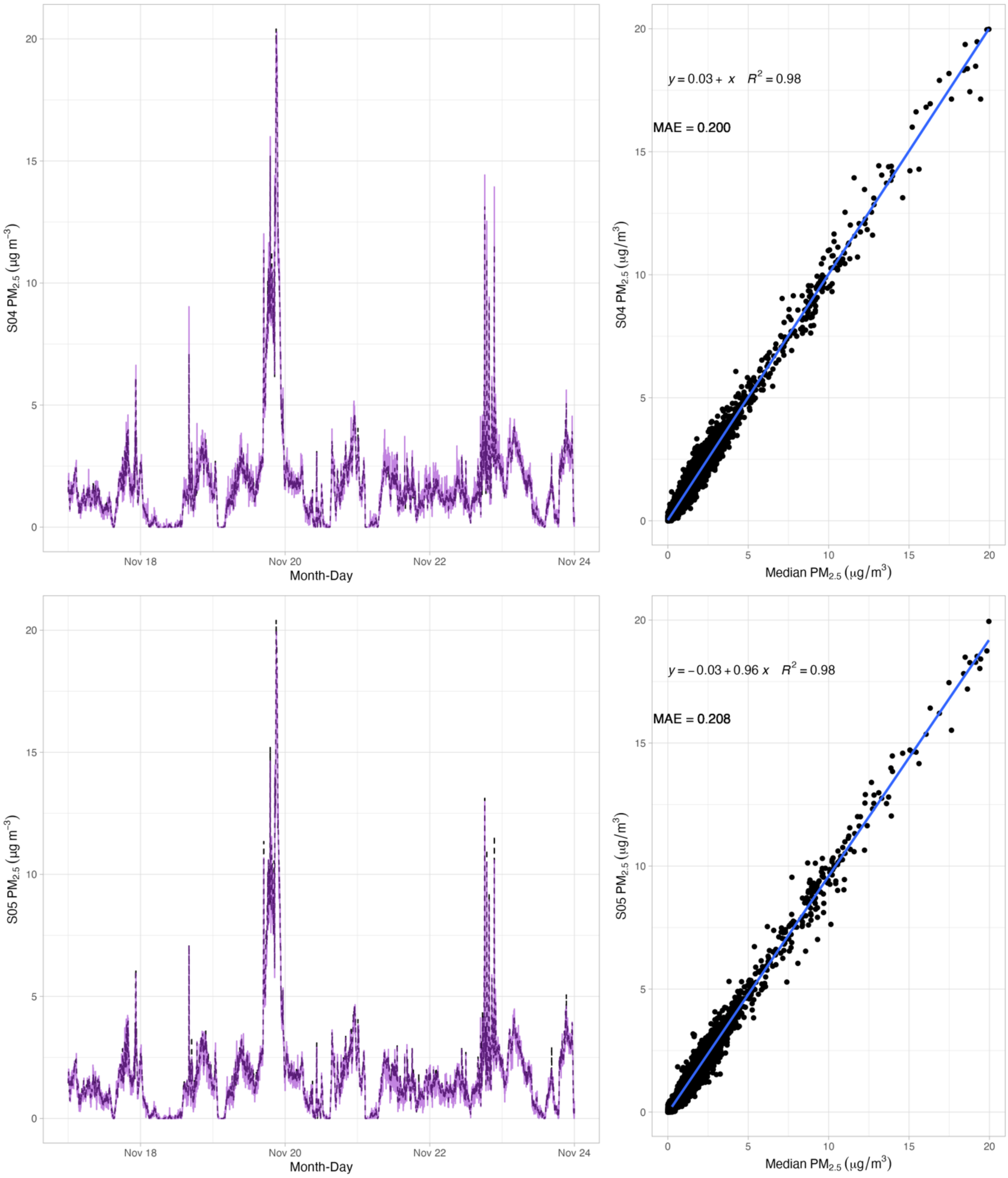
Today's date______________________________

	Time and description of activity	Microenvironment(s)		Asthma symptoms	Inhaler or asthma medication						Description of environment (including details of microenvironment)
					Preventer	Reliever/ nebuliser	Other medication	None	Time administered	If you used your inhaler or asthma medication, then why?	
05:00-06:00		Home ☐ Kitchen ☐ Living room ☐ Bedroom ☐ Bathroom ☐ Dining room ☐ Garden ☐ Other	Non-home ☐ Public building (e.g. café, shop) ☐ Work building ☐ Private residential building ☐ Transport (*what mode?)* -- ☐ Outdoor (public space) ☐ Other *(please note)* --								
06:00-07:00		Home ☐ Kitchen ☐ Living room ☐ Bedroom ☐ Bathroom ☐ Dining room ☐ Garden ☐ Other	Non-home ☐ Public building (e.g. café, shop) ☐ Work building ☐ Private residential building ☐ Transport (*what mode?)* -- ☐ Outdoor (public space) ☐ Other *(please note)* --								
07:00-08:00		Home ☐ Kitchen ☐ Living room ☐ Bedroom ☐ Bathroom ☐ Dining room ☐ Garden ☐ Other	Non-home ☐ Public building (e.g. café, shop) ☐ Work building ☐ Private residential building ☐ Transport (*what mode?)* -- ☐ Outdoor (public space) ☐ Other *(please note)* --								
08:00-09:00		Home ☐ Kitchen ☐ Living room ☐ Bedroom ☐ Bathroom ☐ Dining room ☐ Garden ☐ Other	Non-home ☐ Public building (e.g. café, shop) ☐ Work building ☐ Private residential building ☐ Transport (*what mode?)* -- ☐ Outdoor (public space) ☐ Other *(please note)* --								

