Examining the impact of individuals' microenvironments on asthma for people living in social housing in Cornwall, UK

Submitted by

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I certify that all material in this thesis which is not my own work has been identified and that any material that has previously been submitted and approved for the award of a degree by this or any other University has been acknowledged.

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Jack, Jessica and Holly…. This one is for you x

Carpe Diem

Abstract

This thesis utilizes systematic review and cross-sectional analyses to evaluate the impact of the indoor environment at an individual, household and area level on asthma outcomes, for a sub-population of social housing tenants in Cornwall, UK. Asthma is a chronic and complex disease which can develop or be exacerbated by exposure to air pollution and is responsible for 1400 deaths each year in England and Wales. Whilst much research has examined the health impacts of outdoor air pollution, which is regulated and declining, little has explored the indoor home environment. As a modifiable micro-environment, heavily influenced by individual action, a better understanding of the indoor environment and its components can help both individuals and policymakers to better plan and manage health and homes. As such, identifying the pollutants and allergens in the home which are responsible for the development of, and or exacerbation of asthma, and understanding the relationship with both other exposures, and the resultant asthma related health impacts, is critical to enable better mitigation, regulation, population health, healthier environments and better patient care. Using a pre published protocol, this thesis provides collective new evidence through the systematic synthesis of 14 studies meeting the inclusion criteria, that exposure to volatile organic compounds such as aromatic and aliphatic compounds in the home, is associated with an increased risk of asthma development and/or exacerbation. Exposure to VOCs in the home are also associated with an increased risk of asthma symptoms such as a wheeze, even for individuals without a diagnosis of asthma. Further, using a series of univariate and multiple regression modelling a cross sectional analysis identified that increased time spent in homes with fungal contamination elicit worse asthma symptoms in asthmatic individuals, with noticeable differences in symptom severity between summer and winter. A protocol is demonstrated to model the indoor as a composite measure when examining dose response in relation to indoor air pollution. These findings indicate the need for improved links between health and home providers as well as individuals and pave the way for future research. Key implications for future health and home management, mitigation and education are discussed.

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Author Contributions

The author led the writing of all Chapters in this thesis. Comments were given by supervisors (Tim Taylor, Emma Bland, Richard Sharpe and Karyn Morrissey).

Chapter 3 contains a systematic review, for which the author was the first reviewer and conducted the formal analysis. Richard Sharpe, Tim Taylor and Karyn Morrissey provided suggestions on methodology and edits and acted as second reviewers where appropriate. This Chapter has been previously published in *Environmental Research* as Paterson, C., Sharpe, R.A., Taylor, T. and K. Morrissey (2021) Indoor $PM_{2.5}$, VOCs and asthma outcomes: A systematic review in adults and their home environments.

The Smartline Baseline Survey on which some of the analysis in Chapter 4 is based was designed by members of the Smartline team (which the author was part of**),** and the author was part of the team who interviewed participants. The author was involved in over 100 of the interviews conducted.

Appendix 1 contains one paper that was co-authored by a number of researchers as part of the Smartline project on energy and water usage during COVID-19 lockdowns. The author conceived the study and contributed to the authorship, but would likely have been first or second author had COVID-19 and related events not prevented her from fulfilling these roles.

Glossary

µg/m3	Micrograms per cubic meter
8-OHdG	8-hydroxy-2' -deoxyguanosine
ACH	Air Changes per Hour
AQD	Air Quality Directive
AQI	Air Quality Index
BETSI	Building Energy, Technical Status and Indoor Environment
BHR	Bronchial Hyperreactivity
C_6H_6	Benzine
CH2O	Formaldehyde
CHASE	Child Heart and Health Study in England
CI	Confidence Interval
CMO	Chief Medical Officer
CO	Carbon monoxide
CO_2	Carbon dioxide
COPD	Chronic Obstructive Pulmonary Disease
COVID-19	Disease attributed to the virus SARS-CoV-2
CRP	C-Reactive Protein
DEFRA	Department for Environment Food and Rural Affairs
ECRHS 2	European Community Respiratory Health Survey II
EIA	Exercise Induced Asthma
EPA	Environmental Protection Agency
ERDF	European Regional Development Fund
FEC	Forced Expiratory Capacity
FEV	Forced Expiratory Volume

FVC	Forced Vital Capacity
HDM	House Dust Mites
HSE	Health and Safety Executive
IAQ	Indoor Air Quality
IHI	Index of Housing Insults
LOAEL	Lowest observed adverse effect level
M-AQL	Mini Asthma Quality of Life questionnaire
NHS	National health Service
NO_2	Nitrogen Dioxide
NOAEL	No observed adverse effect level
NOS	Newcastle Ottowa Scale
O3	Ozone
OR	Odds Ratio
PAH	Polycyclic Aromatic Hydrocarbons
PCB	Polychlorinated biphenyls
PFAS	Perflourinated substances
PM 10	Particulate Matter 10
PM2.5	Particulate Matter 2.5
PPB	Parts per billion
PPM	Parts per million
RCT	Randomised Control Trail
RH	Relative Humidity
SAP	Standard Assessment procedure
SES	Social Economic Status
SO_2	Sulphur dioxide
TRAP	Traffic Related Air Pollution

TXIB	2,2,4-Trimethyl-1,3-pentanediol diisobutyrate
UK	United Kingdom
USA	United States of America
VOCs	Volatile Organic Compounds
WHO	World health Organization
WHS	World Health Study
ETS	Environmental Tobacco Smoke

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Chapter 1: Introduction

Chronic non-communicable diseases are escalating across the globe. Understanding the factors that are linked to the onset and/or exacerbation can improve symptom management and severity, quality of life and reduce hospital admissions. Asthma is a chronic and complex respiratory disease characterized by recurrent symptoms of shortness of breath and wheezing. It is the most common chronic disease among children and affects around more than 300 million individuals globally, with 623 million individuals suffering regular asthma symptoms (Loerbroks et al., 2018).

Recurrent asthma symptoms which can occur from rarely, to several episodes a day or week can have a considerable impact on many aspects of an individual's life; daytime fatigue, insomnia, reduced activity levels leading to obesity, and work and school absenteeism are often experienced in individuals who suffer from recurrent asthma symptoms (Singh and Jaiswal, 2013a).

The prevalence of asthma differs by country and region. The United Kingdom (UK) has one of the highest prevalence of asthma in the world, representing a significant economic and societal burden, and costing the National Health Service (NHS) £1.1 billion to treat on an annual basis (Asthma.Org, 2018). The prevalence of asthma has increased rapidly over the last two-three decades (Osborne et al., 2010). In 2018, it was estimated that 12% of the UK population suffer from asthma, with the South West of England having a higher than average increase in newly diagnosed asthma (296 per 100,000) (BLF, 2018).

New diagnoses of asthma appear to have plateaued whilst the number of adults with a lifetime asthma diagnosis continues to rise. At the same time, large socioeconomic inequalities remain, incidence rates of asthma are 36% higher in the most deprived communities in the UK compared to more affluent community groups (BLF, 2018). This complex disease cannot be fully explained by genetic factors (Osborne et al., 2010). This has led to an increased interest in exposure to diverse environmental, physical, biological, and chemical agents found in inside and outside environments (Takaro et al., 2011, Mendell et al., 2011a).

Fungi

1.1 Asthma, Indoor Air Pollution and Fungi

We inhale around six to seven litres of air per minute and around 11,000 litres per day (Camelia, 2018). Understanding the timing and extent of exposure to physical, chemical and biological agents suspended in air and resultant health effects is fundamental to the prevention and/or management of allergic diseases and other health related conditions.

Air pollution has been identified as a potential cause of death and disease for centuries (Anderson, 2009). The World Health Organization (WHO) defines air pollution as follows:

“Air pollution is contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere”(WHO, 2022a)

Air pollution is a major environmental and public health concern which affects all people regardless of country of residence and was the cause of 4.2 million deaths in 2016 globally due to fine particulate matter ($PM_{2.5}$) alone. In England, 26-38,000 deaths are the result of air pollution each year with many others suffering preventable chronic ill health (CMO, 2022). Several diseases have been linked to air pollution, including respiratory diseases, cardiovascular disease, reproductive disorders, neurological conditions, skin conditions and various cancers (Manisalidis et al., 2020, Ohlwein et al., 2019).

Asthma was responsible for 455,000 deaths in 2019. However, in relation to air pollution exposure, there are scant studies in existence which examine specifically, asthma mortality. This is most likely due to advances in asthma care, and deaths for asthma being relatively uncommon. Of those studies that do exist authors indicate that air pollution such as $Pm_{2.5}$ and O_3, are associated with a 7% and 9% respectively, increased risk in asthma death, which is concerning as these pollutants are linked with bronchial hyperreactivity (BHR), airway inflammation and oxidative stress (Beamer, 2019).

Children with asthma who suffer from frequent or persistent wheeze are more likely to experience inflammation and/or remodelling of the airways, impaired lung function and symptoms that can persist all through the life course. Having asthma in childhood which continues into adulthood is also thought to predispose individuals to other comorbidities such as COPD later in life. Individuals with asthma are especially vulnerable to the detrimental health effects associated with air pollution.

To date much research and policy has focused on ambient air quality. However, emerging evidence shows that poor indoor air quality is linked to asthma (Branco et al., 2020). Indoor air pollution contains the same pollutants as ambient air pollution but often in lower concentrations, but with longer exposure rates (Jiang et al., 2016). At a component-specific level, some concentrations such as nitrogen dioxide (NO_2) are often found to be higher indoors than outdoors (Frampton et al., 2002). Nonetheless, the combined effects are cause for concern. Individuals spend around 80-90% of their time indoors, with 60-70% of each day spent indoors within the home environment. This percentage increases for the elderly, young and disabled (Simoni et al., 2003, Matz et al., 2014).

Indoor air pollutants also consist of a variety of volatile organic compounds and allergens such as house dust mites, fungi, cockroach antigen (hyphae fragments, spores and microbial volatile organic compounds) and pollen (Sharpe, 2020). Increased exposure to indoor damp and associated fungal contamination is a worldwide public health concern because of its association with an increased risk of poor health outcomes (Committe on Damp Indoor Spaces et al., 2004).

Early studies of 671 households found that 21% of participants believed damp and fungi impacted their family's health, and in households affected by fuel poverty 23% and 30% respectively, suggested they did not adequately ventilate or heat their homes due to the cost associated with such behaviour (Sharpe et al., 2015c).

More recently, research shows that exposure to fungal odours in the indoor environment increased the risk of asthma in adults over the age of 50 years (odds ratio (OR) 2.4, 95% confidence interval (CI) 1.10–5.34). This risk was higher for females than for males (OR 3.5, 95% CI 1.37–9.08) (Moses et al., 2019b). Exposure to fungi in childhood makes children 1.5 to 3 times more susceptible to wheezing and coughs (CMO, 2022).

A recent review of indoor air quality and asthma morbidity suggests that asthma related indoor pollution exists in many homes (Jie et al., 2011). This can result from increased exposure to indoor dampness (caused by condensation, rising damp and water leaks from poor maintenance) or pollutants such as fungi and fungal spores.

Fungi is a variety of fungus that grows from spores which then latch onto humid/damp surfaces within homes and other buildings. Fungi are most prevalent in the winter months and are associated with a range of health conditions due to their ability to release hazardous toxins into the air (Borràs-Santos et al., 2013, Li et al., 2022).

Associated exposures resulting from elevated dampness, include increased concentrations of fungal spores, hyphae, allergens, mycotoxins, endotoxins, cell wall b-glucans and volatile organic compounds (Harving et al., 1990).The associated risk of asthma in those exposed to increased fungal contamination is influenced by indoor concentrations and species diversity, because fungi vary in physiology, ecology and significance for health (Flannigan, 2011).

Sensitization to indoor pollutants, including air pollution and fungi by exposure, are important risk factors to consider for asthma morbidity and mortality. However, the role of sensitization and allergic diseases may vary by age (Sharpe et al., 2015h). Indoor air quality in terms of pollutants and fungi are modified by a complex interaction between the built environment and modified through changes in individual and household behaviour (Sharpe et al., 2014a).

Even in well maintained and managed homes, individual and household behaviours are influential in how these pollutants emerge. However, unlike ambient air quality standards, indoor air quality standards are relatively new and not as comprehensive (Please see Table 2. for comparison). The World Health Organization has identified indoor air pollution as:

"The use of inefficient and polluting fuels and technologies in and around the home that contains a range of health-damaging pollutants, including small particles that penetrate deep into the lungs and enter the bloodstream"(WHO, 2022c).

However, as with ambient air pollution, the timing, extent and concentration at which an individual is exposed and the resultant health outcomes, are complex and multifaceted, reliant upon individual action, environmental influence, social norms and political will power and motivation to change based on recommendations. As such a greater understanding of the role of indoor air pollution and fungi on health outcomes provides local and national policymakers with evidence to develop the necessary policies to ensure the protection of public health.

Much research to date has focused on the acute effects of air pollution and its symptom onset and/or exacerbation. However, exposure to air pollution is usually unavoidable and involuntary and occurs across the entire lifespan regardless of location. It is within this context that this thesis examines the role of indoor air quality and fungi on asthma outcomes in an adult population in the southwest of England.

1.2 Aims and Objectives

This thesis' main aim is to examine the relationship between the indoor environment (in this context a microenvironment), time spent indoors and poor indoor air quality on asthma outcomes for individuals residing in social housing in Cornwall, South-West of England. This will be carried out by working with and across a range of disciplines and services within the county to address the following interlinked hypotheses:

A) The indoor home environment impacts respiratory health.

B) Time spent indoors is an important factor underlining this relationship.

To improve both the lives of social housing tenants and inform policy makers of best practice for future developments and housing maintenance, the following research objectives were formulated for this thesis:

1. Provide a systematic review of the effect of indoor exposure to volatile organic compounds and particulate matter on asthma in adults.
2. Using a unique dataset on time use among social housing residents, identify whether time spent in the home environment impacts asthma.
3. Identify whether the quality of the indoor air combined with the amount of time spent in the home effects asthma in adults.

To achieve the above research objectives the thesis is organized as shown in Table 1, which relates each Chapter to the research objectives.

Table 1 Research Objectives

Chapter	*Objective*
Chapter 1: Introduction	
Chapter 2: Asthma and the home	
Chapter 3: $PM_{2.5}$, VOCs and asthma outcomes: A systematic review in adults and their home environments	*1*
Chapter 4: Understanding time use: A multi-seasonal study	*2*
Chapter 5: Understanding the effect of time use and indoor air on asthma: A multi seasonal nested regression analysis using novel sensor data: a protocol paper.	*2,3*
Chapter 6: Conclusions and Recommendations	*1,2,3*

1.3 Structure of Thesis

Chapter 2 introduces air pollution (indoor and outdoor) and asthma, its origins, associated health risks and the current practices that are in place to mitigate the negative health consequences of exposure. As such, Chapter 2 explores the complex interaction between indoor air pollution and outdoor air pollution, along with the resultant negative health consequences of such exposure.

A range of literature was examined that studies the development of and exacerbation of asthma and asthma symptoms from exposure to airborne respirable pollution. These pollutants are discussed at a compound level along with their associated health risks.

Chapter 2 investigates current global mitigation policy and practice that is implemented to reduce the risk to health. Asthma is discussed in relation to its development and associated risks from exposure to pollutants. Thus, Chapter 2 identifies knowledge gaps relating to air pollution and asthma which this thesis attempts to address.

Chapter 3 presents a systematic review examining the effect of exposure to particulate matter and/or VOCs in the home environment on asthma outcomes for adults using a robust scientific design with pre-specified and reproducible methodology. Particulate matter and VOCs in the indoor home environment are a growing concern due to their inhalable size and the amount of time people spend inside buildings, thus potential exposure.

The associated asthma risk of exposure to these chemicals indoors is critically understudied in adults with limited data availability. Chapter 3 therefore examines available literature regarding $PM_{2.5}$ and VOCs to provide a comprehensive evidence synthesis. Chapter 3 highlights the VOCs of concern for individuals with asthma providing collective new evidence in the field of associated risk from exposure.

Chapter 4 offers a multi-season cross sectional study which was carried out at three timepoints to assess the impact of time spent in individuals' own homes (including those with fungal contamination) on asthma for a social housing cohort in Cornwall, UK. This is done by first linking a pre-validated questionnaire with a Mini Asthma Quality of Life (M-AQL) questionnaire, housing characteristics and a time use diary. Next, a series of regression modelling is conducted to estimate the probability of reporting asthma, and for individuals with asthma, symptoms and their severity. Finally, analysis examining the impact of time spent inside fungal contaminated homes is conducted.

Chapter 5 is a protocol paper which builds on the study in Chapter 4, outlining the planned data analysis linking a pre-validated questionnaire and novel real time environmental sensor data, with time use diary data. A series of nested regression modelling will attempt to address whether those living in homes with poor indoor air quality have worse asthma outcomes when spending longer periods of time in the home. Finally, **Chapter 6** presents a summary of the key findings of this thesis and several areas of consideration for further research related to the findings.

1.4 Outputs from the thesis

Several papers, posters and presentations have occurred from the research presented in this thesis. While some of the papers and presentations are of joint authorship the work contained in them has been contributed to by the work presented in this thesis.

Firstly, a protocol entitled “*Exposure to particulate matter and volatile organic compounds (VOCs) in the indoor environment and asthma outcomes in adults”* based on the work detailed in Chapter 3 was published on the National Institute for Health Research PROSPERO database:

PATERSON, C. 2018. *Exposure to particulate matter and volatile organic compounds (VOCs) in the indoor environment and asthma outcomes in adults* [Online]. National Institute for Health Research: PROSPERO. Available: https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42018110070 [Accessed 2018 2018].

Following completion of the review detailed in Chapter 3, a paper entitled “Indoor PM 2.5, VOCs and asthma outcomes: A systematic review in adults and their home environments” was published in the journal Environmental Research.

PATERSON, C. A., SHARPE, R. A., TAYLOR, T. & MORRISSEY, K. 2021. Indoor PM 2.5, VOCs and asthma outcomes: A systematic review in adults and their home environments. *Environ Res,* 202, 111631.

The findings and progression of this thesis have been presented both orally and via poster presentations at several events. Firstly, the presentation “Paterson, C. Examining the impact of cold homes, time spent indoors and the individuals' microenvironment on asthma among adults” was delivered to the Smartline participants at a participant event.

Paterson, C. Examining the impact of cold homes, time spent indoors and the individuals' microenvironment on asthma among adults. Participant event. Heartlands, Cornwall. 17.12.2018.

This was also presented at the Peninsula Forum via poster.

Paterson, C. Examining the impact of cold homes, time spent indoors and the individuals' microenvironment on asthma among adults in social housing in Cornwall. Peninsular Annual Forum. Truro, 17.05.2019.

The findings from Chapter 3 were presented at the British Lung Association annual conference.

KARYN MORRISSEY, PHILIP MCBRIDE, CHERYL PATERSON. Respiratory health in a changing climate: Insights from international, national, and local studies. British Lung Association Annual Conference, 26.06.21 2021.

The findings of chapter 3 have been requested by a multi-institutional team to assist in the grant application to develop a toolkit to help GPs teaching sustainable healthcare.

In addition, the findings throughout this thesis have been presented at numerous 'Smartline' project events, conferences, and partner events as well as seminars held within the European Centre for Environment and Human Health, Truro.

There have also been a number of joint author publications that have arisen as part of the Smartline project to which the findings throughout this thesis have contributed to their development.

During the pandemic when face to face access with participants was limited the author and colleagues attempted to examine whether the sensors that had been installed in the participants homes could be applied in other ways, and whether that could inform our thinking around how people interact with the home.

Based on the knowledge gained from this thesis and literature around individuals in social housing being more susceptible to the health effects of fuel poverty, consideration was given as to whether the Government order to stay at home, would impact this group and subsequently have a concatenation of health effects. Therefore, my ideas fed into the formulation of the paper published in the annex which looked at domestic energy use around the covid lockdown periods.

MENNEER, T., QI, Z., TAYLOR, T., PATERSON, C., TU, G., ELLIOTT, L. R., MORRISSEY, K. & MUELLER, M. 2021. Changes in Domestic Energy and Water Usage during the UK COVID-19 Lockdown Using High-Resolution Temporal Data. *International Journal of Environmental Research and Public Health,* 18**,** 6818.

Following the conduct of over 120 baseline interviews which took place in participants' own homes, and asked questions about how they interact with their home, about their health and their community. The interview process offered clear and unique insights into how the participants lived and managed their daily lives. It was clear that communicating information about or indeed to this group of individuals, or with wider stakeholders and others about the intended research or its findings would not be a simple process. Therefore, the use of personas within a research and innovation project via novel qualitative techniques, to support product process, and service development by broadening engagement with, and understanding of the data about the local community was explored via Smartline Archetypes.

WILLIAMS, A. J., MENNEER, T., SIDANA, M., WALKER, T., MAGUIRE, K., MUELLER, M., PATERSON, C., LEYSHON, M., LEYSHON, C., SEYMOUR, E., HOWARD, Z., BLAND, E., MORRISSEY, K. & TAYLOR, T. J. 2021. Fostering Engagement With Health and Housing Innovation: Development of Participant Personas in a Social Housing Cohort. *JMIR Public Health Surveill,* 7**,** e25037.

SHARPE, R., OSBORNE, N., PATERSON, C., TAYLOR, T., FLEMING, L. AND G. MORRIS 2020. *"Housing, Indoor Air Pollution and Health in High Income Countries"* Oxford Research Encyclopedia of Environmental Science.

1.5. Public engagement

Public engagement formed an important part of the work. Engagement was on a number of levels, from participation at Smartline participant events and meeting with participants to discuss the study, to engagement with the Health and Environment Public Engagement (HEPE) group at the University of Exeter Medical School to discuss the design of the study. In addition, the author conducted over 100 interviews as part of collecting data for the Smartline Baseline Survey, gaining insights from meeting with participants in their own homes.

1.6 Impact of COVID-19

Along with many studies conducted in the period 2020-2022, the research contained in this thesis has been impacted by the COVID-19 pandemic. The author had significant caring responsibilities and health issues that meant that time for working on the thesis was limited. This has meant that some of the work in this thesis is less developed than it would otherwise be. In particular, the work on linking asthma outcomes to internal air pollution data has had to be curtailed – hence Chapter 5 has been presented as a protocol rather than an analytical chapter. During the periods of Government stay at home orders access to participants was not possible.

The sensors that had been installed in the properties required maintenance, new batteries and/or reconnection to the hub. All of these activities were prevented from being carried out for quite some time both because of Government stay at home orders and participant preference, which was especially important as many participants are classed as vulnerable to both the effects of Covid19 and in wider society, so decisions were made to protect the health and wellbeing of the participants wherever possible.

1.7 Summary

Asthma, a complex disease affecting millions of people globally, is highly prevalent, and severely effects quality of life for many. Asthma has proven links with air pollution (both indoors and outdoors) in the development of and exacerbation of asthma symptoms. The mechanisms in which air pollution exacerbation of respiratory symptoms occurs is thought to be because of inflammatory responses to pollutants, to which those with allergic asthma may be more susceptible. Air pollution is largely unavoidable and comprises of a range of organic, chemical, and physical compounds which are easily respirable, making mitigation and reducing exposures a global public health priority, to protect health and prevent the deleterious health consequences of such exposure.

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Chapter 2: Asthma and the Home

2.1 Introduction

Asthma is one of the most common chronic, non-communicable diseases affecting around 262 million people globally each year. Defined as a Chronic respiratory condition associated with airway inflammation and hyper-responsiveness. This heterogeneous disease has many different underlying disease processes and variations in severity, clinical course, and response to treatment. Asthma is characterized by symptoms including cough, wheeze, chest tightness, and shortness of breath, and variable expiratory airflow limitation, that can vary over time and in intensity.

Symptoms can be triggered by factors including exercise, allergen or irritant exposure, changes in weather, and viral respiratory infections. Symptoms may resolve spontaneously or in response to medication and may sometimes be absent for weeks or months at a time (NICE, 2022b).

Asthma exacerbation is a term used to describe the onset of severe asthma symptoms, which can be life-threatening. Recurrent asthma symptoms can occur from rarely to several episodes a day or week and can have a considerable impact on many aspects of an individual's life (Singh and Jaiswal, 2013a).

The United Kingdom (UK) has one of the highest prevalence of asthma in the world and represents a significant economic and societal burden accounting for 60,000 hospital admissions and 200,000 bed days per year. Asthma has been responsible for more than 12,700 deaths in England and Wales over the past decade with 1400 deaths in 2018 (Asthma+LungUK, 2019).

Given the manageability of the disease the Royal College of Physicians have been suggesting this figure should be closer to zero since releasing their 2015 ‘why asthma still kills’ report (Royal College of Physicians, 2015).

Asthma is the most prevalent chronic disease among children. Although, non-allergic asthma can occur at any age, children are at greater risk of allergic respiratory problems due to their developing organs actively growing at a higher metabolic rate than adults (Di Cicco et al., 2021).

Although asthma symptoms often abate as children enter adolescence and adulthood (Trivedi and Denton, 2019) persistent airflow limitation through adulthood, and accelerated decline in overall lung function is common in children with severe asthma, making it vital to manage and treat this disease at the earliest onset. In adults, prevalence is higher in females, especially in those who are classed as obese (Scholes and Mindell, 2018).

Not only can asthma have a significant impact on individuals physical health, but a recent study using data from over 50 countries in the World Health Survey (WHS) has also identified that asthma-related symptoms of wheezing were associated with impaired social functioning, this was evident whether a concomitant asthma diagnosis was reported (OR = 2.19, 95% CI = 1.81–2.64) or not (OR = 2.50, 95% CI = 2.09–2.99) (Loerbroks et al., 2018).

Individuals spend up to 90% of their time indoors, especially in their own home environments (Zhang et al., 2016). Healthy indoor home environments are crucial for health and wellbeing, however, the interaction between housing and health is both complex and multifaceted (Sharpe, 2020). Indoor air quality (IAQ) in the home environment is increasingly being seen as being important in the maintenance of good health. This Chapter explores the complex interaction between housing (condition, fuel poverty, air pollution) and asthma.

2.2 Review of literature

To analyze the complex interactions between housing and respiratory health, a review of the academic literature was conducted. This review was designed to give a broad overview of current literature identifying knowledge gaps and opportunities. Databases including Pubmed, Environment complete, BMJ, Science Direct, JSTOR, Embase, Greenfile and Web of Science were searched due to their specialization in health and housing-related areas. Searches were conducted using Boolean methods; this form of search enables different themes to be searched using and/or.

The keywords comprising the search terms used, are listed in Table 2. To further increase the breadth of the search, the limiter 'apply related words' was utilized. Whilst a broad spectrum of evidence was utilized, papers were selected based on prior literature for their relevancy, therefore, there is potential that some papers may have been inadvertently excluded. Further, only papers published within the last ten years, in the English language, and of which were accessible, were included. This was to ensure the literature was as current and as relevant as possible.

Stage (A) searched Environment Complete database for abstracts with 'Housing' in field 1, and terms associated with respiratory health-based studies in the second field based on key words identified in prior literature searching. This returned 148 hits, many of these hits were related to animal studies. To refine the search to the relevant fields that had been identified through resources previously scrutinized in the initial phase, stage (B) included the most prevalent areas in the third field. This narrowed the search to 11 hits.

Further inquiry highlighted that damp and/or fungal contamination were a significant risk factor in the development of respiratory problems. The search terms were expanded to include both damp/fungi and temperature in stage (C); this yielded a further two papers. As the majority of respiratory problems affect both adults and children, no limitation was made to the age inclusion criteria. Stage (D) limited the inclusion criteria when examining respiratory health to only asthma, by excluding any terms within article titles that related directly to other respiratory issues such as chronic obstructive pulmonary disease (COPD) or emphysema, reducing the total number of papers to nine. This process was then repeated in all other databases previously identified, bringing the overall inclusion articles to 28.

Table 2 Search criteria utilized during the academic literature search.

Field	*Search terms*	*Stages of search*			
		A	B	C	D
F1	Housing* OR Home	Abstract	Abstract	Abstract	Abstract
F2	breathing* OR Asthma* OR COPD or breathing problems or respiratory health	Abstract	Title	Title	Title
F3	Damp/fungi * OR temperature OR inactivity OR indoor air pollution			Title	Abstract
F4	COPD* OR emphysema OR bronchitis* OR chest infection				Not title
	Hits	148	11	13	9

Table 2 shows the key terms applied during searches from stage A to D. Asterixis were operated as a truncation tool to ensure all variations of the word were searched. F1-3 was connected with 'AND' as per a Boolean search, and F4 excluded the search terms with 'NOT'.

Grey literature relating to the indoor home environment and asthma were also examined. Primarily local authority and government websites were explored for general information related to housing and health. Data was then extracted if the source was deemed to be reputable, accessible, and not more than ten years old. Five websites yielded 11 sources available to download, including infographics, census data, statistical tables, maps, and interactive health data tools. An initial examination of the available literature identified that housing and health are inextricably linked. Housing, indoor temperature, respiratory health and indoor air pollution warranted further investigation. Due to the breadth and scope of the search, only sources directly relevant to these concerns were utilized.

2.2.1 Analysis and evaluation

The available literature clearly identified numerous leading health issues associated with housing and respiratory health: damp/ fungi in the home, housing temperature and indoor air pollution were noted to be particularly troublesome, and areas of interest in research due to the close links with asthma and other respiratory conditions, these links will be reviewed accordingly.

2.3 Asthma

Asthma is a consequence of multifarious gene-environment interactions and affects approximately 262 million people worldwide (WHO, 2022b). The prevalence of self-reported, doctor-diagnosed asthma in adults is 4.3% (95% CI

4·2–4·4) globally; however, there is wide variation between countries (Papi et al., 2018).

The heterogeneity of immunology of asthma is becoming more understood with advances in medicine and research. Eosinophilic, high type two inflammation of the airway is present in around 50% of adults with asthma. However, corticosteroid withdrawal studies reveal eosinophilic airway inflammation, suggesting its prevalence might be underestimated (Papi et al., 2018).

Atopy is present in around 50–60% of adults and children with asthma; this is more common in both children and adults with severe asthma.
Symptoms of asthma are few and non-specific, vary widely between individuals and are often experienced differently between the age groups. An expiratory wheeze can often be heard on auscultation. Asthma is often associated with co-morbidities such as obesity, eczema, allergic rhinitis and bronchiectasis (adults) (Papi et al., 2018).

Asthma can have an onset period from childhood right through adulthood. In childhood-onset, allergic asthma symptoms are often intermittent and can include or be associated with a food or environmental allergy, wheezing and coughing, eczema, rhinitis, viral infections and tends to have a hereditary prevalence.

In adults, symptoms are similar; however, adults with newly diagnosed asthma tend to have persistent symptoms requiring daily medications to keep symptoms under control (Asthma and Allergies Foundation, 2018). Diagnosis of asthma is usually possible by a physician using a FeNO test (in children 5-16 years and people over 17 years a positive result is anything over 35ppb and 40ppb respectively), spirometry (FEV_1/FVC <70% suggests airflow limitation), or peak flow test. Sometimes individuals require chest X-ray or allergy testing (NHS, 2020, NICE, 2022a).

This heterogeneous disease is further complicated by the amount of differential diagnosis and types of asthma. *Allergic (Extrinsic-Type) Asthma*; occurs because of exposure to allergens. *Non-Allergic (Intrinsic-Type) Asthma*; occurs mostly following chest infections which may be either viral or bacterial. *Mixed-Type Asthma*; often resultant of both allergic and non-allergic factors with symptoms often triggered by nonspecific inhalants (Colbert, 2012).

Exercise-Induced Asthma *(EIA);* intense exercise can induce bronchospasm in individuals with this type of asthma. EIA produces the same types of symptoms as other asthma (wheeze, SOB etc.) and can affect individuals of any age and level of fitness. In children however, prevalence rates in a study of 782 school children indicated that the incidence rate of EIA is estimated at 9.9%. It could be that children and young people have higher rates of this type of asthma due to this demographic being more likely to engage in physical activity than other groups. Airway cooling resulting in bronchospasm is believed to be non-immunologic and non-pharmacologic in origin.

During exertion, the bronchial tree dilates to accommodate increased airflow. When exercise concludes, the airways immediately activate constriction, with peak narrowing occurring within 5 to 10 minutes, often leading to clinical symptoms. The intensity of activity, environmental temperatures and humidity are all known to affect the severity of EIA.

In most EIA attacks symptoms tend to start 5-10 minutes after exercise ends, with symptoms typically resolving within 30 minutes. However, for some individuals, symptoms begin during exercise (Hopkins, 2022, Mahler, 1993, Shaaban et al., 2007). With respect to environmental conditions, when cold air is inhaled, more severe symptoms may occur, especially when the individual is experiencing intense exertion. Often these types of symptoms occur in individuals who may exercise or experience intense exertion in cold environments. Air pollution may also contribute to symptoms.

Although EIA is most commonly caused by exercise, cooling of the airways can also be a result of breathing cold air, shouting, crying or other physical activity (Gerow M and Bruner PJ, 2022)

Occupational Asthma is a result of exposure to an irritant or allergen found in the workplace. This usually occurs in industries such as animal care, concrete, works, bakeries etc. where airborne particles of allergens are prevalent. Evidence synthesis shows that the average population attributable risk was 17.6% (Torén and Blanc, 2009, HSE, 2022).

Cough-Variant Asthma is characterized by repetitive bursts of a dry or a hacking cough as the sole manifestation of asthma. Phlegm production is low, and shortness of breath and chest tightness may be experienced, but wheezing is typically absent in individuals with this type of asthma and testing reveals airway hyperresponsiveness to methacholine challenge, shows obstruction on spirometry, and typically responds to standard treatment (bronchodilators and corticosteroids) (Ramanuja and Kelkar, 2010).

Nocturnal Asthma is similar to other asthmas, but the individual suffers from frequent asthmatic attacks at night.

Aspirin-Induced Asthma; is a type of asthma that is exacerbated when an individual is exposed to aspirin-based products. It is often referred to as triad asthma as aspirin-sensitive individuals (3-4% of asthmatic individuals) often have very difficult-to-manage asthma usually occurring in conjunction with chronic sinusitis and/or nasal polyps (Asthma.UK, 2020a, Hamad et al., 2004).

Potentially Fatal Asthma poorly managed asthma can result in death. Individuals who are most at risk are

- Individuals who experience respiratory failure from asthma.
- Had to have airway intubation and mechanical ventilation.
- Experienced two or more recent episodes of severe asthma despite oral corticosteroid use.
- Experienced two or more recent complications of severe asthma.
- Individuals who do not accurately sense their degree of respiratory difficulty or over or underuse medications (non-compliance) are at the greatest risk of fatal outcomes (Greenberger, 2019).

Coexistent Asthma and COPD*;* in some individuals who have chronic obstructive pulmonary disease (COPD), it is not unusual also to have a significant component of reversible airway obstruction due to asthma. The co-existence between these two respiratory diseases are thought to stem from early life exposures compared to COPD alone (Marcon et al., 2021). As well as actively trying to prevent coexistent asthma right from early childhood, diligently defining and treating the asthmatic component involved with COPD could significantly improve symptoms.

Low-grade systemic inflammation has been identified as playing an important role in the pathological processes of numerous chronic diseases. C-reactive protein (CRP) a well-known marker of systemic inflammation has been associated with lower spirometry readings in healthy subjects aged 7-12. Strong and independent associations were also found between higher CRP and increased frequency of bronchial hyperresponsiveness to methacholine according to a recent review (Hacken, 2009). Furthermore, it suggests that reduced physical activity can increase CRP in the body and reduce lung function; this may be an important risk factor in the development of respiratory conditions such as asthma.

2.3.1 Asthma Risk Factors

Biological agents have tended to be the focus of evidence synthesis to date concerning the pathophysiology of asthma. A vast proportion of patients have allergic asthma involving many cells, tissues and inflammatory molecules which result in airway inflammation that is both complex and variable. Moreover, these multiple biological mechanisms are a likely critical determinant of the phenotypes associated with the development and severity of inflammation within individual patients and therefore a likely mechanism to disease (Darveaux and Busse, 2015).

The cause of asthma is poorly understood, however, there are several factors that are thought to contribute to its development, including:

1. Genetic factors: Asthma tends to run in families, suggesting that there is a genetic component to its development. People with a family history of asthma are more likely to develop the condition themselves.

2. Environmental factors: Exposure to certain environmental factors, such as air pollution, tobacco smoke, and allergens, can trigger asthma symptoms. Allergens such as dust mites, pet dander, pollen, and fungal contamination in the home can irritate the airways and trigger inflammation, leading to an asthma attack.

3. Immunological factors: Asthma is likewise considered to be an autoimmune disease, which indicates that the body's immune system attacks its own tissues. In asthma, the immune system overreacts to triggers such as allergens, leading to inflammation and the characteristic symptoms of asthma.