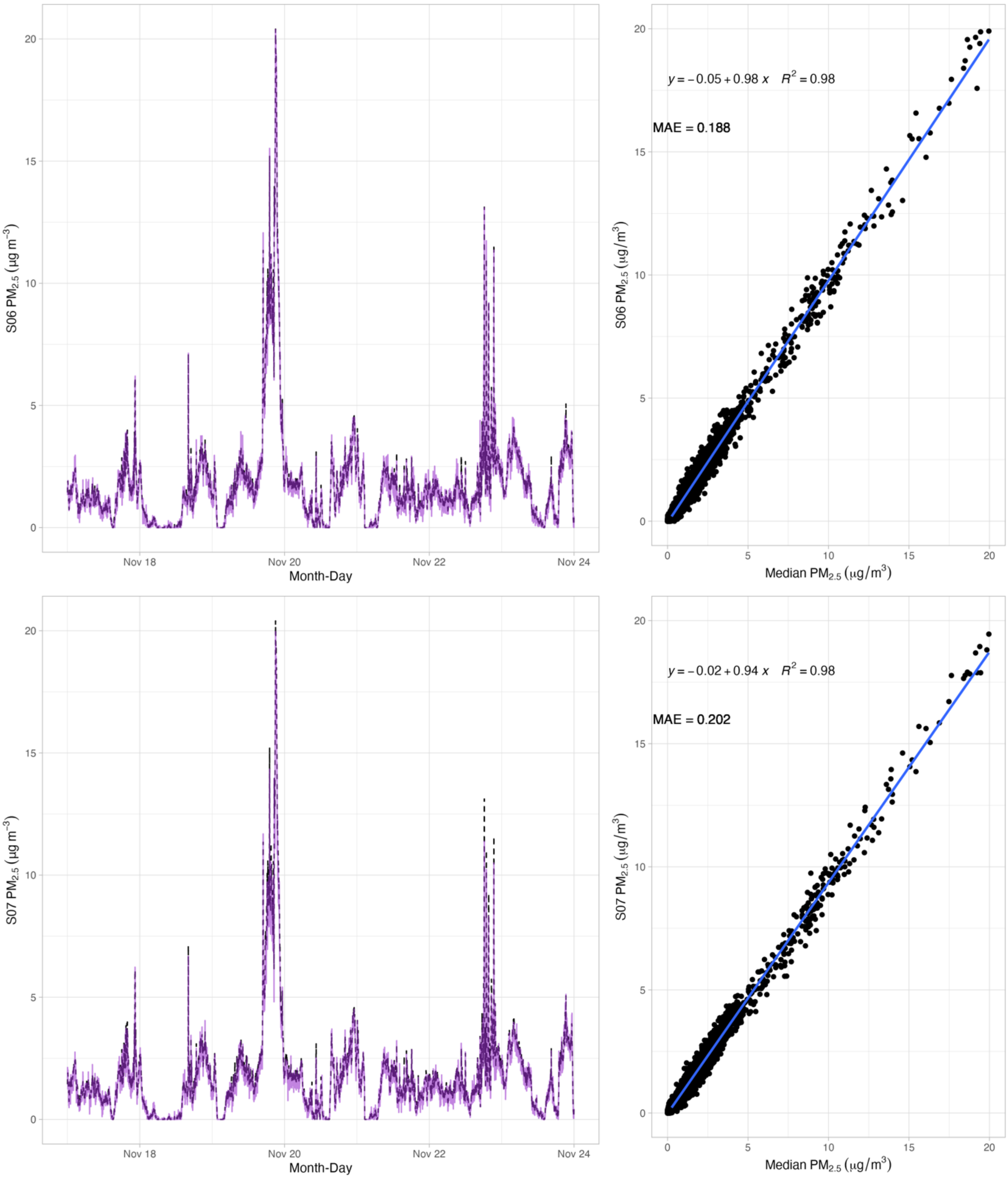
Supplementary Material F – Timeseries and scatterplots for each sensor compared to 'true' concentration. Results are reported in the main text in Chapter 4.