4. Respiratory infections: Respiratory infections, particularly viral infections such as the common cold, can trigger asthma symptoms in some people.

This section discusses several risks factors that have been identified in the development of and the exacerbation of its associated symptoms, mortality risk and co-morbidities.

Reviews such as Sio and Chews 2021 systematic review and meta-analysis of asthma risk factors, identify that a family history of allergy related conditions was the most frequently reported risk factor (pooled OR 4.66 95% CI: 2.62-4.67)) in asthma etiology, as well as allergic rhinitis and atopic dermatitis.

Respiratory viruses such as the common cold, and RSV in children are one of the most pertinent triggers of asthma exacerbations as they are highly prevalent in the community, contribute to asthma development and can be a marker of asthma susceptibility (Jartti et al., 2020). In young children, especially the preschool age group rhinovirus (RV) is frequently responsible for the initiation of acute wheezing illness.

For children who wheeze when infected with RV not only do they have an increased risk of going on to develop asthma, once asthma is established future RV infections serve as potent triggers for exacerbations of asthma throughout the life course (Jackson and Gern, 2022).

Although inconsistent, there is evidence to suggest gene-environment interactions on asthma risk, implicating oxidative stress pathways in the pathogenesis of asthma. It is thought that the damage that results from oxidative stress may be involved in bronchial inflammation and reduced lung function. Due to their very function, the antioxidant genes in the glutathione S-transferase family are understood to be associated with development and progression of asthma (Dai et al., 2021).

Bacterial gut microbiota and bacterial-derived short-chain fatty acids found in infants have been shown to be protective against childhood asthma, yet a role for fungal microbiota in asthma etiology is ill defined. However, overgrowth of the yeast *Pichia kudriavzevii* in the gut microbiota in both mice and humans was demonstrated to be causal of increased asthma risk in Ecuadorian and Canadian infants, as well as causal associations between early life gut fungal dysbiosis and later allergic airway disease (Boutin et al., 2021). Modulation of gut bacteria could therefore be considered an important area of future research in allergen response management, and thus asthma management and prophylactics.

In housing related risk, the presence of mould, mouldy odour, water damage, and the burning of incense have all been reported as significant risk factors with pooled OR ranging from 1.43-1.73. Other significant risk factors include, BMI, air pollution through a variety of exposures both internal (including occupational exposures) and external (Sio and Chew, 2021)

Asthma is becoming increasingly well known for its associated risk in developing cardiovascular disease, which is more common in women (Picado et al., 2019). Particularly uncontrolled eosinophilic phenotype asthma which is thought to increase the risk by not only presenting in these groups with classic coronary artery obstruction but non-obstructive vasospastic events.

The risk of stroke for example was higher for individuals who had uncontrolled asthma (adjusted HR 1.34, 95% CI 1.03–1.73) or smoked (HR 1.48, 95% CI 1.10–2.00) in an analysis of the HUNT study- a prospective population-based cohort study of 58, 712 adults in Norway (Cepelis et al., 2020). This could be linked to having similar immunological and or inflammatory responses, long-term airway remodeling, and or irreversible airway obstruction leading to reduced lung function over time, which O'Byrne and colleagues (2009) noted can be more rapid in individuals who have severe exacerbations of asthma.

Exposure to environmental toxins in utero such as particulate matter and maternal smoking lead to later airway remodeling, airway hyperresponsiveness, and airway inflammation (Wang et al., 2020).

There has been much debate as to whether asthma leads to lung cancer, Zhou et al (2018) for example in their analysis of publicly available genetic summary data from two large consortiums, found no such associations (Zhou et al., 2018). A recent systematic review however found that female patients with asthma were more likely to develop lung cancer (RR: 1.32, 95 % CI: 1.10–1.58) (Zhang et al., 2022). This could be due to differences in other exposures between the sexes rather than solely genetics.

Overall, the development of asthma is likely due to a complex interplay between genetic, environmental, immunological, and other factors. Researchers continue to study the underlying mechanisms of asthma to develop more effective treatments and preventative measures.

Asthma is a chronic condition, signifying that it is ongoing and can progress over time. The progression of asthma can vary between individuals, although generally, it follows a pattern of worsening symptoms and lung function over time (Mansbach et al., 2023).

In the early stages of asthma, individuals may experience occasional episodes of wheezing, coughing, and shortness of breath. These symptoms can be triggered by allergens, exercise, or respiratory infections. However, lung function may still be within normal limits.

As asthma progresses, symptoms may become more frequent and severe, occurring several times a week. Lung function may also begin to decline, with decreased airflow in the airways. Treatment may be necessary to manage symptoms and prevent exacerbations (Bloom et al., 2021).

Moderate persistent asthma is common as asthma progresses. symptoms can occur daily and may interfere with daily activities. Pulmonary fibrosis can develop leading to airway remodelling and lung function is further reduced, meanwhile, the risk of exacerbations increases. Treatment with daily controller medication is usually necessary to maintain control (Abadoglu et al., 2005).

Severe persistent asthma: This is the most severe stage of asthma is referred to as severe persistent asthma and symptoms are constant and severely limit daily activities. Lung function is significantly reduced, and the risk of exacerbations is high. Treatment with high-dose controller medication and possibly oral steroids may be necessary to manage symptoms (NICE, 2023). It's important to note that not all individuals with asthma will progress to severe asthma. With proper management and adherence to treatment, many people with asthma can maintain good control and avoid progression of the disease. Regular monitoring and follow-up with a healthcare provider are key to managing asthma effectively.

2.3.2 Inactivity

Physical activity is generally defined as any bodily movement produced by the skeletal muscles that require energy expenditure (WHO, 2017). Physical inactivity is well established as an objective risk factor for several chronic diseases including; stroke, heart disease, obesity, diabetes, breast and colon cancer (NCD Alliance, 2022). Furthermore, studies indicate that physical inactivity is a solid and independent risk factor in the development of bronchial hyperresponsiveness in adults of the general population (Hacken, 2009). However, limited evidence to date exists that examines the impact of inactivity on respiratory health specifically.

Decreased deep inspiration and sigh rate during physical inactivity is thought to lead to smooth muscle latching and subsequently, an increased risk of asthmatic symptoms. A systematic review which used 39 longitudinal and cross-sectional studies found that individuals with higher physical activity levels had lower incidences of asthma (odds ratio 0.88 (95% CI: 0.77–1.01)) (Eijkemans et al., 2012).

As physical activity is often compounded by poor mobility, this is an important area that warrants further investigation.

Bronchial hyperresponsiveness (BHR) is a risk factor for the development and advancement of asthma and its associated symptoms. It is deemed one of the characteristics of airway inflammation in asthma and is recognized more frequently as a clinical endpoint for therapeutic intervention in asthma management.

BHR is largely unknown in the general population. A large population-based study which investigates the association between usual levels of physical activity and BHR in a representative sample of adults participating in the European Community Respiratory Health Survey II (ECRHS II) found a negative association between physical activity and BHR (Janson et al., 2001). The association was consistent across several subgroups independently of potential confounders for BHR and physical activity. The study indicates that the cut-off point for the frequency (or duration) of physical activity at which BHR would be significantly reduced is relatively low suggesting that, if causal, even modest physical activity may have a positive effect on BHR (Shaaban et al., 2007).

2.3.4 Asthma and air pollution

Certain pollutants have been found to both increase symptoms and aid in its development. Exposures to $PM_{2.5}$, Particulate matter 10 (PM_{10}), nitrogen dioxide (NO_2) and black carbon, for example, are associated with an increased risk of asthma development as demonstrated in a recent meta-analysis (Khreis et al., 2017).

Environmental tobacco smoke (ETS), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide and carbon dioxide (CO and CO_2), volatile organic compounds (VOCs), Sulfur Dioxide (SO_2) and particulate matter (PM10 and PM2.5) have also been linked to the development of and exacerbation of asthma (Levy Zamora et al., 2018, Schiltz et al., 2018, Wing et al., 2018).

Although not exhaustive, an overview of some of the asthma related relationships associated with air pollution explored in this chapter are described in Figure 1. The pollutants responsible for the respiratory effects of air pollution have been shown to differ mechanistically by age (Halonen et al., 2008) and gender.

Literature suggests that in children asthma exacerbations are more prevalent in boys than in girls. However, in adults, active asthma is more prevalent in women than in men (Guarnieri and Balmes, 2014a).

The UK's Committee on the Medical Effects of Air Pollutants have identified four main mechanisms in which air pollution may contribute to the development and exacerbation of asthma; oxidative stress, airway remodeling, inflammatory pathways and immunological responses and enhancement of respiratory sensitization to aeroallergens (Guarnieri and Balmes, 2014a) which are inhalable and often unavoidable. Preventing acute episodes of exacerbation is a pivotal strategy in disease management (Sama et al., 2017).

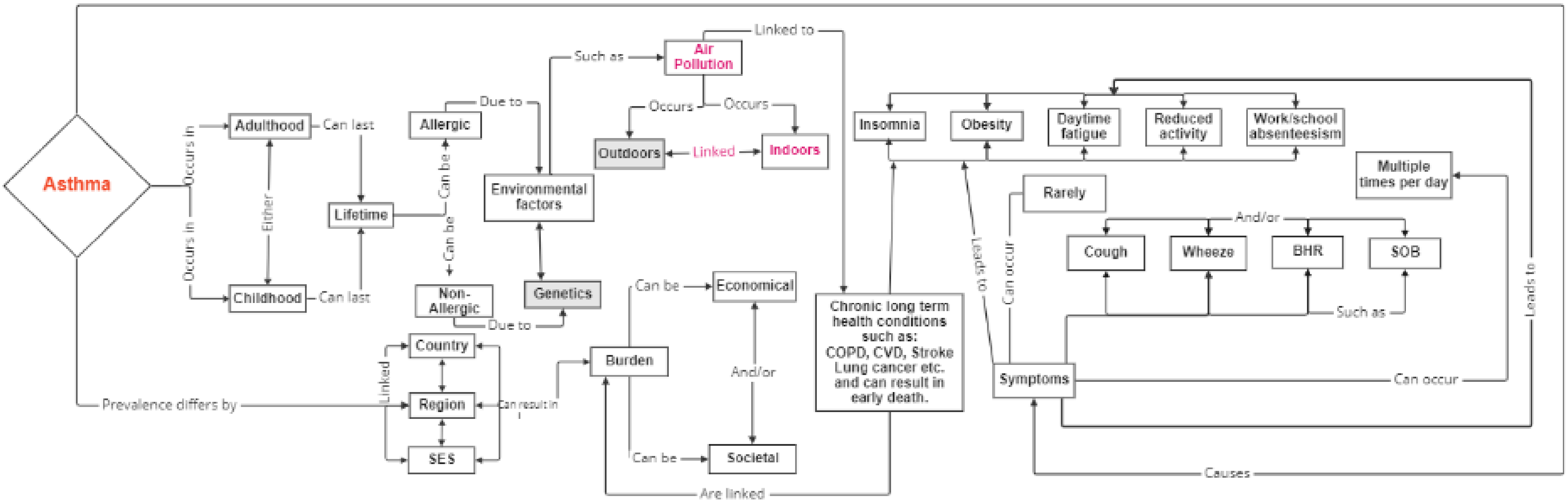

Figure 1 A Model to explain the role of asthma in air pollution exposure.

1

[1] BHR Bronchial hyperreactivity
SOB Shortness of breath

2.4 Air pollution

Air pollution, which occurs both outdoors and indoors is linked with poor asthma outcomes in all age groups (Guarnieri and Balmes, 2014c, Breysse et al., 2010, Paterson et al., 2021, BLF, 2022). Air pollution consists of inhalable particles that have the ability to cause harm and is produced both organically and as a biproduct. Pollutants can affect the quality of both the indoor and outdoor air and are determined by a range of factors.

Understanding and mitigating pollutants, both indoors and outdoors, can reduce the risk of some of the negative short and long-term health effects associated with exposure. Some individuals may be more susceptible to the detrimental health effects such as the vulnerable and those with asthma and heart disease for example, who are more likely to require hospital intervention during high levels of pollution.

Around three billion individuals still cook using solid fuels, this type of practice produces high levels of indoor air pollution with toxic particles that can penetrate deep into the lungs. Poor air quality is especially prevalent in low-middle income countries which often have poorly ventilated dwellings where indoor smoke can reach levels one hundred times higher than what is deemed acceptable for fine particles. This is a major public health concern due to the health effects associated with such exposure.

2.5 Key Air Pollutants and Sources

Air pollutants associated with health risks include carbon monoxide, Sulphur dioxides, lead, ground-level ozone, nitrogen dioxides and particulate matter with particle pollution and ground-level ozone posing the most widespread health risks (Kelishadi and Poursafa, 2010). These pollutants are known to exacerbate respiratory symptoms and can be heterogeneous in their composition (Kim and Lee, 2017). These pollutants can be found both indoors and outdoors.

Sources of indoor air pollution can differ between developed and developing countries. In developing countries coal, or solid fuel such as biomass are a major fuel source for both cooking and heating. This type of combustion can produce nitrogen dioxide (NO_2), PM, carbon dioxide (CO), benzene (C_6H_6), volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs). PAHs derived from cooking combustion can be in both PM and gas phases, although literature suggests that PAHs of a gaseous nature tend to be higher than particulate PAHs (Jiang et al., 2016).

In developed countries, although trends are similar, differences in the management of such emissions from coal and biomass etc., are much more regulated with mitigation in place for many (i.e. shift to cleaner fuel use, flu-gas-desulphurization) (Williams, 1999). Emission rates are declining in the UK with the exception of $PM_{2.5}$ which appears to have ceased in reduction (CMO, 2022). This is worrying as exposure to $PM_{2.5}$ alone was attributable to 14,400 deaths in the UK in 2019 and is one of the largest drivers of air pollution’s burden of disease globally (SoGA, 2022).

2.5.1 Particulate Matter

Particulate matter (PM) is a heterogeneous mix of small particles and liquid droplets which are suspended in the air. The size of the particle is linked to their potential in the causality of poor health outcomes. PM is categorized based on its aerodynamic diameter; PM_{10} (inhalable coarse particles with a diameter of 2.5-10 μm), $PM_{2.5}$ (fine particles with a diameter of < 2.5 μm) (Kelishadi and Poursafa, 2010).

These particles are of growing concern. The cardiovascular system is a known target for ultrafine particles (UFP's) as they can translocate from the lungs to the systemic circulation. UFP's associated with some cardiovascular effects are able to penetrate the epithelium and then reach the blood and other organs within the body due to their high deposition efficiency in pulmonary regions (Zhu et al., 2008). This has been observed in both human subjects and animal models (Zhu et al., 2008).

$PM_{2.5}$ is composed of elementary and organic carbon, metals, and chemical components and is the most widely studied air pollutant. These components can each directly influence clinical outcomes for patients with respiratory disease (Kim and Lee, 2017).

Constituents of PM that are of interest to individuals, researchers and policymakers are polycyclic aromatic hydrocarbons, transition metals and environmentally persistent free radicals due to their oxidative stress potential and the phenotypic changes associated with asthma. Further, PM often contains immunogenic substances independently associated with asthma exacerbation such as fungal spores and pollen (Guarnieri and Balmes, 2014a).

Oxidative stress can cause inflammation in the airways, this plays an important role in symptom exacerbation for individuals with respiratory diseases. Those with an allergic response to environmental triggers are likely to suffer the worst effects of air pollution.

2.5.2 Traffic-Related Air Pollution (TRAP)

Traffic-related air pollution (TRAP) comprises of a complex mixture of combustion-related PM, non-combustion sources and primary gaseous emissions including nitrogen oxides. These emissions lead to secondary pollutants such as organic aerosol, nitrates and ozone (Guarnieri and Balmes, 2014a).

Diesel exhaust particles account for around 90% of airborne PM throughout the world, especially in large cities (Jiang et al., 2016) and exposure is associated with poor health outcomes. Some studies have suggested that time spent in traffic 1 or 2 hours earlier increases the risk of the onset of myocardial infarction two to three-fold (Zhu et al., 2008) and adults who have never had asthma have been found to have increased risk of incident asthma associated with TRAP (Guarnieri and Balmes, 2014a).

Given that the majority of employed individuals spend a significant amount of time commuting, this is a worrying finding. However, the concentration of many of the constituent pollutants in TRAP rapidly diminishes with distance away from roads with the worst health effects being experienced within 300-500m of roadsides (Guarnieri and Balmes, 2014a).

Some occupational exposures to outdoor air pollution are relevant to the general population such as those working in the transport industry (bus/lorry drivers) due to the overlap of exposure experienced through daily commuting (Neophytou et al., 2013). A recent study found statistically significant associations between average $PM_{2.5}$ levels and levels of oxidative damage through Urinary 8-Hydroxy-2'- Deoxyguanosine (8-OHdG) (a form of free-radical-induced oxidative lesion commonly used as a biomarker for oxidative stress) measured through urinalysis of 95 trucking industry participants (Neophytou et al., 2013). This demonstrates that inflammatory responses to TRAP may be more prevalent than current indications suggest.

2.5.3 Nitrogen oxides

Nitrogen Oxides (NO_x) are highly reactive gases which contain varying levels of nitrogen and oxygen. Nitrogen oxides, which include nitrogen dioxide form primarily by the reaction of ozone with nitric oxide, which is emitted during fossil fuel combustion (Guarnieri and Balmes, 2014a).

2.5.4 Nitrogen Dioxide

Nitrogen dioxide (NO_2) is a gas which produces free radical oxidants and is derived from both direct and indirect sources and occurs as a result of the partial oxidation of nitric oxide. In outdoor air, NO_2 occurs directly from combustion (burning of fossil fuels and combustion engines) and indirectly from reactions in outdoor air. In indoor air, the main sources are tobacco smoke and cooking equipment (Solomon et al., 2000).

NO_2 is a deep lung irritant, and exposure at high concentrations can cause acute lung injury and even death (Frampton et al., 2002). Due to the low water solubility of NO_2 (0.037mL.mLH2O-1 at 35°C), large amounts can be inhaled and deposited in the airways (Mohsenin, 1994).

NO_2 can also be formed in the lung during inflammation. An end product of NO_2 reactivity and the result of the catalytic activity of eosinophil peroxidase and myeloperoxidase or the decomposition of peroxynitrite is nitrotyrosine formation which is often present in the lung of patients with pulmonary disease, COPD, asthma and other inflammatory disorders. High levels of NO_2 can be found in ambient air and are associated with bronchial symptoms. The extent of damage as a result of exposure and the time in which repair occurs is an important factor to consider.