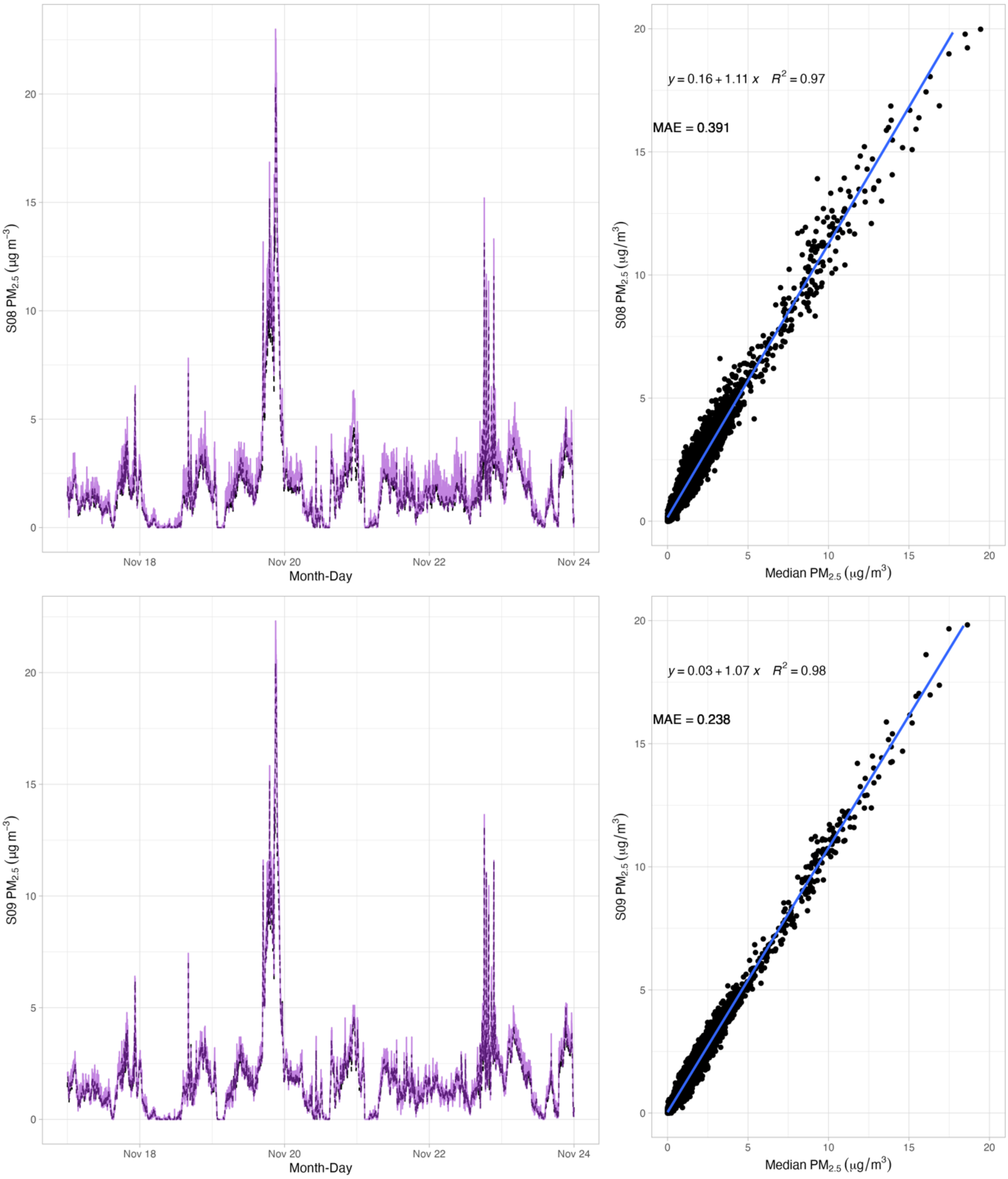

S3 PM2.5 (μg m-3)
Month-Day
Nov 18
Nov 20
Nov 22
Nov 24
y = 0.01 + 1.06 x   R2 = 0.98
MAE = 0.229
S3 PM2.5 (μg/m3)
Median PM2.5 (μg/m3)
S03 PM2.5 (μg m-3)
Month-Day
y = 0.95 x   R2 = 0.97
MAE = 0.221
S03 PM2.5 (μg/m3)
Median PM2.5 (μg/m3)

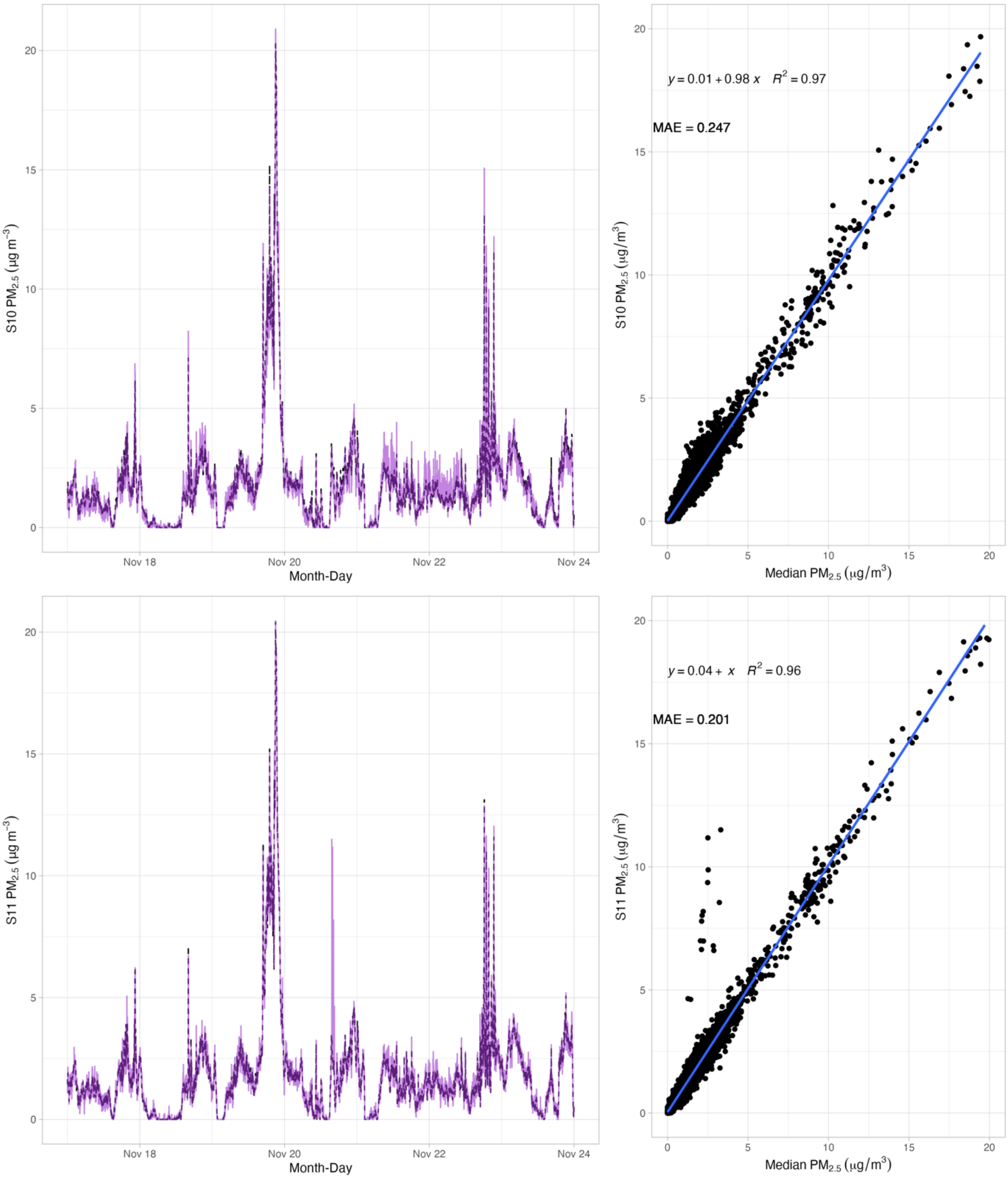


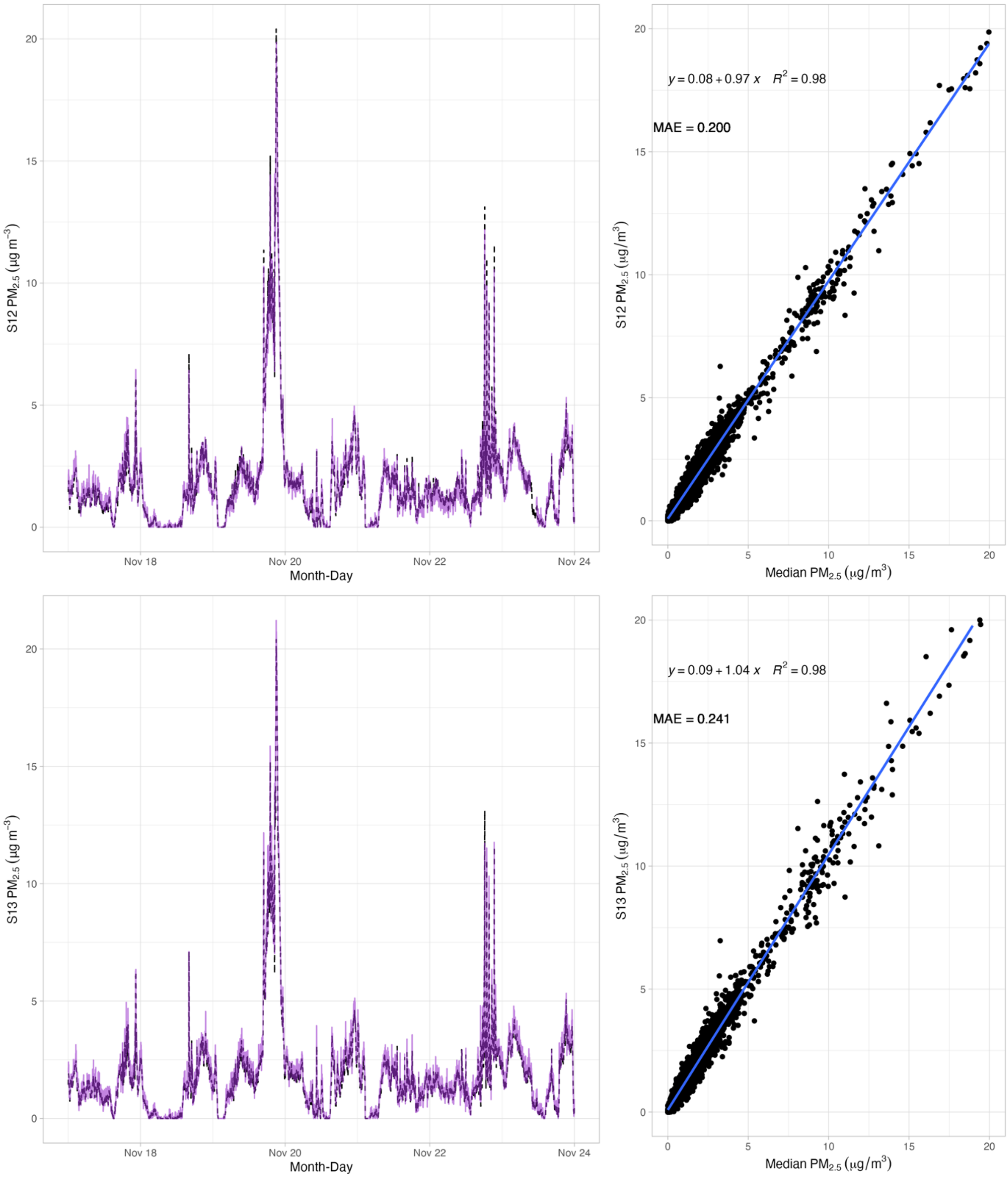
S04 PM2.5 (μg m⁻³)
Month-Day
Nov 18
Nov 20
Nov 22
Nov 24
y = 0.03 + x   R² = 0.98
MAE = 0.200
S04 PM2.5 (μg/m³)
Median PM2.5 (μg/m³)
S05 PM2.5 (μg m⁻³)
Month-Day
y = −0.03 + 0.96 x   R² = 0.98
MAE = 0.208
S05 PM2.5 (μg/m³)
Median PM2.5 (μg/m³)