Animal studies which examined exposure to NO_2 for 1,3 or 5 days at an exposure rate of 5 ppm for 6 hours per day resulted in little lung injury or inflammation. However, when exposed to 25 ppm acute and reversible injury occurred, indicating that NO_2 can induce airway hyperresponsiveness and that NO_2 may be an important pathological factor in the effects observed in the allergic inflamed lung (Poynter et al., 2006).

NO_2 can affect both the function and viability of cells as it damages proteins, lipids, and other biomolecules due to free radical oxidation and formation of nitrous and nitric acid. A study by Soloman et al. (2000) which examined the effect of serial-day exposure to NO_2 found that exposure to NO_2 for four hours per day for three consecutive days at an exposure rate of 2.0 ppm can induce mild bronchial airway inflammation (Solomon et al., 2000). Household concentrations of NO_2 are often higher than those found outdoors. Literature suggests that a 16ppb increase in indoor NO_2 is associated with a 20% increased risk of respiratory problems in children. Recent findings suggest that for those with compromised airways such as those with asthma, exposure of just 0.26ppm of NO_2 for 30 minutes at rest is sufficient to induce increased airway responsiveness (Frampton et al., 2002). Exposure to NO_2 in infancy increases the risk for the development of asthma throughout childhood, and long term exposure to air pollution can damage lung function in children (Jiang et al., 2016).

2.5.5 Carbon monoxide

Carbon monoxide (CO) is an odourless and colorless gas formed by incomplete carbon combustion. CO is predominantly emitted from vehicle exhaust, construction equipment and wood burning. Increasing numbers of vehicles on the road plays an important role in the worldwide increase of CO emissions (Kelishadi and Poursafa, 2010).

2.5.6 Combustible biproducts

Combustion pollutants can be found indoors and include, outdoor air, tobacco smoke, e-cigarettes, exhaust emissions from transportation, and other activities such as burning wood, and from vented and unvented combustion appliances such as gas cookers, furnaces, fireplaces and woodstoves which use natural or LP gas, kerosene, wood or coal (Osei et al., 2019). Pollutants such as carbon monoxide, sulphur dioxide, and nitrogen dioxide, as well as unburned hydrocarbons and aldehydes are produced when burning these types of fuels.

The form and quantities of pollutants produced are variable depending on type of appliance, fuel type, installation and maintenance (EPA, 2022c). The use of biomass fuel in cooking produces variable respiratory impairment mostly via early-stage small air-way obstruction. This is likely explained by the high concentration of respirable pollutants in the air during combustion processes. The degree of impairment following exposure to combustible bi-products such as biomass correlates with the duration the individual is exposed (Pravallika Pagadala, 2018).

2.5.7 Ozone (Ground level)

Ozone (O_3) is a gas made of three oxygen atoms. Ground-level ozone is formed by photochemical reactions between sunlight and pollutant precursors such as nitrogen oxides and VOCs (Guarnieri and Balmes, 2014a). In hot and sunny weather, O_3 can form in harmful concentrations (Kelishadi and Poursafa, 2010). Exposure to ozone results in airway inflammation, airway hyper-responsiveness, and decreased lung function in both healthy and asthmatic individuals (Guarnieri and Balmes, 2014a).

Other health risks are associated with O_3 exposure, for example, O_3 can increase the risk of appendicitis and at higher levels can increase the risk of perforated appendicitis. Other exposures, such as that of PM containing PAHs and diesel, increase the risk of bladder cancer (Jiang et al., 2016). An important consideration for the future is that climate change is predicted to increase the concentration of ozone across multiple locations due to the increased sunshine and ambient temperatures projected (Guarnieri and Balmes, 2014a). This could have catastrophic consequences for people worldwide.

2.5.8 Sulphur Dioxide

Sulphur dioxide (SO_2) is a gas formed as a result of burning fuel containing Sulphur and during gasoline extraction from oil or in the extraction of metals from ore (Kelishadi and Poursafa, 2010). SO_2 can cause breathing difficulties and more prominent bronchoconstriction in asthmatic individuals (Guarnieri and Balmes, 2014a). Lead and benzene homologues are also pollutants that should be considered (Jiang et al., 2016).

2.5.9 Volatile Organic Compounds

Volatile organic compounds are a large group of carbon-containing compounds that are of particular concern due to their high volatility (50-240°C). They are described as compounds with a vapour pressure above 1mmHg at room temperature and present as vapour in atmospheric photochemical reactions (Tsai, 2019). Concentrations of VOCs can be consistently up to ten times higher indoors than concentrations found outdoors (EPA, 2022b).These compounds include benzene, toluene and trichloroethylene, however polycyclic aromatic hydrocarbons are generally known as semi-volatile organic compounds.

There is further subdivision still between aromatic, aliphatic, oxygenated, and chlorinated hydrocarbons and hundreds of VOCs have been identified, however their impact on health either causative of disease or exacerbation of existing conditions or the interaction between each individual VOC and the resultant impact on health is still largely under investigation.

VOCs can be found in many household products such as: air fresheners, carpet cleaners, washing detergents, furniture polish, paints and paint strippers as well as varnishes, glues, and other new furnishings (BLF, 2022). According to the Health and Safety Executive, products containing formaldehyde (CH_2O) should be clearly labelled (HSE, 2022). However, no such regulation is yet in place for many other VOCs despite there being clear evidence of the health risks associated with exposure. Because they are easily inhaled, VOCs are associated with a number of acute health outcomes such as respiratory problems, headache and eye, nose and throat irritation, with long term exposure especially at higher concentration leading to cardiovascular problems, immune suppression and cancer (Yue et al., 2021, EPA, 2022b, BLF, 2022).

Personal exposure to VOCs is reliant upon a number of factors; mechanical ventilation, natural air exchange rate/ ventilation and interaction with indoor environments (Lv et al., 2016). Individuals can reduce the levels of VOCs with appropriate source control (i.e., proper storage of chemicals) or implementing air filtration systems. More broadly, guidelines are published both for governments and workplaces detailing how to mitigate to the lowest possible levels to ensure the health of the workforce is best protected. There is however little guidance for households on the management of this.

2.5.10 Microbial Volatile Organic Compounds

Microbial volatile organic compounds (mVOCs) consist of a collection of compounds created in the metabolism of fungi and bacteria. mVOCs are formed during the primary (DNA, amino and fatty acid synthesis) and secondary metabolism mainly as side-products in metabolic oxidation of glucose. Production of mVOCs is largely affected by microbial growth and conditions such as humidity and temperature. Exposure to mVOCs results in eye and upper-airway irritation (Korpi et al., 2009).

Sources of air pollution and their composition differ between locations with some countries experiencing worse effects than others. A recent study which examined gender differences and the effect of air pollution in children with and without allergies in Northeast China found that that the average levels of ambient coarse particulate matter (PM_{10}) and Sulphur dioxide (SO_2) were around 6 and 2.5 times higher respectively than the limit recommended by the WHO. Ambient air pollution was associated with respiratory symptoms in children. For those without allergic predisposition, males had an increased risk. For those with an allergic predisposition, the highest risk was found to be in females (Dong et al., 2011).

2.5.11 Carbon dioxide

Carbon dioxide (CO_2) is a ubiquitous gas that is naturally occurring in Earth's atmosphere in trace amounts. Crowded rooms with numerous people breathing the same air can lead to increased CO_2 levels. Increased levels of CO_2 can impact on individuals' level of focus, productivity and comfort resulting in fatigue.

ASHRAE (2022) who aim to improve heating, ventilation, air conditioning and refrigeration systems design and construction, caution that indoor concentrations of CO_2 do not indicate overall air quality, but can be a useful tool in indoor air quality assessments providing the limitations of the tool is understood. Indoor concentrations of CO_2 below 1000 ppm are considered an acceptable indicator of indoor air quality. However, this indicator is at best a proxy for outdoor air ventilation rate per person. Cognitive health effects of short-term (2-8 h) exposure at concentrations between 600 and 5000ppm sick building syndrome at concentrations over 1000ppm have been observed (ASHRAE, 2022).

There are many complex interactions between the outdoor environment and the indoor environment. What the indoor environment looks like in terms of air quality or exposure is dependent upon several factors some of which this chapter has addressed and are sumarised in figure 2.

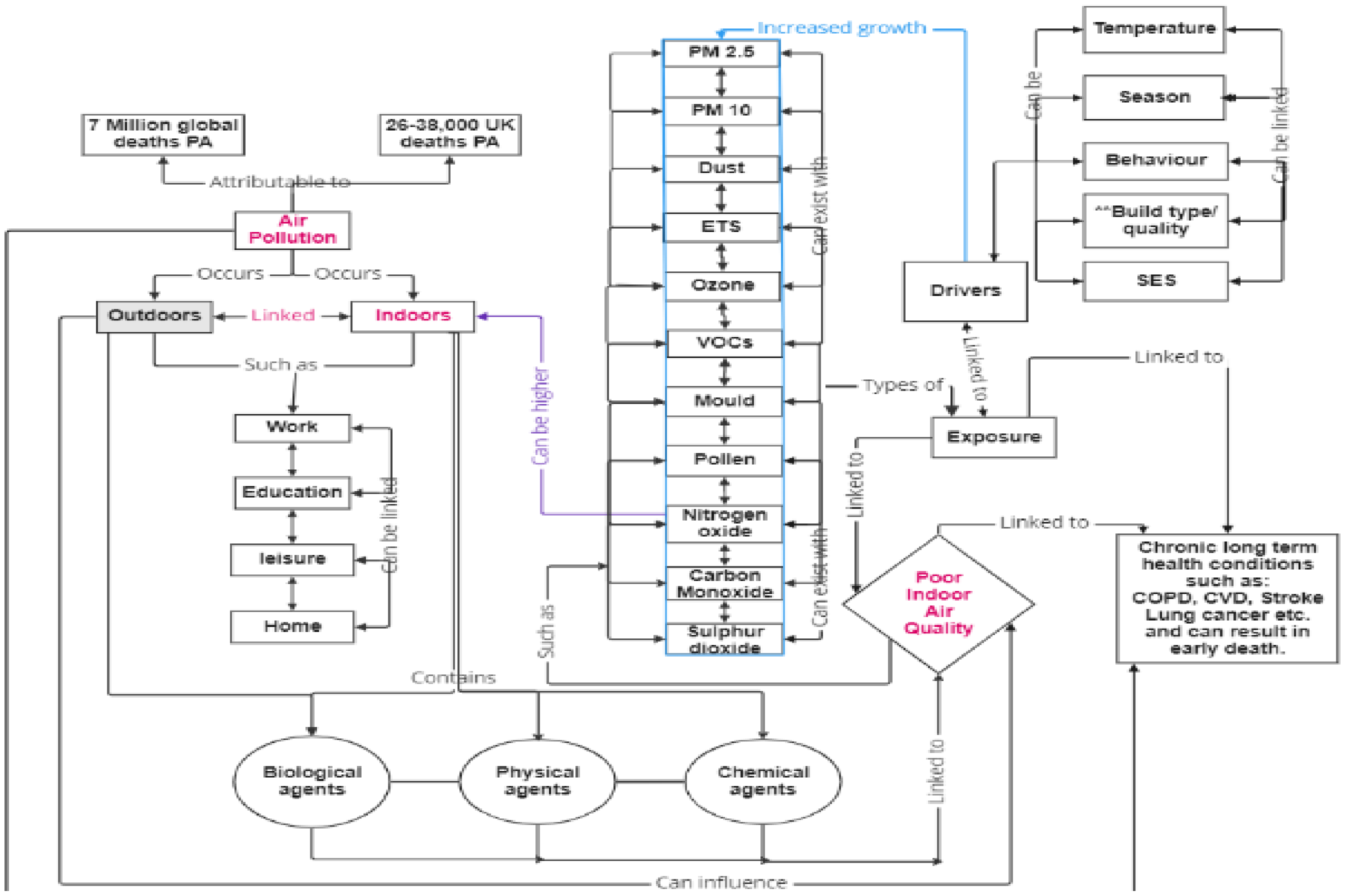

Figure 2 Pillar of pollution model: A concept model describing some of the relationships between air pollution and health.

2.6 Mitigating Health Risks: Guidance Values for Exposures

2.6.1 Global and European Standards

The World Health Organization (WHO) published guideline values for selected compounds with known health risks associated to exposure. Under this directive many local governments and The European Environment Agency also publish standards of air quality that all countries within Europe should adhere to, to protect human health. These standards relate to the limits set by the Air Quality Directive (AQD) and the WHO guidelines for outdoor air pollution; these figures are detailed in Table 3 (DEFRA, 2012, WHO, 2018a, European Commission, 2018).

The guidelines indicate discrepancies about what the target and limit concentrations should be depending on country affected, making adherence and reduction troublesome. In recognition of the magnitude of the risk to health posed by air pollution these guidelines underwent extensive review and updated guidelines were published in 2021, the key findings of which are summarized in Table 3. Table 4 summarizes the indoor air exposure guidance issued by the WHO which demonstrates how much more limited this guidance is. For individuals, The Daily Air Quality Index (DAQI) was established in 2011 to deliver easily accessible, real-time and forecast ambient air pollution levels (DEFRA, 2022).

Table 3 Exposure guidelines for ambient air pollution

Component specific exposure guidelines for air pollution

		Objective concentration in micrograms per cubic meter of air (µg/m³)				
Pollutant	**Averaging Period**	**Air Quality Directive**	**WHO**	**UK air quality objectives**	**European obligations**	**Target reduction**
PM_{10}	Daily	Limit 50[2]*	50 15 µg/m³	50*	50 *	
PM_{10}	yearly	Limit 40	20 15 µg/m³	40	40	
$PM_{2.5}$	daily	5 µm/m3	25 15 µg/m³			
$PM_{2.5}$	yearly	Target value 25	10 5 µg/m³	25	25	15% (UK) and 20% (EU)
O_3	Daily 8hr mean	Target value 120 [3]	100	100 [4]	120 [5]	
NO_2	One hour	Limit 200 [6]	200	200 [7]	200 [8]	
NO_2	Yearly	Limit 40	40 10 µg/m³	40	40	
	24-hour		25 µg/m³			
SO_2	15 min mean			266 µm/m³ [9]		
SO_2	1-hour mean			350 µm/m³ [10]	350 µm/m³ [11]	
SO_2	24-hour mean		40 µg/m³	125 µm/m³ [12]	125 µm/m³ [13]	
PAH	Yearly			0.25 ng/m³	1.0 ng/m³	

1 Overview of current guidelines adapted from the WHO Air Quality Guidelines (2005) (with key updates from the 2021 Global Update noted in red); DEFRA's Air quality objectives (2010-2015) and the EU Air Quality Directive (2018).key 1. Concentrations are given in micrograms per cubic meter of air (µg/m³) unless otherwise stated.

Indoor air pollution, however, is far less regulated and recommendations to which governments, organizations and individuals can aspire to achieve, comes with a much less conjoined approach. Therefore, the World Health Organization

[2] * Not to be exceeded more than 35 times per year
[3] Not to be exceeded more than 25 days per year over a 3 year average
[4] Not to be exceeded more than 10 times per year
[5] Not to be exceeded more than 25 times per year over a 3 year average
[6] Not to be exceeded more than 18 times per year
[7] Not to be exceeded more than 18 times per year
[8] Not to be exceeded more than 18 times per year
[9] Not to be exceeded more than 35 times per year
[10] Not to be exceeded more than 24 times per year
[11] Not to be exceeded more than 24 times per year
[12] Not to be exceeded more than 3 times per year
[13] Not to be exceeded more than 3 times per year

(WHO) published guideline values for indoor air pollution. This was based on three criteria: presence of indoor sources, availability of toxicologic and epidemiologic data, and indoor air quality levels exceeding no observed adverse effect level (NOAEL) and/or lowest observed adverse effect level (LOAEL) (WHO, 2010a).

With more research illuminating and emphasizing the need for regulation of the indoor environment scientists are calling for coordinated global action to reduce the vastly underestimated problems associated with indoor air pollution. Sonne et al., (2022) recognize the progress thus far but highlight that more is required to mitigate emerging VOCs that are otherwise unregulated (Sonne et al., 2022). The authors implore global action to include guidelines and legislation for ventilation, absorbing materials, filters, phytoremediation and photocatalysts following international guidelines, including the United National Sustainable Development Goals #3, good health and wellbeing, and #11, Sustainable cities and communities.

In relation to semi-volatile organic compounds a ban on the more toxic and relentless chemicals (e.g., polychlorinated biphenyls (PCBs), per-fluorinated substances (PFAS), brominated flame retardants) is warranted (Sonne et al., 2022). The Environment Act (2021) recommended new targets of an annual average for PM2.5 in the UK of 10 $\mu g/m^3$. The UK has committed to achieving this for every geographical area by 2040. However, there are currently no systematic long-term monitoring data available regarding indoor pollution trends in the UK (CMO, 2022).

Table 4 Maximum indoor air pollution exposure as recommended by the World Health Organization

	15 min	*30 min*	*1 hr*	*8hr*	*24hr*	*Annual*	*Other measure*
Carbon monoxide	11mg/m^3		35mg/m^3	10mg/m^3	7mg/m^3		
Formaldehyde		0.1mg/m^3					
Naphthalene						0.01mg/m^3+	
Nitrogen Dioxide						40 µg/m^3	
Polycyclic aromatic hydrocarbons						8.7 × 10–5 per ng/m^3 of B[a]P.++	
Radon							100 Bq/m^3+++
Trichloroethylene							1/10 000, 1/100 000 and 1/1 000 000 are respectively 230, 23 and 2.3 µg/m^3 .

+ In the absence of mothballs or other sources such as combustion of biomass, indoor air concentrations of naphthalene are just above the typical limit of detection of about 0.001 mg/m3

++ The corresponding concentrations for lifetime exposure to B[a]P producing excess lifetime cancer risks of 1/10 000, 1/100 000 and 1/1 000 000 are approximately 1.2, 0.12 and 0.012 ng/m3, respectively.

+++, If countries are unable to meet this level due to country-specific conditions, the reference levels should not exceed 300 Bq/m3 which represents approximately 10 mSv per year according to calculations from the International Commission on Radiation Protection

The Environmental Protection Agency National Air Quality Standard (NAAQS) has been established. The recommended 8 hr. ambient O_3 level is 80 ppb, the 24 hr. average ambient $PM_{2.5}$ is 35 μm/m^3 (Delfino et al., 2008). Although some small particle pollution shows health effects at low levels, no threshold has been identified below which no adverse health effects are found. It is therefore important to achieve the lowest concentrations of PM as possible. Reducing the annual average $PM_{2.5}$ level from 35 μm/m^3 to 10 μm/m^3 could reduce deaths related to air pollution by around 15%. In cities where air quality does not comply with the standards set, the average life expectancy is reduced by 8.6 months.