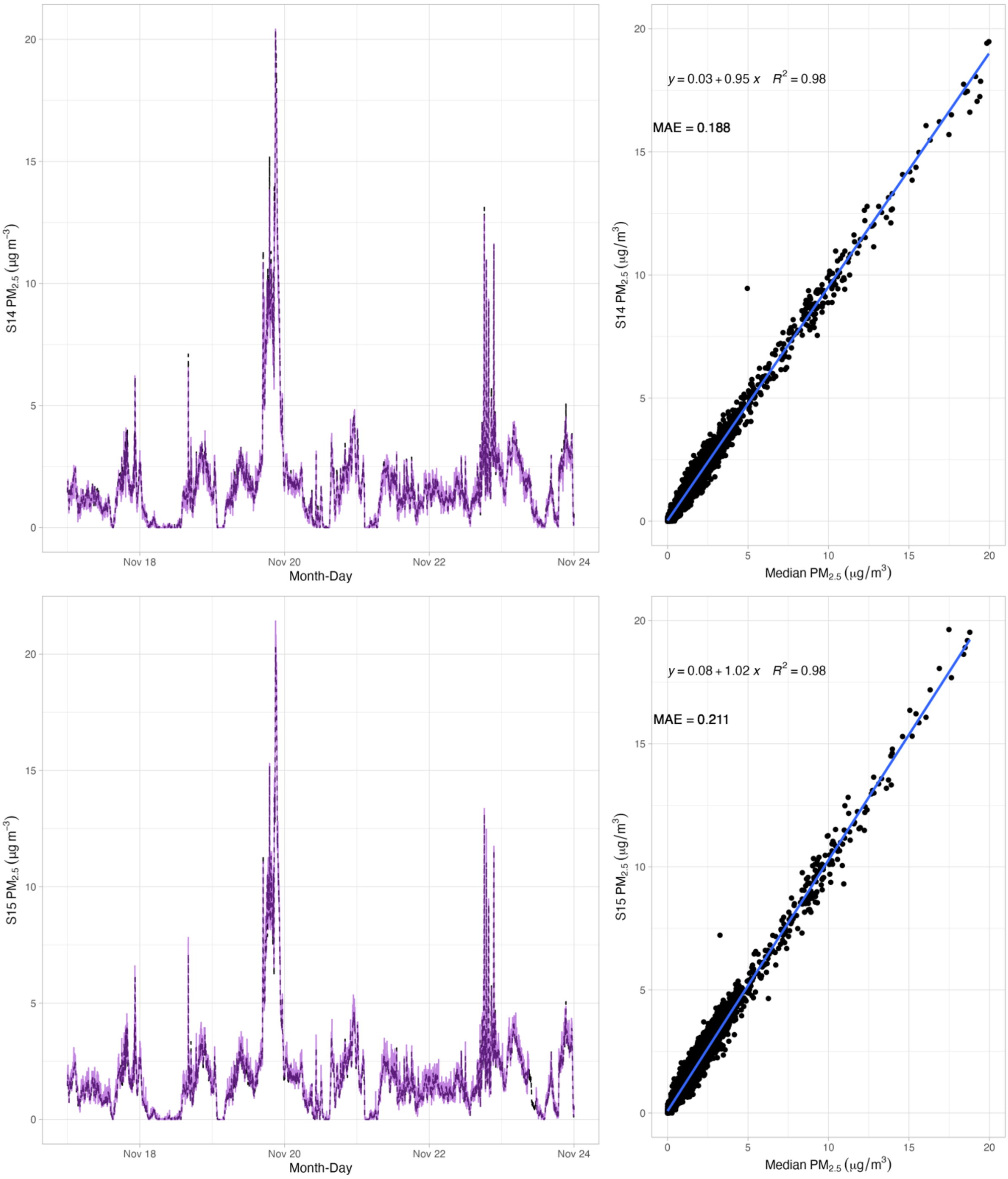


S06 PM2.5 (μg m-3)
Month-Day
Nov 18
Nov 20
Nov 22
Nov 24
y = −0.05 + 0.98 x   R2 = 0.98
MAE = 0.188
S06 PM2.5 (μg/m3)
Median PM2.5 (μg/m3)
S07 PM2.5 (μg m-3)
y = −0.02 + 0.94 x   R2 = 0.98
MAE = 0.202
S07 PM2.5 (μg/m3)