The Environmental Protection Agency (EPA) developed The Air Quality Index (AQI) to make understanding air pollution easier. AQI is determined by indoor pollution concentrations and ranges from 0 being “Good” to 500 being “Hazardous”(EPA, 2018). This draws on the NAAQS as summarized in Table 5.

Table 5 Air Quality standards and their recommended thresholds based on the EPA's Air Quality Index (AQI).

Particulate Matter (PM2.5): 0 – 12 ug/m3 (yearly*[14])	Particulate Matter (PM10): 0 – 54 ug/m3 (24hr*[15])
Volatile Organic Compounds (VOCs): 0 – 15 ppm 8-hr.	Carbon Dioxide (CO_2): 400 – 650 ppm For an 8- hr. work day
Formaldehyde: 0 – 0.2 ppm for an 8-hr. workday	Carbon Monoxide (CO): 25 ppm limit for an 8-hour workday
Nitrogen Dioxide (NO_2): 100 ppb 1-hour standard[16]	Radon: No safe exposure levels
Methylene chloride: 250 ppm odour threshold	Polycyclic Aromatic Hydrocarbons (PAHs): Less than 10 ppm

2.7 Asthma and the home environment

Adult asthma accounts for approximately 7-10% of asthma diagnoses in western countries (Enilari, 2019). Dampness within the home is a common occurrence and is related to the presence of fungi, bacteria, and house dust mites (Björnsson et al., 1995, EPA, 2022a). The housing stock in Europe is reported to be afflicted with dampness in around 10-15% of all homes and is associated with respiratory problems, including asthma (Wang et al., 2017).

[14] annual mean, averaged over 3 years.
[15] Not to be exceeded more than once per year on average over 3 years
[16] 98th percentile of 1-hour daily maximum concentrations, averaged over 3 years.

Studies indicate that adults who live in homes affected by damp and fungi were more likely to experience the onset of asthma and see a decline in overall lung function over time (Jie et al., 2011, Committe on Damp Indoor Spaces et al., 2004).

Cold, damp, and fungal contamination is associated with chronic respiratory symptoms such as asthma even after controlling for any potential confounding factors such as smoking and socioeconomic status, social class and employment. This makes it critical, therefore, that measures are taken to ensure that housing (build type/ leaks/ poor maintenance etc.) is not causal in the exacerbation or onset of symptoms associated with poor housing conditions (damp/ fungal contamination/ temperature/ventilation).Furthermore, the location of housing, such as its proximity to vehicle exhaust emissions, airports and major roads all play a significant role in determining the respiratory outcomes of the population (Kim et al., 2008). This is especially prevalent in those individuals of low socioeconomic status who are often housed in areas with high deprivation and poor housing stock. These are typically located in areas that are far from affluent, which may in part be attributable to disproportionate exposure to asthma triggers in the indoor environment which are associated with residing in substandard housing (Krieger and Higgins, 2002b).

Further larger-scale studies to assess the impact that the indoor environment has on asthma outcomes over time are needed. These will help to identify the true impact on health, as well as to assess how these types of environments affect adults. To date little research has been conducted examining the effect of indoor environments on adult's respiratory health (Shajahan et al., 2019).

2.7.1 Housing

There is a substantial and growing evidence base that suggests the thermal quality and overall condition of property have important influences on individual health outcomes such as mental and physical health, cardiovascular disease, and respiratory illness such as asthma (Dear and McMichael, 2011). Studies indicate that socioeconomic status can be a major confounding factor in the type and quality of housing an individual may reside in. Individuals with low-income and poor health are often forced into health-risky homes due to market processes with those classed as disabled or in poor health becoming especially vulnerable to the effects of poor housing on their individual health (Baker et al., 2017a).

Individuals are reported to spend up to 90% of their time indoors, especially in their own home environments (Zhang et al., 2016). However, some suggest this figure is much lower with individuals reportedly spending around 70% of their time indoors (Richardson et al., 2006). Healthy indoor home environments are crucial for health and wellbeing.

The home environment is reported to be the main source of airborne pollutant exposure. An Australian based study which applied an Index of Housing Insults (IHI) to a sample of 1000 low-income households to predict the levels of general and mental health, as well as clinical depression, identified that a broader understanding of the complex interaction of the effects of housing on health needs to be developed, instead of just examining separate housing components as the interaction between the two is multifaceted (Baker et al., 2017a).

To address this issue a toolkit was designed to execute indoor assessment protocol that can be used for short-term discrete measurements that can be carried out by non-specialists such as health visitors or housing officers to assess the quality of the indoor environment in a simple and cost-effective way. This toolkit focuses more closely on breathing-related illnesses than others which have not measured microbial or pet allergens, which have been linked to asthma. Therefore, making it an important tool in helping to reduce respiratory symptoms and ensuring that housing is not detrimental to occupant's health. The protocol looked at other toolkits and protocols that were available and devised a comprehensive assessment that addresses the 14 components that have been validated as being the greatest risk.

These components include humidity, temperature, dampness, number of people residing in the dwelling, presence of pets, dust mite, plant-related microbes, airborne microbes, volatile organic compounds, CO_2, weather data and ventilation (Richardson et al., 2006). Whilst the toolkit will undoubtedly be an expedient resource for many professionals, care must be taken to ensure that intrinsic country and regional variations are considered when utilizing this resource.

Housing cannot just be considered shelter; it is a collection of individual components that collectively affect individuals' lives, including health, wellbeing, education, employment and wealth (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, U.S. Department of Housing and Urban Development and CDC, 2006).

To date, much research on housing and health has focused on the effects of singular dimensions of housing which include affordability (Baker et al., 2017a), housing quality and housing tenure (Baker et al., 2016) which do not necessarily take into consideration the influence of location, structure, and condition of the dwelling and also the sub-populations that may be particularly vulnerable to the effects of housing on their health. These subpopulations comprise of disabled individuals, lone parents, or long-term tenants. Individuals who rent their property have poorer health on average than those individuals who own or are purchasing their property (ONS, 2021).

In England, private renting is the second largest tenure type and has expanded in the last decade or so. The latest Government statistics show that in English Housing Survey (2020/1) 19% of the population in England rent their property (4.4 million people) (Department for Levelling Up Housing and Communities, 2021), which represents an increase of 2.8 million over the preceding decade and a half. Younger households are now more likely to rent in the private rented sector than to own their own home (Department for Levelling Up Housing and Communities, 2021). Over recent years families in the private rented sector have seen a large increase, particularly in lone-parent families.

The proportion of households with tenure in the private rented sector with dependent children increased from 30% in 2005-06 to 36% in 2015-16. Given the growth of this sector during this period, about one million more households with dependent children are in the private rented sector (Department for Communities nd Local Government, 2017). In 2009, 31 per cent of UK homes were rented either from the social sector (18 %) or privately (13%) indicating that more individuals and families are living in homes that are subsidized and may contain more vulnerable populations (Randall, 2011). in 2016 to 2018, 17% of households (3.9 million) in England lived in social housing (homes rented from a local authority or housing association)(Gov.UK, 2020a).

The Decent Homes Standard is a predefined minimum standard that determines the action point, which no social housing should fall below. The minimum standard for compliance is that the home is in a reasonable state of repair, has reasonably modern facilities and services, and provides a reasonable degree of thermal comfort (Department of Communities and Local Government, 2006).

Over a quarter (28%) of private rented homes in the UK failed to meet the Decent Homes standard in 2015. The comparative figure for social sector rented was 13%. From as early as 2001, the health changes attributable to housing improvements have been examined. A Cochrane review highlighted the importance of improved home warmth and the provision of adequate space within homes as the most prevalent effects on health improvements of occupants (Thomson et al., 2013).

There is still no definitive consensus in academia as to exactly which ‘improvements’ improve or reduce symptoms of what illness/disease. Further, instead of examining housing components singularly in determining the effects of housing on health, Sharpe et al (2019) propose that a more holistic approach is needed.

Using a more integrated, bundled approach of measures may have an enhanced impact on health (Sharpe et al., 2019). However, Baker et al (2017) suggest that the identification and separation of housing and health determinants components imply that the effects can be separated, and measured independently which may misrepresent the actual effect of the relationship between housing and health (Baker et al., 2017b). Further analysis of the effect of separate component measuring in determining specific health effects are needed to develop a sound protocol and methodological validity.

Evidence that links housing improvements with specific health outcomes is lacking. Moreover, little research has been undertaken to date that explores whether housing improvements can have a preventative effect on specific health problems. To address this, studies involving deprived populations at higher risk of poor health have emerged.

The GoWell project (Glasgow, UK) for example, which was established in 2006, was a 10-year study which had previously identified that improvements in kitchens and bathrooms improved mental health outcomes, and that receipt of fabric works could cure the onset of many health problems including respiratory problems, however, they found no preventative effects of housing improvement (Curl and Kearns, 2015). The study was conducted in an area of high depravation that was undergoing regeneration so received heavy investment. It could be considered that any home that may have been significantly substandard at recruitment would likely have seen a vast improvement in health outcome regardless of intervention with the very worst homes likely seeing the biggest improvements.

Quality and type of housing are known to affect all individuals. Longitudinal data of 2400 children and adolescents of low-income families in three different cities were utilized to examine the effects of housing on children's well-being, including their emotional, cognitive, and behavioural functioning over a six-year period and found that; poor quality housing was the strongest predictor of children's well-being, specifically, those residing in low-quality homes had greater emotional and behavioural problems than those in higher quality homes (Coley et al., 2013). With increasing populations and housing growth, it is imperative that safe and healthy homes are developed.

For safe and healthy housing to be created there needs to be a collaborative multi-agency approach. Early reviews however, identified that a lack of information at the community level is a major barrier to developing effective housing policy (Krieger and Higgins, 2002a). In future planning of new home development it is recommended that the use of Health Impact Assessment is fundamental, designing communities that afford opportunities for both physical activity and social interaction are key in the planning stage if healthy communities are to be made (NHS, 2021).

2.7.2 Temperature

Cold homes are well documented in the literature to be associated with poorer health outcomes. A household is considered 'fuel poor' when the fuel poverty energy rating (Standard Assessment Procedure of energy efficiency accounting for policy interventions directly affecting household energy cost) is Band D or below and household disposable income falls under the poverty line. It is important to note that not all poor households experience fuel poverty (Department of Energy and Climate Change, 2014). Some households would not typically be considered poor but may be plunged into fuel poverty in an attempt to meet the high energy costs (Department for Business Energy and Industrial Strategy, 2017).

The generally low standard of energy efficiency across the housing stock of England's ageing housing has resulted in homes being costly to heat, particularly for those individuals on a low income. This can result in individuals keeping their homes at a temperature that might be lower than desired (PHE, 2014). In the UK, the energy efficiency of a home is determined by assessing how much energy a property will consume over a given period - usually 12 months. It is measured using the governments Standard Assessment Procedure (SAP) (Gov.UK, 2020b).

Residing in cold, damp housing can have a profound impact on human health. This is particularly pertinent to children, as children living in inadequately heated homes are at increased risk of poor health outcomes such as respiratory infections, mental health problems, poor educational attainment and asthma

(Tod et al., 2016).

A single-blinded randomized control trial found similar findings; the study indicated that more effective heating (not unflued gas, open fires, or low kilowatt heating) could lower winter school absences for asthmatic children by an average of 21%. Although the study identified that adequate heating was effective in reducing school absence, it recognized that the mechanisms in which this happens are not. It is thought that increased indoor air temperature reduces respirable asthma related indoor air pollutants such as mould spores associated with cold/damp homes, resulting in lower asthma-related symptoms through reduced illness, however this was not measured (Free et al., 2010).

Cold homes are associated with a range of poor health outcomes. Living in cold homes increases the risk of developing and/or exacerbating symptoms of respiratory problems such as asthma. The elderly, the young and those with pre-existing conditions are especially susceptible to cold, making them a vulnerable population within the housing sector.

Around 10% of excess winter deaths are attributable to fuel poverty. Further, evidence suggests that greater than one in five (21.5%) excess winter deaths in England and Wales are attributable to cold housing. It would, therefore, seem pertinent to ensure every effective measure is taken to ensure the safety of public health in a collaborative way given the cost of fuel poverty to the NHS in England is estimated to be around £1.36 billion per year (Grey et al., 2017). This is a conservative figure and does not reflect any additional costs associated with social care costs. To ensure that as many fuel-poor homes achieved a minimum energy efficiency rating of a Band C 2, by 2030, the UK Government introduced a new statutory fuel poverty target for England.

A qualitative study which examined the influences and decisions made by households with children diagnosed with asthma in regard to the way in which they keep warm and stay well during the winter, found that there are numerous factors which affect households' decision making. The main findings of the study suggest that parents are continuously working with other authorities, often with conflicting knowledge learnt from a variety of sources. This is often in the form of trade-offs, for example trading off adequate ventilation of their property in pursuit of reduced damp and fungal contamination against saving heat and energy; they are also more likely to pay higher rates for consumed energy as at-risk individuals tend to use pre-pay meters for fear of debt (Tod et al., 2016).

As previously highlighted individuals are reported to spend up to 90% of their time indoors, (Ault et al., 2020) making the indoor environment one of the most important aspects to consider when evaluating the impact housing may have on health, specifically the quality of the home environment. Early studies from Sommerville et al. (2000) which involved installing central heating to 59 cold and damp homes in Cornwall UK, to address whether the use of NHS funding to address housing-related health issues was beneficial, found that all respiratory symptoms were significantly reduced following the intervention. The most noticeable being a reduction in a nocturnal cough. School-age children had significantly lower school absences for asthma from 9.3 days per 100 school days prior to intervention to 2.1 days after intervention ($P<0.01$) (Somerville et al., 2000) therefore indicating that health problems associated with poor housing can be reduced when mitigation measures are taken to improve the quality of homes.

The social determinants of health framework have assisted in the understanding of health by identifying direct causes of pathology and disease as well as the pathways in which individual action, environment, and resources can influence these. The framework brings to light that health is influenced by multiple factors such as age, gender, lifestyle choices, communities, wealth, environment, and living/working conditions. Within the framework, housing is viewed as only one of the eight sub-components of living and working conditions (WHO, 2018b). This is a cause for concern; around 2.4 million households are affected by fuel poverty resulting in increased winter deaths, poor hygrothermal conditions and increased risk of indoor dampness, therefore indicating the need for housing to be reconsidered as a fundamental aspect in the maintenance of good respiratory health (Sharpe et al., 2015g).

2.7.3 Damp and Fungal Contamination

Numerous studies have been conducted examining the relationship between indoor dampness, moisture content or the humidity of inspired air and asthma symptoms, control of the problem and airway response to exertion (Shajahan et al., 2019). An increase in humidity of the air in the homes of people with asthma is associated with an increase in asthma symptoms due to increases in fungi and house dust mite content, both of which are known triggers for asthmatics.

As such, control measures such as mechanical ventilation are commonplace in an attempt to reduce moisture content and alleviate the health risks associated with exposure to fungi (Singh and Jaiswal, 2013a).

Government-backed energy efficiency upgrades such as improved insulation, installing better windows/doors, upgraded heating and draft proofing to prevent heat loss have benefitted many households. However, these initiatives can have a detrimental effect through a range of unintended consequences (Shrubsole et al., 2014).

Reduced ventilation can diminish indoor air quality (IAQ), increase indoor air moisture, dampness and increase the risk of fungal growth, thus increasing the risk of allergic respiratory conditions. This is evident when air changes per hour (ACH) drop below the European standard of 0.5 ACH (Sharpe et al., 2015g).

To ascertain the energy and performance of homes, the Standard Assessment Procedure (SAP) is used. The purpose of SAP is to provide reliable and accurate assessments of energy performances which are required to underpin energy and environmental policy initiatives (Gov.UK, 2013).

A study by Sharpe et al. (2015) analyzed data from 944 homes in Cornwall. The SAP rating of the properties ranged from 24-88. 44% of homes had visible fungal contamination inside the property and 21% of respondents had doctor-diagnosed asthma. The study indicated that a one-unit increase in SAP rating was associated with a 2-3% increase in adult asthma. Homes with SAP ≥71 had a 60% reduced risk of visible fungal contamination. Adults living in homes with

SAP ≥71 had a two-fold increased risk of asthma(Sharpe, 2015b). This finding is particularly interesting, as even though insulated homes had less visible fungal contamination, the risk of Asthma was doubled. It would, therefore, seem that other factors may be contributing to the burden. This indicates that a multidisciplinary approach to health and housing is required if true improvements are to be observed.

There is abundant evidence to suggest that dry indoor environments limit the risk of asthma, by maintaining a relative humidity (RH) of between 40-60%, the majority of adverse health effects can be halted (Arundel et al., 1986). Mechanical ventilation (dehumidification) is thought to assist in the reduction of asthma symptoms by extracting moisture from the air to less than 50% relative humidity which is reported to be adequate in the control of dust mite populations (Sauni et al., 2013).

House dust mite is a known allergen which exacerbates asthma symptoms. Further, allergens such as fungi thrive in a moisture-rich environment; thus extracting excess humidity is a fundamental aspect of symptom control (Singh and Jaiswal, 2013a).

However, a systematic review which examined the effect of dehumidification of the home environment on asthma control reveals that to date, there is little evidence to indicate clinical benefit in the use of dehumidification in patients with asthma due to measures (of data) being difficult to perform in domestic dehumidifiers (Singh and Jaiswal, 2013b). Additionally, the results of RCTs show uncertainty, revealing the need for further investigation in this area (Singh and Jaiswal, 2013a).

The Building Energy, Technical Status and Indoor Environment study (BETSI), a Swedish study involving 1160 adults from 605 single-family homes, found that moisture load in the indoor environment (difference in absolute humidity between indoor/outdoor air) was associated with respiratory infections (OR= 1.21 per 1g/m^3,95% CI 1.04-1,40)(Wang et al., 2017). Asthma symptoms were associated with air exchange rate (OR=0.85 per 0.1/h, 95% CI 0.73-0.99) elucidating that low ventilation flow within homes, as well as a high moisture load from damp foundations and other construction materials, are high-risk factors in the manifestation of respiratory symptoms. However, this was a cross-sectional study, therefore, limiting the ability to draw conclusions on causality. Furthermore, due to the size of the study only limited statistical power could be achieved (Wang et al., 2017). Nonetheless, the study has highlighted the need for improved ventilation whether by structural changes in the home or by resident individual actions (opening windows etc..).