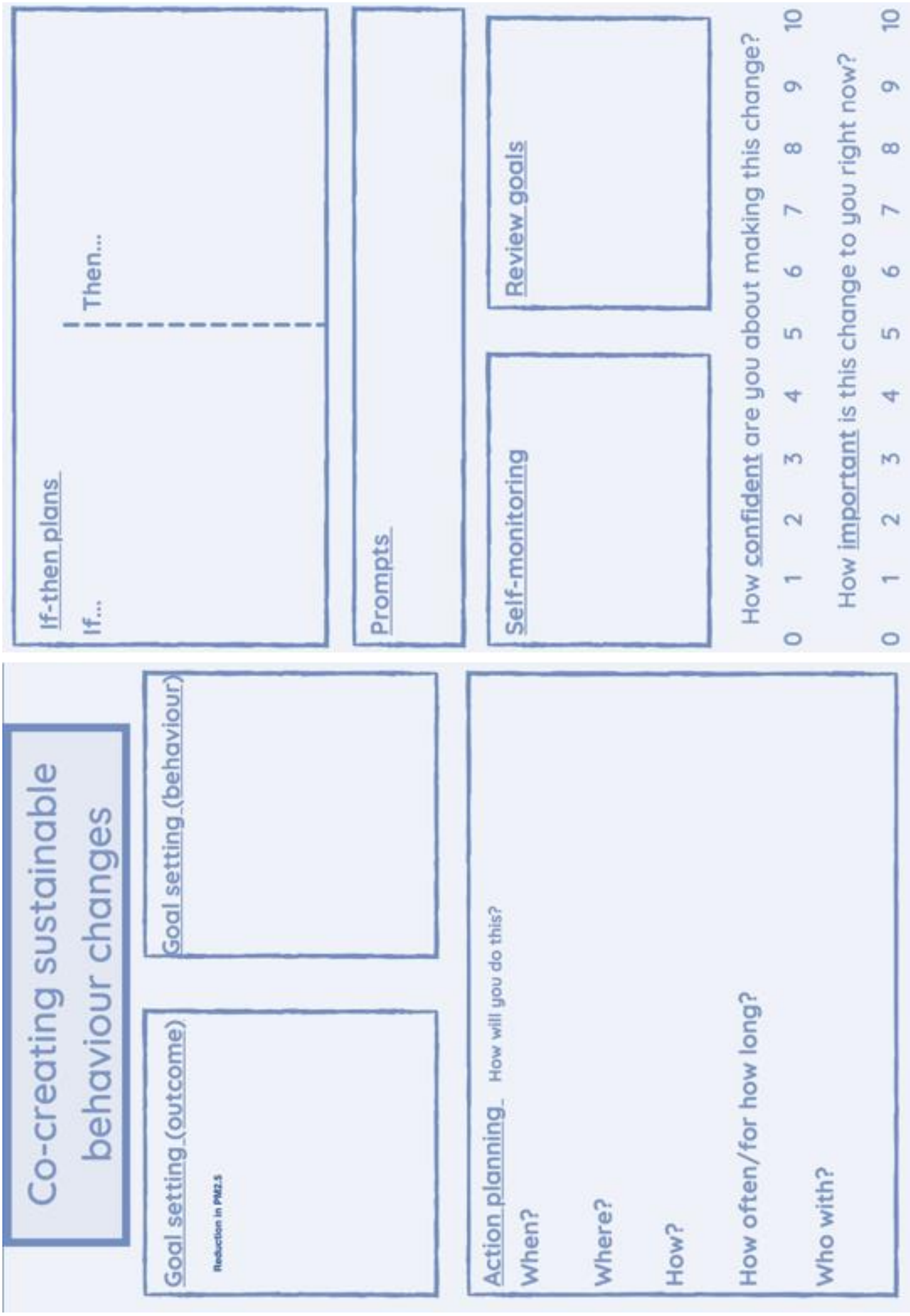

S08 $PM_{2.5}$ ($\mu g\, m^{-3}$)
Month-Day
Nov 18
Nov 20
Nov 22
Nov 24
$y = 0.16 + 1.11\,x \quad R^2 = 0.97$
MAE = 0.391
S08 $PM_{2.5}$ ($\mu g/m^3$)
Median $PM_{2.5}$ ($\mu g/m^3$)
S09 $PM_{2.5}$ ($\mu g\, m^{-3}$)
Month-Day
$y = 0.03 + 1.07\,x \quad R^2 = 0.98$
MAE = 0.238
S09 $PM_{2.5}$ ($\mu g/m^3$)
Median $PM_{2.5}$ ($\mu g/m^3$)


S10 PM$_{2.5}$ (μg m^{-3})
Nov 18
Nov 20
Nov 22
Nov 24
Month-Day
$y = 0.01 + 0.98\,x \quad R^2 = 0.97$
MAE = 0.247
S10 PM$_{2.5}$ (μg/m^3)
Median PM$_{2.5}$ (μg/m^3)
S11 PM$_{2.5}$ (μg m^{-3})
Nov 18
Nov 20
Nov 22
Nov 24
Month-Day
$y = 0.04 + x \quad R^2 = 0.96$
MAE = 0.201
S11 PM$_{2.5}$ (μg/m^3)
Median PM$_{2.5}$ (μg/m^3)


S12 $PM_{2.5}$ ($\mu g\,m^{-3}$)
Month-Day
Nov 18
Nov 20
Nov 22
Nov 24
$y = 0.08 + 0.97\,x \quad R^2 = 0.98$
MAE = 0.200
S12 $PM_{2.5}$ ($\mu g/m^3$)
Median $PM_{2.5}$ ($\mu g/m^3$)
S13 $PM_{2.5}$ ($\mu g\,m^{-3}$)
Month-Day
$y = 0.09 + 1.04\,x \quad R^2 = 0.98$
MAE = 0.241
S13 $PM_{2.5}$ ($\mu g/m^3$)
Median $PM_{2.5}$ ($\mu g/m^3$)


S14 PM2.5 (μg m−3)
Month-Day
Nov 18
Nov 20
Nov 22
Nov 24
y = 0.03 + 0.95 x R2 = 0.98
MAE = 0.188
S14 PM2.5 (μg/m3)
Median PM2.5 (μg/m3)
S15 PM2.5 (μg m−3)
y = 0.08 + 1.02 x R2 = 0.98
MAE = 0.211
S15 PM2.5 (μg/m3)

Supplementary Material G - Behaviour change planning template completed collaboratively with participants based upon the 'MAP of health behaviour change' (NHS Education for Scotland, 2023).



Supplementary Material H - Number-needed-to-treat tables calculated based on the calculated proportion of patients who benefited from receiving treatment (Guyatt *et al.*, 1998).

Overall	**NNT**	**5.1**	
		Treatment	
Control	Improved (0.11)	Unchanged (0.89)	Deteriorated (0.00)
Improved (0.25)	0.03	0.22	0.00
Unchanged (0.38)	0.04	0.33	0.00
Deteriorated (0.38)	0.04	0.33	0.00

Symptoms	**NNT**	**3.5**	
		Treatment	
Control	Improved (0.33)	Unchanged (0.67)	Deteriorated (0.00)
Improved (0.38)	0.13	0.25	0.00
Unchanged (0.13)	0.04	0.09	0.00
Deteriorated (0.50)	0.17	0.34	0.00

Activity limitation	**NNT**	**7.7**	
		Treatment	
Control	Improved (0.00)	Unchanged (1.00)	Deteriorated (0.00)
Improved (0.25)	0.00	0.25	0.00
Unchanged (0.38)	0.00	0.38	0.00
Deteriorated (0.38)	0.00	0.38	0.00

Emotional function	**NNT**	**7.2**	
		Treatment	
Control	Improved (0.33)	Unchanged (0.56)	Deteriorated (0.11)
Improved (0.38)	0.13	0.21	0.04
Unchanged (0.25)	0.08	0.14	0.03
Deteriorated (0.38)	0.13	0.21	0.04

Environmental stimuli	**NNT**	**6.1**	
		Treatment	
Control	Improved (0.33)	Unchanged (0.56)	Deteriorated (0.11)
Improved (0.25)	0.08	0.14	0.03
Unchanged (0.50)	0.17	0.28	0.06
Deteriorated (0.25)	0.08	0.14	0.03

Supplementary Material I - Demographic tables for a) all participants with pre-post exposure and health data and b) for intervention arm participants who co-developed a behaviour change intervention.

a) **All with pre-post (n=17)**

Participant characteristic	**Statistic**
Age (years, $\bar{x}$ (range))	46.8 (24-74)
Sex (n (%))	
Female	11 (64.7)
Male	6 (35.3)
Other respiratory condition (n (%))	
No	16 (94.1)
Yes	1 (5.9)
Pregnant (n (%))	
No	17 (100.0)
Yes	0 (0.0)
SIMD Quintile (n (%))	
1	0 (0.0)
2	1 (5.9)
3	7 (41.2)
4	3 (17.6)
5	6 (35.3)
Type of dwelling (n (%))	
Apartment	6 (35.3)
Semi-detached house	3 (17.6)
Detached house	4 (23.5)
Semi-detached bungalow	0 (0.0)
Detached bungalow	2 (11.8)
Detached cottage	1 (5.9)
Terraced house	1 (5.9)
Number of residents ($\bar{x}$, (range))	2.3 (1-5)
Live with pets (n (%))	
No	7 (41.2)
Yes	10 (58.8)
Live with smoker (n (%))	
No	17 (100.0)
Yes	0 (0.0)
Have a solid fuel burner (n (%))	
No	13 (76.5)
Yes	4 (23.5)
Type of hob (n (%))	
Gas	7 (41.2)
Other (electric, induction)	10 (58.8)
Urban-rural Classification (n (%))	
Accessible rural	2 (11.8)
Accessible small town	1 (5.9)
Large urban	3 (17.6)
Other urban	8 (47.1)
Remote small town	1 (5.9)

Very remote rural	1 (5.9)
Very remote small town	1 (5.9)

b) Intervention (n=15)

Participant characteristic	**Statistic**
Age (years, $\bar{x}$ (range))	43.7 (24-74)
Sex (n (%))	
Female	10 (66.7)
Male	5 (33.3)
Other respiratory condition (n (%))	
No	15 (100.0)
Yes	0 (0.0)
Pregnant (n (%))	
No	15 (100.0)
Yes	0 (0.0)
SIMD Quintile (n (%))	
1	0 (0.0)
2	3 (20.0)
3	4 (26.7)
4	4 (26.7)
5	4 (26.7)
Type of dwelling (n (%))	
Apartment	6 (40.0)
Semi-detached house	3 (20.0)
Detached house	2 (13.3)
Semi-detached bungalow	0 (0.0)
Detached bungalow	2 (13.3)
Detached cottage	1 (6.7)
Terraced house	1 (6.7)
Number of residents ($\bar{x}$, (range))	2.7 (1-5)
Live with pets (n (%))	
No	5 (33.3)
Yes	10 (66.7)
Live with smoker (n (%))	
No	15 (100.0)
Yes	0 (0.0)
Have a solid fuel burner (n (%))	
No	12 (80.0)
Yes	3 (20.0)
Type of hob (n (%))	
Gas	5 (33.3)
Other (electric, induction)	8 (53.3)
Missing	2 (13.3)
Urban-rural Classification (n (%))	
Accessible rural	3 (20.0)
Accessible small town	2 (13.3)
Large urban	3 (20.0)
Other urban	4 (26.7)
Remote small town	1 (6.7)

Very remote rural	1 (6.7)
Very remote small town	1 (6.7)

Supplementary Material J – mini–Asthma Quality of Life Questionnaire score differences for each participant.