Indoor damp and fungal contamination exposure are associated with an increased risk of allergic diseases and as such, poses a significant risk to global public health. Culturable fungi such as Aspergillus, Penicillium, Ulocladium, Alternaria, Epicoccum, Cladosporium, Trichoderma and Fusarium species are known to cause allergic reactions(Sharpe et al., 2016b).

Sharpe et al (2016) examined culturable allergenic fungi in visible fungal growth in energy-efficient homes and found that Aspergillus, Penicillium, Ulocladium, Alternaria, Epicoccum, Cladosporium, Trichoderma and Fusarium constituted 82% of the fungal species found on contaminated surfaces that had areas of visible fungal growth in homes, indicating a health risk for susceptible individuals. This is especially important for future research as nearly half of the fungal isolates were recovered from bedrooms of the surveyed properties (n=91). As most individuals spend around eight out of each 24 hour period in their bedroom, and these type of fungi can dominate indoor environments, identification and control of these fungi may assist in the improvement of health and be of benefit to asthma sufferers (Sharpe et al., 2016a).

Research that has examined the interaction between different fungal types and their effect on asthma and other respiratory outcomes is limited. A recent systematic review and meta-analysis of risk factors relating to indoor fungal diversity and asthma revealed that exposure to Penicillium, Aspergillus, and Cladosporium species were associated with an increased risk of reporting asthma symptoms.

The presence of these fungal species increased current asthma symptom exacerbation by 36% to 48% compared to those who were exposed to lower concentrations of these fungi. This was demonstrated by using random-effect estimates (Sharpe et al.).

The indoor fungal profile varies by season, temperature, humidity, air exchange rates and geographical location (Ponce-Caballero et al., 2013). However, each is modifiable by occupant behaviours. Sharpe et al.'s 2016 review disclosed that increased exposure to indoor fungal contamination prior to the development of asthma symptoms suggests that Penicillium, Aspergillus, and Cladosporium species pose a respiratory health risk in susceptible populations (Sharpe et al., Sharpe et al., 2016b). This highlights the need for both awareness, monitoring and individual action if the risk to the individual and population health is to be reduced.

2.8 Conclusions

This review has explored some of the complex and multifaceted interactions between housing and health. Numerous factors associated with housing and poor health outcomes have been identified. As individuals spend around 90% of their time in the indoor home environment, ensuring the safety of these homes is paramount in reducing and alleviating health problems associated with residing in poor quality homes.

This review has identified that socioeconomic status can be a major confounding factor in the type and quality of housing an individual may reside in, with low-income families and those with poor health often being forced into antiquated and/or poorly maintained homes. Mitigation measures to improve homes are becoming more conjoint, as such aids such as toolkits have been developed.

Although effective to some extent improvements still need to be made. What is currently available tends to omit a focus on breathing-related illnesses, although one toolkit was identified that measured microbial or pet allergens which have been linked to asthma. There is limited evidence examining inactivity on respiratory health, although numerous studies indicate that increased activity lowers the incidence of asthma. As physical activity is often compounded by poor mobility, it is an area that warrants further investigation.

Over a quarter (28%) of private rented homes in the UK failed to meet the Decent Homes standard in 2015. Inadequate quality housing was identified as the strongest predictor of children's well-being. Specifically, those residing in low-quality homes had greater emotional and behavioural problems than those in higher quality homes.

Cold and damp properties and those contaminated with fungal growth pose a significant risk to health. 10% of excess winter deaths are attributable to fuel poverty, with 21.5% of winter deaths directly related to cold housing and costing the NHS around £1.36 billion each year. However, evidence that links housing improvements with specific health outcomes is lacking. It would, therefore, be pertinent to ensure measures are in place to reduce this figure considerably.

Asthma is reported to affect 262 million individuals globally, and housing environments play a fundamental role in managing this condition. Location of the housing, such as its proximity to vehicle exhaust emissions and other environmental factors plays a significant role in determining health status, poor air quality leads to poor respiratory health outcomes.

Studies indicated that increased humidity in homes increases the risk of poor respiratory health. The ideal RH level was identified as 40-60% however, other studies indicate no clinical benefit in dehumidification. Other factors such as Indoor damp/fungal contamination, increased risk of allergic diseases, especially when Penicillium and Aspergillus were present. This is the subject of Chapter 4 and 5.

This chapter has highlighted a number of key gaps in the literature. In Chapter 3, a systematic review of the literature on indoor air quality and asthma is presented.

2.9 Summary

The interaction between housing and health is complex, as demonstrated in Figure 3. The quality of the air in the home environment is becoming more important in the maintenance of global public health to reduce the negative impacts on health due to exposure of pollutants, particularly respiratory health. Asthma, a complex long term chronic respiratory disease affecting millions globally, is associated with an increased risk of development and or exacerbation from exposure to a variety of chemicals and compounds found in inside and outside environments, the home environment being one environment where people spend around 60-70% of each day.

The health effects of exposure to indoor air pollution are gaining traction within the field of health research and new health effects from different exposures are being identified. Fungal contamination is one of these exposures which occurs in damp locations in homes and has a significant impact on asthma. Whilst many pollutants have received extensive examination other pollutants have received little attention. How these pollutants affect individuals' health, particularly indoors is understudied.

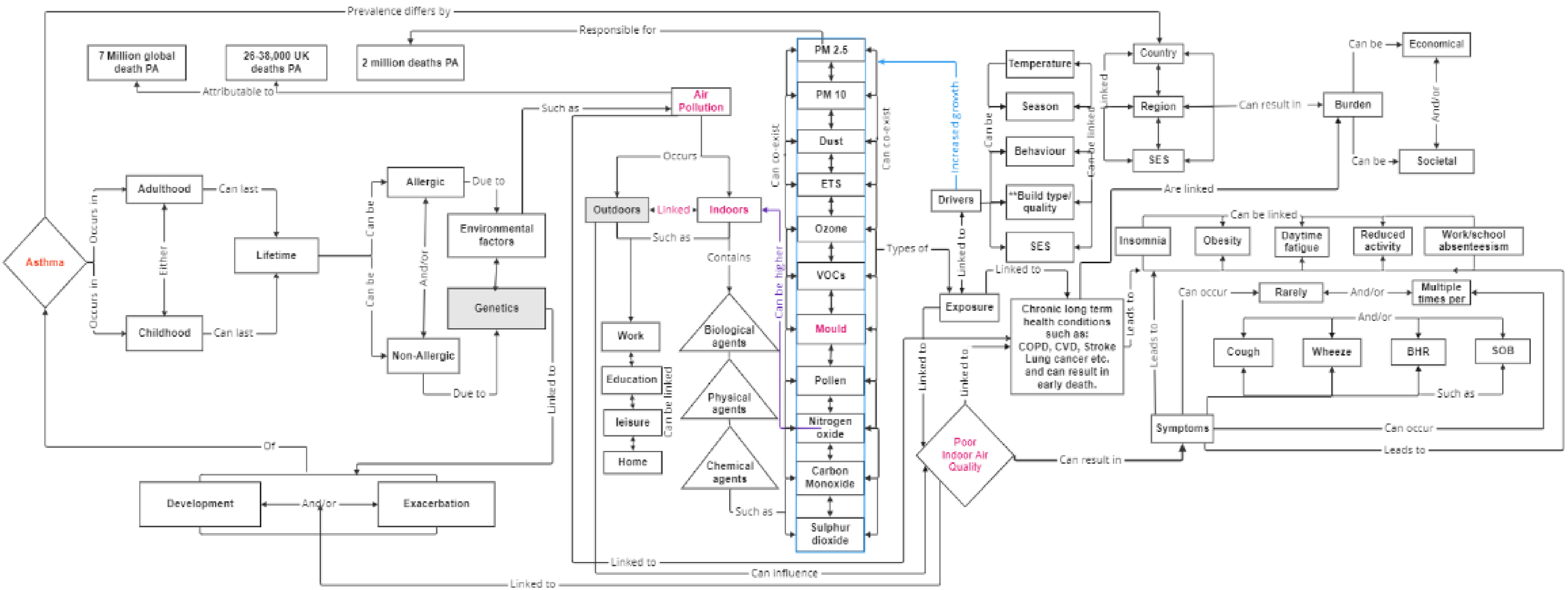

Figure 3 A concept model describing the relationship between asthma and the indoor environment.

1718

[17] SOB- Shortness of breath
[18] BHR- Bronchial Hyperreactivity

Chapter 3: Indoor $PM_{2.5}$, VOCs and Asthma outcomes: A systematic review in adults and their home environments

3.1 Introduction

The prevalence of asthma among children and young people have been well documented (Asher et al., 2006, Pearce et al., 2007) but fewer studies have investigated asthma in adulthood. While rates vary (BLF, 2019) (Mukherjee et al., 2016), it is thought that around 10% of adults have doctor diagnosed asthma in the United Kingdom (UK). This represents one of the higher prevalence rates in the world (Netuveli et al., 2005), which poses a significant economic and societal burden (Takaro et al., 2011, Salo et al., 2014) and costs the UKs National Health Service (NHS) around £1.1 billion a year to treat (Nunes et al., 2017).

The rise in the prevalence of asthma since the 1960s cannot be explained by genetic factors alone (Sharpe et al., 2015e, Ross Anderson et al., 2007), which has led to an increased focus on environmental exposures as determinants of health (Osborne NJ, 2010, Dharmage et al., 2019). Exposures to indoor air pollutants are a public health concern because in many European countries people spend 80-90% of time indoors (McGratha et al., 2017). Around 70% of this time is in the home environment (Klepeis et al., 2001, Schweizer, 2007, Torfs et al., 2008), which increases to around 90% in vulnerable populations such as the very young, the infirm and elderly (Torfs et al., 2008)(Spalt et al., 2016).

Asthma is a complex heterogeneous disease characterised by airway inflammation. It is caused and/or exacerbated by increased exposure to diverse chemical, physical and biological exposures (Sharpe et al., 2015h), which result from multiple indoor and outdoor sources. Consequently, asthma can be caused and/or exacerbated by both non-allergic and allergic stimuli (Doreswamy and Peden, 2011).

Prior studies have investigated the role of indoor allergens such as exposure to increased concentrations to house dust mites, fungi (e.g. spores and hypha fragments) and microbial organic compounds (mVOCs) (Fisk et al., 2007, Sharpe et al., 2015b, Gaffin and Phipatanakul, 2009, Dales et al., 2008), which have been consistently associated with multiple allergic and respiratory health effects (Mendell et al., 2011b).

Fewer studies have investigated the potential impact of indoor particulates ($PM_{2.5}$ and PM_{10}) and volatile organic compounds such as formaldehyde (WHO, 2010b). The concentrations of indoor PM and VOCs are largely dependent on resident behaviours (e.g. cooking, heating and environmental tobacco smoke), and the reintroduction of chemicals into the home environment (e.g. new furnishings and building products (Sharpe et al., 2014b). Increased exposure to indoor PM and VOC concentrates are thought to increase the risk of asthma (Arif and Shah, 2007a, Wu et al., 2018, Guarnieri and Balmes, 2014b, Hulin et al., 2012) and can enhance the bronchial responsiveness to other allergens in sensitised individuals (Casset et al., 2006).

However, the variability of indoor PM has been found to have no impact on daily control of patients with asthma and allergic sensitisation (Hussain et al., 2019). Prior studies have also reported inconsistent evidence and evidence of shown associations between formaldehyde and volatile organic compounds and risk of asthma (Mitha et al., 2013). The risk of childhood asthma and interest in these exposures (e.g. particulates increases oxidative stress and inflammation in the lungs (Mir, 2007)), has led to a number of prior reviews investigating elevated PM and VOCs and childhood asthma (Patelarou et al., 2015, Dick et al., 2014).

To our knowledge, there has been no comprehensive systematic review investigating the relationship between increased indoor PM and VOC concentrations (i.e., objectively measured) and risk of adult asthma in higher income countries (World Bank Atlas method of $12,376 GNI per capita or more) which is the focus of this study.

3.2 Methods

3.2.1 Search strategy

In accordance with our study protocol (PROSPERO reference: CRD42018110070), electronic searches of 11 databases were conducted on 1st February 2019 and again on 2nd February 2020. Using the keywords; asthma, bronchial hyperreactivity, bronchial spasm, particulate, $pm_{2.5}$, pm10, volatile organic compounds, formaldehyde, formocresols, benzene, nitrogen oxide, No_2, Housing/house(s)/ home(s), flat, apartment, bungalow, housing for the elderly/ or public housing/household, indoor, property, dwelling, adult, women, female as described in the previously published protocol.

Searches were conducted across 11 databases (Cochrane Library (Wiley), MEDLINE (via the OVID platform), AMED, Web of Science, Scopus, Environment Complete (EBSCO), GreenFile (EBSCO), EMBASE (via the OVID platform), British Nursing Database, Applied Social Sciences Index and Abstracts (ASSIA), ScienceDirect and the TRIP Database). The World Health Organisation (WHO) and the Department for Environment Food and Rural Affairs (DEFRA) were also searched. Forward and backward citation searches were conducted alongside contacting all authors of included studies to identify additional studies.

Articles were independently screened by three team members (C.P, R.A.S and K.M) at title and abstract. The full text of articles meeting the inclusion criteria were obtained and screened. Where there was any disagreement, a fourth reviewer (T.T) was consulted, and any discrepancies resolved through discussion.

3.2.2 Eligibility criteria and study selection

Included articles consisted of those reporting associations between the indoor home environment, PM and VOCs exposure and risk of developing and/or the exacerbation of asthma (Figure 1). The populations investigated encompassed adults aged over 18 years and both sexes. Studies deemed eligible for the analysis comprised:

1. Original peer-reviewed journal articles publishing primary data.
2. Cohort; case-control studies; randomised control trials; non-randomised control trials; cluster-randomised trials and cross over trials.
3. Studies published in 1990 or later (due to rise in publications after this date).
4. Investigation of the indoor home environment.
5. Environmental monitoring and reporting of PM and/or VOC concentrations.
6. Studies with outcomes of asthma ever and/or asthma symptoms in the last 12 months (including wheeze, whistling in the chest or a dry cough), doctor diagnosed asthma (e.g., peak flow or spirometry), and

initiation/development of asthma requiring newly diagnosed cases of asthma by a physician or doctor.

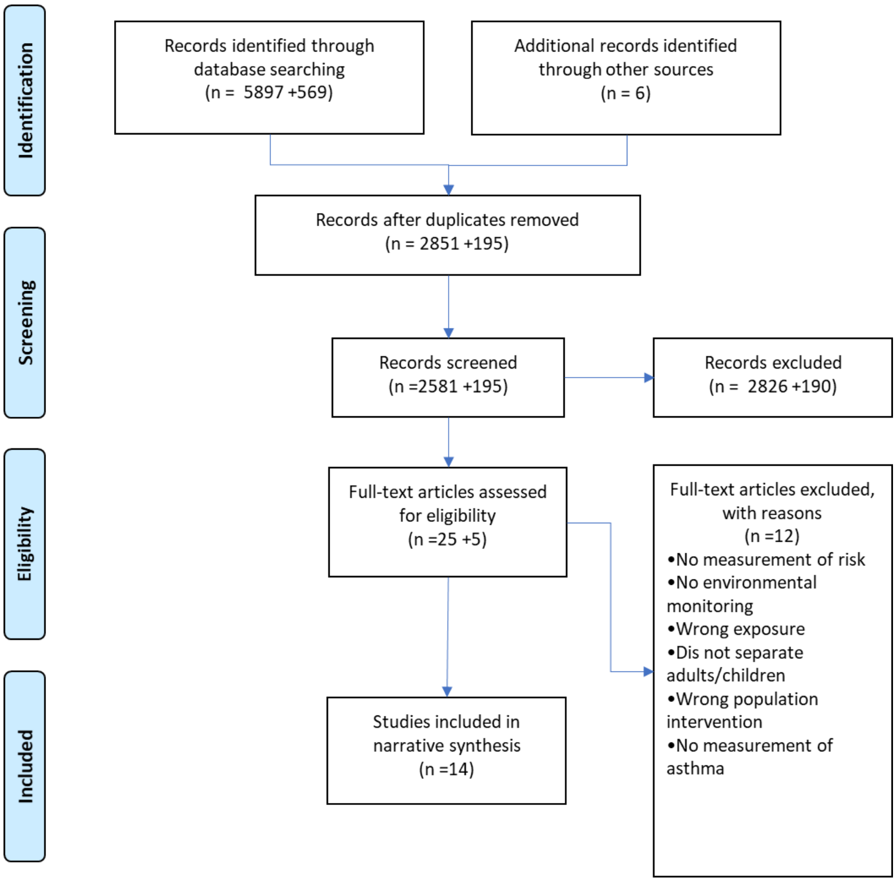

Figure 4 Diagram of systematic search and included studies.

3.2.3 Data extraction

Relevant study and participant characteristics were extracted using a data extraction tool, which was adapted from the Cochrane guidelines for systematic review (Furlan et al., 2009). The form was subsequently used to populate data synthesis tables developed using the PROGRESS plus framework, which applies equity when reporting findings (O'Neill et al., 2014).

3.2.4 Quality assessment

Included studies were assessed for exposure and quality by two review authors (CP, R.A.S) by using the Newcastle-Ottawa Scale (NOS) (Moher et al., 2009) and Critical Appraisal skills programme (CASP)(CASP, 2023). This assesses studies rrepresentativeness of the exposed cohort, ascertainment of exposure, comparability of the included sample and outcomes. Where disagreements persisted a third review author (KM) was consulted. Studies were independently assigned an overall score out of 10 and a final score reached by consensus.

3.3 Results

The results of our investigation are as follows:

3.3.1 Synthesis

Due to significant heterogeneity, we provide an overarching synthesis of 14 included studies that met our inclusion criteria; (Arif and Shah, 2007b, Balmes et al., 2014, Billionnet et al., 2011, Frisk et al., 2009, Hulin et al., 2013b, Jarvis et al., 1996, Levesque et al., 2001, Norback et al., 1995, Sharpe et al., 2015h, Simoni et al., 2004, Simoni et al., 2002, Triche et al., 2005, Wieslander et al., 1997, Dales and Cakmak, 2019). Studies were prioritised according to their quality rating score and considered as low (≤4), medium (5-7) and high (≥8) quality. For this reason, we treat and synthesise included studies together. Studies were then grouped in our synthesis according to those reporting:

- Increased risk of spirometry-diagnosed asthma through exposure to particulate matter or VOCs.
- Increased risk of self-reported asthma through exposure to particulate matter or VOCs.
- Increased risk of asthma symptoms through exposure to particulate matter or VOCs.