Intervention										
	Total Difference	**0.07**	**0.40**	**0.20**	**0.33**	**0.07**	**0.27**	**0.33**	**-0.13**	**0.53**
	Symptoms	-0.20	0.80	0.40	0.60	0.40	0.40	0.20	-0.20	1.20
	Activity limitation	0.00	0.00	0.00	0.25	0.25	0.00	-0.50	0.25	0.00
	Emotional function	0.00	0.00	0.33	0.67	-0.67	0.67	0.67	0.00	0.33
	Environmental stimuli	0.67	0.67	0.00	-0.33	0.00	0.00	1.33	-0.67	0.33

Control									
	Total Difference	**2.07**	**0.00**	**1.27**	**-0.93**	**-1.33**	**-0.20**	**-0.60**	**0.47**
	Symptoms	2.00	-0.60	2.00	-1.80	-0.60	0.00	-1.60	1.20
	Activity limitation	2.50	0.00	1.75	-0.75	-1.75	0.25	-0.75	0.25
	Emotional function	2.33	0.67	0.67	-1.00	-1.67	-0.67	0.00	0.00
	Environmental stimuli	1.33	0.33	0.00	0.33	-1.67	-0.67	0.67	0.00

Supplementary Material K – Mobilising Air Quality Conscious Communities in Stirlingshire interview topic guide.

Interview/ think-aloud schedule

Thank you for agreeing to take part. In total this will take around 30 minutes. We'll start and finish with some more traditional interview style questions and in-between we're going to do something called 'thinking aloud'. I'll tell you a bit more about this in a minute. You'll have read the information sheet and consent forms. Remember you can stop at any time during the session.

- Do you have any questions for me before we get started?

- Can you confirm for me that you're happy to be audio recorded and have your screen recorded?

Opening questions

- Thank you for attending at least one of the air quality workshops. What motivated you to come along to that workshop?

- How did you find the workshop? What did you like best? What could have been improved? Why?

- Do you access air quality information currently or have you in the past?
    - Why? / Why do you think someone would access air quality information?
    - Do you/ have you used it to inform your behaviours?

- Since taking part in the workshop, have any of your activities or thinking changed around local air quality?

Introduction to thinking aloud - example

I'm going to ask you to complete a few tasks and activities and think aloud while you are doing so. As you navigate around websites, can you verbalise your thought processes, why you are clicking where you are clicking, what you are looking for, if anything is causing you to be stuck or confused etc.

Before we get started, I'm going to conduct an example of 'thinking aloud' on an unrelated website to give you an idea what we are looking for and what we mean by 'think aloud'. This is to demonstrate that there are no right or wrong answers, it's about gaining understanding how the resource works for the user. If you have any questions, please stop me and let me know.

Task 1
The first task isn't specific to any particular website, and we'll start on the Google search engine page.

Can you take me to a site which tells you about the air pollution forecast for where you live for today. When you find what you're looking for, let me know.

Task 2
For this next task, we're going to use a specific resource. You'll see a tab open at the top of your screen (https://www.scottishairquality.scot). Can you open this tab for me.

Can you find out what the air quality is like for where you live? When you find what you're looking for let me know.

Can you find out what the daily air quality index value is for today for where you live. When you find what you're looking for, let me know.

Now can you find out what the recommended actions and health advice are for this index value. When you find what you're looking for, let me know.

Task 3
There is a tab already open on the top of your screen (https://www.environment.gov.scot/our-environment/air/stirlingshire-villages-project/). Can you open this tab for me. This page contains the resource we are going to use for this section.

Take me to the Stirlingshire Villages air quality project tool.

Can you find out what villages were included in this project?

Can find out about the different pollution events identified in Aberfoyle?

Can you take me back to the home screen?

Can you find out where the monitoring sites in Doune and Deanston were?

Can you find out what pollution events were identified in Fintry?

Can you navigate to the page for the village where you live?

Closing questions
For the final section you don't need to navigate around the website, though you can do if you like or if you want to illustrate the point you are making. We will start discussing the Stirlingshire resource specifically and then move on to more general questions.

- The last question I asked you was about pollution events in your village. Compared to your thoughts on your local air quality coming into the first workshop (if attended)/ before using this resource, has this altered you thinking in any way?
    - Can you explain?

- In terms of the overall usability of the site, how easy or difficult is it to use? Can you explain what you mean.

- What improvements would you make to the interface to make it easier to navigate?

- Do you feel like you have learned anything by accessing this resource?

- How could you use this resource to inform your decision-making/ behaviours? Would you?

- Compared to the AQiS website, do you find this resource more or less useful? Why?

- Thinking specifically about the DAQI, how informative or useful do you find this resource?

- Are you more likely to use the AQiS website, DAQI, this resource, neither or all etc to engage with air quality information in the future? Why?

- If you were going to change your behaviours to improve air quality or minimise your exposures, what resource would you be more likely to consult and why?

- Has accessing any of these resources changed how you think about air pollution in any way?

- Do you have any suggestions or comments about any of the resources?

- What do you think an 'ideal' online air quality resource would look like? What would you be able to do with it?

- Do you have anything else you'd like to add?

Thank you for your time and participation.