3.3.2 Study and participant characteristics

Seven studies were performed before 1999 and seven after this time. Included studies were from five countries and included cross-sectional, cohort and case-control design methodologies (Table 6). Four studies were conducted in the USA, three in France, three in Sweden, two in Canada and two in Italy. Not all studies reported whether they had investigated rural or urban environments. Seven studies reported on ethnicity; however, this was not consistent across the studies. No studies reported any religion, disability, or time-dependent relationships. Social-economic status (SES) was recorded in five studies and reported in four. We grouped education and employment with SES as health opportunities, outcomes and SES are generally closely linked. Six studies reported on education and employment

Table 6 Summary of participant characteristics of included studies.

Reference	Country	Study population	Non-respondents	Urban/rural, region	% Female	Ethnicity	SES	% Current Smokers	Current Asthma %	Final quality score
(Frisk et al., 2009)	Sweden	Adults aged 19-54 y	No details	Orebro	63	Not reported	Occupation	24	No details	2/10
(Levesque et al., 2001)	Canada	Adults aged 23- 52 y	No details	Within 50km Quebec	86.5	No details	Family income recorded but not reported	No details	No details	4/10
(Arif and Shah, 2007b)	USA	Adults aged 20-59 y	No details	No details	51.2	Non-Hispanic whites, Mexican Americans, Non-Hispanic blacks, Other race/ethnicity	13.7 % below the poverty line	26.8	12.3	4/10
(Norback et al., 1995)	Sweden	Adults aged 20-44 y	14 who didn't attend medical investigation, 12 who were uncontactable, 14 refused exposure measurements	Urban, Uppsala	72	No details	No details	No details	30	6/10
(Sharpe et al., 2015h)	USA	Adults and children 6 – 18 y	No details	USA	51.8	Non-Hispanic White, Non-Hispanic Black, Mexican American, Other	Family income-to-poverty ratio	No details	8.1	6/10
(Simoni et al., 2002)	Italy	Adults aged 15-72 y	No details	Po River Delta	51.4	No details	No details	No details	13.7 (f) 34.9 (m)	6/10
(Simoni et al., 2004)	Italy	No details	No details	Urban, Pisa Rural, Po Delta	50.9 51.4	No details	No details	No details	25 24	6/10
(Triche et al., 2005)	USA	No details	Summary of excluded	Connecticut and	100	White or Asian Black or Hispanic	Education	No details	9	6/10

			respondents	Southwest Virginia					
(Wieslander et al., 1997)	Sweden	Adults aged 20-44 y	Non-responders did not differ from participants in age, gender and smoking status	Uppsala	51.6	No details	No details	29 with symptoms 17 without symptoms	21	6/10
(Balmes et al., 2014)	USA	Adults aged 18-50 y	Non-responders were younger and more likely smokers	Urban, Suburban, Rural, Northern California	73.5	Non-Hispanic white 58.9%	High school education	7.9	41.4	6/10
(Bentayeb et al., 2013)	France	No details	No details	19 regions	52	French 96%	Education	27	No details	6/10
(Billionnet et al., 2011)	France	Adults aged 15-89 y	No details	74 municipalities, 19 regions	52.1	French 96%	Employed 47.9% Higher education 52.25%	27	8.6	8/10
(Dales and Cakmak, 2019)	Canada	Adults aged 17-19 (children measured in the study but excluded from this analysis)	No details	Two sites in each of Atlantic Canada, the Prairies, and British Columbia, and four sites in Quebec, and six in Ontario.	50.9	Caucasian 76.5%	83.9% Household income above $1000 96.1% educated greater than high school	No details	9.3	8/10
(Hulin et al., 2013a)	France	Adults aged 26- 60 y	Were younger, more of foreign nationality, and lower educational level	Urban, rural, peri urban	51.6	Nationality	Recorded but not reported	26.2	8.4	9/10

We included two cohort studies with follow-up periods of 12 and 13 months. Twelve studies were cross-sectional, one of which was of case-control design. Recruitment, funding, and statistical analyses differed between studies. Significant heterogeneity between study designs and the defined exposure and outcomes prevented the use of meta-analysis. For example, the definition of asthma varied across included studies from self-reported based on a positive response to a question derived from a respiratory survey to methacholine challenge, spirometry, reduced PEF and FEV (Table 7).

According to the Global Initiative for Asthma, in the diagnosis and management of asthma lung function testing is considered the optimum means of testing. Asthma is characterised by variable expiratory airflow limitation. As an indicative measure, forced expiratory volume in 1 second (FEV1) from spirometry is considered more reliable than peak expiratory flow (PEF) as PEF can differ between meters by up to 20%. It is therefore essential that if PEF is used the same meter should be used each time for consistency. A reduced ratio of FEV1 to forced vital capacity (FVC) (0.75 to 0.80) is usually indicative of airflow limitation (GINA, 2022).

Table 7 Summary of study design characteristics of included studies.

Reference	*Study design*	*Study size*	*Follow up*	*Exposure of interest*	*Exposure measurement*	*Definition of asthma*	*Outcome measure*	*Final quality score*
(Balmes et al., 2014)	Cross-sectional	549 Interview 302 Home visit	N/A	Particulate Matter 2.5	Nephelometer	No clear definition	Spirometry, questionnaire	6/10
(Simoni et al., 2004)	Cross-sectional	Pisa 707 Po Delta 383	N/A	PM2.5, No2	Passive sampling	Chronic bronchitic and/or asthmatic symptoms (i.e., sputum from the chest, shortness of breath, attack of shortness of breath, and wheeze) without the presence of fever and the reported presence of infection.	Symptom diary, PEF	6/10
(Simoni et al., 2002)	Cross-sectional	383	N/A	Respirable suspended particulate (RSP) (<2.5μg/m3), NO2	Passive sampling	Chronic bronchitic and/or asthmatic symptoms (i.e., sputum from the chest, shortness of breath, attack of shortness of breath, and wheeze) without the presence of fever and the reported presence of infection.	PEF	6/10
(Triche et al., 2005)	Cohort	888	1 year	NO2, SO2	Passive monitoring	No clear definition	Symptom diary	6/10
(Levesque et al., 2001)	Case-control	89	1 day	C.O., NO, HCHO, PM10	Gilian HFS 113 pump /Diffusion monitoring	Asthma defined as complicated lower respiratory tract illness which also included wheezing or respiratory difficulties, medical diagnoses of pneumonia, bronchitis	Questionnaire	4/10

						or asthma attacks.		
(Hulin et al., 2013a)	Cross sectional	897	N/A	VOCs: 4 aldehydes (acetaldehyde, acrolein, formaldehyde, hexaldehyde), 12 hydrocarbons (benzene, 1,4-dichlorobenzene, ethylbenzene, n-decane, n-undecane, styrene, tetrachloroethylene, toluene, trichloroethylene, 1,2,4trimethylbenzene, m/p-xylene, o-xylene), and 4 glycol ethers (2-butoxyethanol, 2-butoxyethylacetate, 1-methoxy-2-propanol, 1-methoxy-2-propylacetate).	Passive diffusion sampling	A positive response to: "Have you had an attack of asthma in the last 12 months?" or "Are you currently taking medicines for asthma?" and "Have you been woken by an attack of shortness of breath at any time in the last 12 months?"	Questionnaire	9/10
(Billionnet et al., 2011)	Cross-sectional	1612	N/A	20 VOCs including 4 aldehydes, 12 hydrocarbons ad 4 glycol ethers, 4 common allergens (dust mite allergens (derp1 and Derf1), dog and cat Canf1 and Feld1,	Radial diffusive sampling	As suggested by ECRHS: (i) having an asthma attack in the last 12 months; (ii) having been woken by an attack of shortness of breath in the last 12 months; and (iii) currently using asthma medicine	Questionnaire	8/10
(Bentayeb et al., 2013)	Cross-sectional	1012 Individuals 490 Homes	N/A	Aldehydes: formaldehyde, acetaldehyde, acroleine, hexaldehyde. - Aromatic hydrocarbons: benzene, toluene, m/p-xylenes, o-xylene, 1.2.4-trimethylbenzene,	Radial diffusive sampling	No clear definition	Questionnaire	6/10

				ethylbenzene, styrene. - Aliphatic hydrocarbons: n-decane, n-undecane; halogenated hydrocarbons: trichloroethylene, tetrachloroethylene, 1.4-dichlorobenzene; Glycol ethers: 1-metoxy2-propanol, 2 butoxy ethanol, 2-butoxyethylacetate, 1-methoxy-2-propylacetate.				
(Norback et al., 1995)	Cross-sectional	154	N/A	Temp, air humidity, VOCs, respirable dust, Co2, formaldehyde, and guanine from HDM	Direct reading instrument based on light scattering/ Diffusion sampling	Attacks of asthma during the past 12 months, nocturnal breathlessness in the past 12 months, or current use of asthma medication.	Blood samples, Interviews, SPT, FEV1, PEF, Methacholine challenge	6/10
(Arif and Shah, 2007b)	Cross-sectional	9965 Interview 9282 Physical exam 669 Exposure monitoring	N/A	Benzene Chloroform Ethylbenzene Tetrachloroethene (TCE) Toluene, trichloroethene, o-xylene, m-,p-xylene, 1,4-dichlorobenzene, and methyl tertiary butyl ether (MTBE)	Personal exposure via a passive monitoring device	Positive response to the question "Has your doctor or other health professional ever told you that you have asthma?"	PEF	4/10
(Wieslander et al., 1997)	Cross-sectional	Interview, blood tests, SPT, bronchial	N/A	Temperature, Humidity, VOCs,	Passive sampling	A combination of bronchial hyperresponsiveness	Questionnaire, SPT, FEV1,	6/10

		provocation 699 Q'aire building characteristics, occupation, and symptoms 562. Subsample 62		Formaldehyde		(BHR) and at least one symptom related to asthma. Symptoms related to asthma were recorded when subjects reported in previous 12 months: (1) wheezing or whistling in the chest or (2) at least one daytime attack of shortness of breath during exercise or while resting; (3) at least one nighttime awakening because of breathlessness or tightness in the chest	PEF, Methacholine challenge, blood	
(Dales and Cakmak, 2019)	Cross-sectional	2846	N/A	Limonene	Diffusion sampling with Carbopack B 60/80®	Asthma: "We are interested in "long-term conditions" which are expected to last or have already lasted 6 months or more and that have been diagnosed by a health professional. Do you have asthma?"	FeNO FEV1 FVC Questionnaire	8/10
(Sharpe et al., 2015h)	Cross-Sectional	8412	N/A	house dust (endotoxin): A. alternata (Alt a 1 allergen), A. fumigatus antigens, Dermatophagoides pteronyssinus (Der P1 allergen), Dermatophagoides farina (Der f1 allergen) and endotoxin (gram-negative bacteria) antigen measured from	Air sampling via Vaccum	A positive response to: 'Has a doctor or health professional ever told you that you have asthma?' and 'Do you still have asthma?'	Blood samples, A self-reported questionnaire, dr diagnosed asthma	6/10

				the house dust samples. German cockroach Blattella germanica (Bla g1 & Bla g2 allergens), Canis familiaris (Can f1 allergen), Felis domesticus (Fel d1 allergen), mouse urinary protein (Mus m1 allergen) and rat urinary protein (rat n1 allergen).				
(Frisk et al., 2009)	Cohort	49	13 months	Temp + RH Co2, No2, Formaldehyde ETS, 15 respirable allergens (not stated other than pets)	Diffusion sampling	A physician-diagnosed asthma, current use of asthma medicine, attacks of breathlessness and episodes of wheezing	Self-assessment diary, FEV1 and vital capacity (V.C.). Histamine provocation test, Blood samples, PEF, SPT	2/10

3.4 Results of studies included in our narrative synthesis.

3.4.1 Participants

The characteristics of the participants were generally reported in detail across the studies and are summarised in Table 6. The participants were all adults as defined by the inclusion criteria with the exception of the (Levesque et al., 2001 and (Dales and Cakmak, 2019) study which included adult and child pairs, however, due to the focus of this review, only data relating to adults was considered. Recruitment was generally a random sample of the population in the cross-sectional studies designed to be representative of the general population.

3.4.2 Exposure

In total, three studies measured $PM_{2.5}$. The study by Levesque (2001) however, measured PM10. Where VOCs were measured these were generally broken down into aldehydes, hydrocarbons, glycol ethers and allergens found in dust mite (Table 7). Three studies examined formaldehyde separately to the other included VOCs. Three studies also recorded temperature and relative humidity in the properties.

3.4.3 Monitoring

VOCs were monitored with reasonable consistency across studies in both duration and sampling location. For 11 studies VOCs were measured continuously in either the bedroom and or living room for one week with the exception of Weislander et al. (1997) and Arif and Shah (2007). Measures were collected via one measurement in the bedroom over two hours and by personal exposure over 48-72 hours in these cases. Sampling techniques for the VOCs were similar and consisted of diffusive sampling. For the studies examining PM similar techniques were utilised in two of the studies (active sampling with Dorr Oliver type pre-selector) (Simoni et al., 2002) (Simoni et al., 2004), in one study sampling was via nephelometer and recorded three measurements of three-minute duration. For all other measurements (Temperature, house dust mite (HDM), humidity, CO_2) standardised techniques were utilised.

3.4.4. Health Outcomes

All studies used self-administered questionnaires to survey various health-related issues. The majority of the health-based questions related to respiratory health. Objective measurements were used in six studies: Six measured peak expiratory flow (PEF) rate variability (Dales and Cakmak, 2019) Simoni et al., 2002, Wieslander et al., 1997, Frisk et al., 2009, Simoni et al., 2004, Norback et al., 1995); four studies measured forced expiratory volume in one second

(FEV1) ((Dales and Cakmak, 2019) Balmes et al., 2014, Wieslander et al., 1997, Frisk et al., 2009, Norback et al., 1995,). In all objective measurements, the same sampling techniques were utilised; the Mini Wright peak flow meter for PEF and an EasyOne Spirometer for FEV1. A reduction in per cent predicted FEV1 is suggested to be more closely related to the incidence of chronic respiratory symptoms in the general population than other measures of lung function impairment (Jakeways et al., 2003), and therefore a useful measure in this review.Health outcomes and associated risks are summarised in Table 8.

Table 8 Health outcomes and associated risks

Reference	*Exposure*	*Exposure level (µg/m3)*	*Health measure*	*Health outcome*	*Risk ratio: Adjusted*	*Risk by Gender: Male*	*Risk by gender: Female*	*Final Quality Score*
(Balmes et al., 2014)	Pm 2.5	39.1 ± 107.3 21 µg/m3 (kitchen)	FEV1	Self-rated "asthma bother"	N/A	2.52 (95%CI: 0.88-7.24)	Not reported	6/10
(Simoni et al., 2004)	PM2.5	67 / 76	Self-reported daily diary PEF	Asthma symptoms PEF variability	1.39 (1.17-1.66) 1.37 (1.23-1.53)	Not reported	Not reported	6/10
(Simoni et al., 2002)	Respirable suspended particulate (RSP) (<2.5µg/m3), RSP No2	68/45 winter/summer 31/19 (ppb)	PEF	Asthmatic symptoms without a fever	1.23 (1.03-1.48)	Not reported	Not reported	6/10
(Triche et al., 2005)	SO2 NO2	10 ppb increase	Telephone interview and daily symptom recording	increased wheezing chest tightness		N/A	1.57; 1.10–2.26 1.32; 1.01–1.71	6/10
(Levesque et al., 2001)	Mould	No details	Self-administered questionnaire and symptom diaries	Respiratory pathologies	P=0.03	Not reported	Not reported	4/10

(Hulin et al., 2013a)	Mould	No details	ECRHS	Current asthma	1.35 (0.81-2.27)	Not reported	Not reported	9/10
(Billionnet et al., 2011)	Aromatic hydrocarbons Aliphatic hydrocarbons	No details	ECRHS	Asthma risk	N/A	Not reported	Not reported	8/10
(Bentayeb et al., 2013)	Toluene o-xylene	8-20 3-5	ECRHS	Breathlessness	3.36(1.13, 9.98) 2.85(1.06, 7.68)	Not reported	Not reported	6/10
(Norback et al., 1995)	Formaldehyde HDM Toluene C8-Aromatics TVOC	120 (1-2330) 55 (5-690) 790 (90-9380)	PEF ECRHS	Nocturnal breathlessness	12.5 (2.0-77.9) 4.9 (1.1-22.8) 6.7 (1.0-45.1) 9.9 (1.7-58.8)	Not reported	Not reported	6/10
(Arif and Shah, 2007b)	Benzene Ethylbenzene Toluene o-Xylene m,p-Xylene	Geometric mean 1.21 (0.74–1.98) 2.55 (1.73–3.75) 14.33 (11.09–18.52) 2.16 (1.53–3.04) 5.97 (3.92–9.07)	Questionnaire	Asthma or Wheeze	1.33 (1.13-1.56) 1.34 (1.01-1.78) 1.21 (0.93-1.58) 1.32 (1.04-1.67) 1.33 1.08-1.64)	Not reported	Not reported	4/10
(Wieslander et al., 1997)	Wood paint Kitchen Paint	Average TVOC in painted rooms= 413	PEF	Asthma (BHR+ symptoms)	2.33 (1.22—4.46) 2.21 (1.09—4.51)	Not reported	Not reported	6/10
(Dales and Cakmak, 2019)	Limonene 100% increase	45 ppb (SD 61)	FeNo Fev1 FVC	Increase in asthma	1.16 (1.15, 1.16)	1.01 (1.01, 1.02).	1.42 (1.41,1.43)	8/10

(Sharpe et al., 2015h)	HDM/Mould	total IgE < 170 KU/L	Questionnaire	Asthma risk	1.61 (1.00–2.57)	Not reported	Not reported	6/10
(Frisk et al., 2009)	HDM	84.7 (SD 15.6)	FEV1 PEF	Reduced lung function	1.31 (0–8.72)	Not reported	Not reported	2/10

3.4.5. Increased risk of asthma through exposure to particulate matter

Conclusive evidence of the relationship between indoor $PM_{2.5}$ and asthma outcomes in adults is lacking. No high-quality evidence was found that measured risk of either development or exacerbation of asthma via a measure of spirometry in relation to exposure to $PM_{2.5}$.

Two medium-quality studies (Simoni et al., 2002, Simoni et al., 2004) measured $PM_{2.5}$ and found that high levels of exposure were associated with increased PEF maximum amplitude and variability; however, the studies primary outcome focus was that of indoor pollution and associated acute respiratory symptoms and mild lung function impairment rather than asthma specifically so although the studies are indicative of lung function changes, assumptions cannot be drawn between exposure to $PM_{2.5}$ and increased PEF variability in this instance.

Only one study of medium quality found that exposure to particulate matter in the kitchen at 21 µg/m3 and hair nicotine of 0.14ng/mg were associated with increased odds of asthma-like symptoms, this was true in men but not women (Balmes et al., 2014).

3.4.6 Increased risk of asthma through exposure to volatile organic compounds

We found evidence to suggest that exposure to VOCs in the indoor home environment increases the risk of asthma and asthma-related symptoms (Table 8). One study of high-quality evidence (Dales and Cakmak, 2019) identified a 15% (95% CI: 1.14, 1.16) increased risk of asthma via measure of spirometry following a 100% increase in exposure to Limonene, a naturally occurring terpene (aliphatic compound) which may induce sensitisation and had been found to be associated with increased airway hyperresponsiveness in other studies (Norbäck et al., 2017).

One medium quality study found wood and kitchen painting to be associated with an increased risk of asthma symptoms (OR 1.43; 95% CI: 1.01-2.06), bronchial hyperreactivity, nocturnal breathlessness and current asthma via measure of spirometry, in this case, the most commonly detected compounds were aromatic compounds, aliphatic compounds and 2,2,4-Trimethyl-1,3-pentanediol diisobutyrate (TXIB) (Wieslander et al., 1997).

One study which was deemed to be of high quality and one of low-quality found an increased risk of asthma via measure of self-report in relation to exposure to both aromatic and aliphatic compounds. Further, an additional two medium quality evidence studies found an increased risk of asthma-like symptoms following this exposure. High-quality evidence indicated that n-undecane and

1,2, 4-trimethylbenzene were significantly associated with asthma (OR 2.02; 95% CI: 1.18–3.46 and OR 2.10; 95% CI: 1.21–3.65 respectively).

In adjusted marginal models, positive associations between asthma and global VOC scores were also observed suggesting the risk of asthma to be 1.07 times higher for exposure to each additional VOC with a high exposure level (OR 1.07; 95% CI: 1.00–1.13). For individuals exposed to five additional VOCs, the risk was increased by 40%. There was no difference between sex. Two specific VOC scores were significantly associated with an increased risk of asthma: aromatic hydrocarbons (OR 1.12; 95% CI: 1.01–1.24) and aliphatic hydrocarbons (OR 1.41; 95% CI¼1.03–1.93) (Billionnet et al., 2011).

(Arif and Shah, 2007) conducted personal exposure monitoring of 669 individuals and found statistically significant odds of physician-diagnosed asthma for individuals exposed to aromatic compounds (Adj OR 1.63; 95% CI: 1.17-2.27). When observing aromatic compounds individually toluene was associated with 21% increased odds of physician-diagnosed asthma (95% CI: 0.93-1.58).

Personal exposure monitoring also identified that individuals without asthma were at increased risk for experiencing symptoms with a significantly increased odds of one to two wheezing attacks observed, following exposure to aromatic compounds (adj OR 1.68 95% CI: 1.08-2.61) and chlorinated hydrocarbons (adj OR 1.50 95% CI: 1.01- 2.23) compared to no wheezing. This increased nearly twofold in the odds of experiencing three or more wheezing attacks following exposure to benzene (adj OR 1.85 95% CI: 1.13-3.04) (Arif and Shah, 2007b). Medium quality evidence suggests a relationship between Toluene and o-xylene (aromatic compounds) and nocturnal breathlessness, a symptom of asthma, in the elderly (Bentayeb et al., 2013).

Other VOCs our review identified that were related to increased asthmatic symptoms were formaldehyde and SO_2, but the evidence was limited. One medium quality study found formaldehyde in the bedroom to be associated with nocturnal breathlessness (Norback et al., 1995). One medium quality study found So2 to be associated with symptoms of a wheeze and chest tightness (Triche et al., 2005).

Exposure to house dust mites increase symptoms of asthma, however, the evidence is not conclusive. One low-quality study found that exposure to house dust mites resulted in lower mean FEV1 and lower PEF (Frisk et al., 2009). A medium quality study also found that exposure to house dust mites increase symptoms of asthma (Norback et al., 1995).

We found one high and one medium quality evidence study that was suggestive of an increased risk of asthma when subjects were exposed to fungi. In the high-quality study by (Hulin et al., 2013b) associations were found between exposure to fungi (according to the fungal index) and risk of current asthma (OR 1.35, 95% CI: 0.81-2.27).

When analyses were restricted to bedrooms, only those living in rural environments were found to have a higher risk of asthma than those in the urban population. Interestingly, fungal contamination did not have to be seen to have a negative health impact as observed in the case of (Sharpe et al., 2015h), here the reporting of a fungal contamination or musty odour was associated with an increased risk of current asthma (OR 1.61; 95% CI 1.00–2.57).

One medium and one low-quality evidence study reported that visible damp, fungal contamination on the walls or microbial growth in properties were related to increased asthma-like symptoms and respiratory pathologies (Norback et al., 1995, Levesque et al., 2001).

3.5 Risk of bias of individual studies

Included studies varied in terms of assessed NOS quality (Table 6), with the majority being of medium quality, which suggests potential inclusion of bias. There is also significant heterogeneity between studies and therefore the potential for reporting bias, resulting from studies collecting and reporting data inconsistently.

3.6 Economic outcomes

Of the included studies, no information was provided regarding any economic implications relating to their investigations.

3.7 Discussion

This systematic review is the most up to date and comprehensive investigation undertaken to understand the role of PM and VOCs in the development and exacerbation of asthma in adults. This review provides collective new evidence that in adults, aromatic and aliphatic compounds in the indoor home environment are associated with an increased risk of asthma. Further, individuals without a diagnosis of asthma or history of respiratory illness are more likely to experience symptoms related to asthma such as wheeze and shortness of breath as a result of such exposure, especially when exposure is at high concentration. We also found PEF variability in relation to respiratory symptoms that could be suggestive of asthma, but the evidence is inconclusive.

There is a growing body of evidence indicating that in children, aromatic compounds are associated with an increased risk of asthma development and exacerbation (Dick et al., 2014, Karimi et al., 2015, Al-Daghri et al., 2013). To date, there has been little evidence of this in adults.

This review provides collective new evidence that in adults, VOCs from aromatic and aliphatic compounds in the indoor home environment are associated with an increased risk of asthma. Further, individuals who have no diagnosis of asthma or history of respiratory illness are more likely to experience symptoms related to asthma such as wheeze and shortness of breath, as a result of exposure to such compounds, especially when they are at a high concentration.

However, the true exposure, combination and concentration to which individuals are exposed inevitably varies, due to complex interactions both between how individuals use and interact with their own environment, and how different biological and chemical compounds interact together within that environment; as no single exposure appears to be responsible for the development of asthma or its associated symptoms, as each exposure is invariably contaminated by other exposures.

Each of these interactions and the potential impact on health relies on a number of largely modifiable factors to reduce the burden of disease; cleaning products used, furnishings, leaks in building fabric, ventilation patterns etc. Previous authors have already highlighted the dangers of aerosolised domestic cleaning products on respiratory health, noting an increased incidence of asthma following exposure (Zock et al., 2010). Many of these types of cleaning products may contain aliphatic compounds such as limonene; also found in commonly used products such as air fresheners, perfumes and other personal care products (Buckley, 2007).

Policymakers and industry alike need to take a more concerted effort in protecting public health by better informing them of the associated health risks by raising awareness and using more explicit health warnings on product labels, detailing the importance of adequate ventilation both during and after use. People can control exposure in their own environment and potentially alleviate to some extent the burden of this disease.

Limonene was found to be present in 78% of household products (Buckley, 2007). Because the mean concentration has such a vast range (6-9400ppm) some products do not meet labelling thresholds, those that do often contain antioxidants such as ascorbic acid, alpha-tocopherol and butylated hydroxytoluene to reduce allergy frequency induced by chemical oxidation, which tends to occur rapidly without additives.

For example, Limonene, when exposed to air at normal room temperature, oxidises by around 60%. Prolonged exposure to air at room temperature increases the sensitising potential. (Dales and Cakmak, 2019) noted a 17 % increased risk of wheeze and that household exposure to limonene may increase the prevalence of asthma in the general population.

Antioxidants which deplete during the natural ageing of a product, help to extend the usable period for consumers, with a one-year shelf life being the usual recommendation under optimum conditions. Nevertheless, often individuals do not adhere to these standards and continue to use products past this recommended period, and store products inadequately, such as leaving the lid off a product which only accelerates oxidation therefor increasing sensitisation potential.

Also, of concern in household cleaning products, candles and air fresheners is many of the associated compounds involved in their creation which can react rapidly with ozone, producing chemical emissions that irritate the upper airways, however little is known about the reactive chemistry between each individual compounds, the chemical emissions and constituent gas-phase concentrations that result from the use of multiple household products and air fresheners simultaneously.

Studies indicate that ozone-reactive terpenoids can exist in high quantities in the air for many hours after product use (Singer et al., 2006), this is a concern as often people are rarely exposed to individual compounds but a large number of different exposures contemporaneously that have potential to react with each other forming secondary air pollutants, the effect this might have on respiratory health is largely unexplored and poses a potentially significant risk to public health.

Asthma outcomes across the included studies were inconsistent and, in some cases, poorly defined, better case definition must be adopted by future research to enable clearer and more thorough investigations into such vital areas so targeted interventions can be implemented where needed most.

3.8 Limitations

This systematic review of literature associated with PM/VOCs and asthma has been conducted with all phases in accordance with our published protocol using clearly defined objective exposure measures. However, we acknowledge a number of limitations; the number of volatile organic compounds are vast, to date, there is limited knowledge to the extent in which inhalation of each can cause harm.

The compounds measured and the way in which they are measured varies greatly both in and between studies. Whilst this review attempted to collect data from articles which have studied VOCs thought to be associated with adverse respiratory outcomes, there is an ever-evolving knowledge base of exactly which chemicals that consists of, therefore, the potential for some studies to have been inadvertently omitted.

There is no definitive definition of asthma and what it encompasses among the included studies, and as such different outcomes have been used, such as asthma or wheeze which may not be interchangeable and alter associations with different exposures. It was our intention to assess publication bias with a funnel plot however, the number of studies was insufficient.

3.9 Conclusion

This systematic review provides new evidence that VOCs such as aromatic and aliphatic compounds in the indoor home environment, are associated with an increased risk of asthma and asthma like symptoms including wheeze in adults. The greater the concentration of exposure to these chemicals the worse the health outcome. In practice, individuals are exposed to a ubiquitous concoction of toxic chemicals from everyday cleaning products, air fresheners, candles, home furnishings and more.

Whilst studies collect air samples of individuals exposures and assign a level of risk, individuals are rarely exposed singularly, rather, collectively to a noxious collective which without careful ventilation of the property and storage of products could be harmful to health and increase the risk of asthma. To prevent poor health outcomes individuals, health professionals and industry must make a concerted effort to better inform the general population of the importance of appropriate use of and storage of chemicals, as well as better health messaging on product labelling.

3.10 Summary

Indoor $PM_{2.5}$ and VOCs are a public health concern due to their inhalable size and resultant respiratory outcomes. In children much research has been conducted to analyze the risk of exposure to these pollutants, however in adults the evidence is lacking. This chapter used a standard reproduceable methodology to synthesize the available literature within this field.

The review found insufficient study numbers to draw any conclusions on the relationship between indoor $PM_{2.5}$ and asthma in adults. However collective new evidence was highlighted regarding the risk of VOCs and asthma in adults in the home environment. Particularly in aromatic and aliphatic compounds which were associated with asthma and asthma symptoms even in individuals who did not have a diagnosis of asthma. Better health messaging and product labelling is urgently required to reduce these risks.

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Chapter 4: Time Spent in the Indoor Home Environment, Fungal Contamination and Associated Asthma Outcomes: A Cross-sectional Study of Social Housing Tenants

4.1 Introduction

As outlined in Chapter 1**,** whilst most of our time is now spent indoors, data limitations have meant that little research has examined the impact of the time spent in the home environment on respiratory health. Prior studies investigating the links between biological, chemical, and physical pollutants and risk of asthma fail to account for the time residents spend within different indoor microenvironments, across different times of the year.

At the same time, previous studies have indicated the changing pattern of the fungal spores that influence indoor fungal contamination throughout the year (Cochran et al., 2022, Sharpe et al., 2014a, Sharpe et al., 2015a).

These pollutants infiltrate the home, for example outdoor PM can significantly influence indoor concentrations (Kuo and Shen, 2010, Song et al., 2015), and then viable pollen spora patterns (Zhang et al., 2020). Pollen spora patterns have shifted from long seasons of production to shorter periods across season and location, for example in subtropical regions and areas of higher latitude, indicating that solar radiation is a strong influence in pollen production across the seasons (Rahman et al., 2020).

Fungal spores are usually smaller than pollen spores (most fungal species are between 3 and 30 μm), and there is often marked variation in spore morphology both in and between fungal species (Dijksterhuis, 2019). Production of these types of spores can coincide and coexist with each other offering potential for multiple allergens to exist in the indoor environment which can significantly affect individuals who suffer from allergic asthma. Due to climatic conditions and climate change these spores travel large distances outdoors and are often found indoors (Haas et al., 2007).

As discussed in Chapter 2, indoor air pollution consists of a diverse collection of chemicals and other pollutants generated from multiple sources; indoors from new furniture, cooking, cleaning products, air fresheners etc.; outdoors from sources such as industry and emissions that migrate indoors and naturally occurring radon entering a home from the ground (UK Government, 2010, WHO, 2022c, WHO, 2009). At the same time, the quality of the indoor air is modified to a large extent by the resident's behaviour, time spent in the home and heating and ventilation patterns (Sharpe et al., 2014a, WHO, 2009).

As we begin to understand the multitude of pollutants individuals are exposed to across different microenvironments and the impact of these pollutants on human health, it is important to consider levels of exposure to pollutants from a temporal and spatial perspective that reflects the micro-environments in which humans carry out their daily activities.

In much of the research to date, data collection is but a snapshot in time and rarely reflects an individual’s true lived situation. For example, while many studies which monitor the quality of indoor air for asthma ask participants to reflect on their health over the monitoring period, few studies have considered the amount of time the individual has spent within the home specifically, which therefore makes it difficult to distinguish the impact of the home environment.

Human activities and interactions with the home environment therefore impact the timing and extent of pollutant exposure individuals encounter and play an important role in explaining exposure to different pollutants and resultant health outcomes.

Sensitization to indoor pollutants including airborne particles and allergens (e.g., house dust mites, cockroach, pet and fungal allergens), as the result of exposure, are important risk factors to consider for asthma morbidity and mortality.

As noted in Chapter three, many studies have examined the association between indoor factors linked with poor asthma outcomes in children. This occurs largely in day care settings due to data availability. However, adults are exposed to the same factors linked with poor asthma outcomes in a variety of settings (home, work, leisure etc.), with as much as 90% of their time spent within those environments. For example, exposure to an indoor mouldy odour has been found to increase the risk of asthma in adults aged over 50 years (Moses et al., 2019b).

Previous studies have found that time-use and time spent in different microenvironments is affected by several factors including sex, age, and employment status of the individual in question – with temporal factors such as season as well as the day of the week (weekday/weekend) at time of data collection (Matz et al., 2014, Hussein et al., 2012). For example, a previous study in the Po Delta area in North Italy found that older people over the age of 65 have previously been identified as spending a significantly larger number of hours per day at home than younger age groups (Simoni et al., 2003) which is reported to be around 60-70% of each day around the globe (Matz et al., 2014).

Further studies have found that there are associations between the characteristics and location of the home, time spent at home and occupant individual action (Brasche and Bischof, 2005). Brasche and Bischof study found that on average women spend slightly higher periods of time at home than men (16.6 hours per day and 15.7 hours per day respectively) (Brasche and Bischof, 2005). Those who lived alone or with one other person were found to spend the most amount of time at home, but older people spent the highest amount of time indoors than all other groups at 19.5 hours per day. They also noted that behaviour such as smoking affects the amount of time people spend in the home with smokers spending less time indoors than non-smokers.

Using a modular tool that combines standardized questions, and building evaluation, to record responses for duration of stay within the home, the study found Individuals reporting having physician diagnosed asthma spent approx. 18 hours per day at home (mean= 18.6 CI 17.7–19.4). However, the development and/or exacerbation of asthma can be influenced by the amount of time people with diagnosed asthma spend indoors due to avoidance of outdoor triggers, where they can be exposed to higher concentrations of indoor agents, which, in turn can increase the risk of development and/or exacerbation of asthma.

Given Cornwall's ageing population, understanding how people interact with their home environment and the impact of doing so will be important to inform future policy and planning for the health needs of the South-West of England, UK.

A further area of consideration regarding time spent in the home environment is changing behaviour patterns (Simoni et al., 2003), for example individuals that work at home (Huang et al., 2023) and sub-populations that do not fit the standard (home and care home workers, community care givers etc.).

The changing profile of outdoor air pollutants (e.g., new discoveries of health risk, changing weather patterns, climate change and climate change mitigation), infiltration into the home environment and exposure to additional indoor sources (e.g. from environmental tobacco smoke, heating and cooking), time spent indoors across the seasons, and the differing activity profile of different sub-populations make it vital to examine the impact of indoor air pollution on respiratory health at different intervals throughout the year.

An important sub-population from a housing and health prospective are social housing residents who can live in more deprived areas. In the UK, local not-for profit organizations, Housing Associations or local authorities assist individuals by providing homes at affordable below market rates to the most vulnerable in society (Shelter, 2022). Supplying homes at around 50-60% of that of the private rental market (Ministry of Housing Communities and Local Government, 2018), the English housing survey (2020/1) estimates that 19% of the population in England rent their property (4.4 million people). (10%) 2.4 million households were renting from a social housing provider in 2020-21 and 8% (1.8 million) from a local authority (Department for Levelling Up Housing and Communities, 2021).

Social housing residents are, on average, older individuals or families, with complex health and/or economic circumstances, who may spend more time in their home environment (Hills, 2007). Despite this, little research has focused on how and where social housing residents use their time throughout the day and how this may impact their wider health and wellbeing. A better understanding of social housing residents' daily activities and time spent in their home environment is essential. Within this context, the aim of this Chapter was to examine the relationship between time spent indoors and reported fungal contamination on asthma outcomes for Smartline participants, hence addressing the second research objective identified in Chapter 1.

Linking the Smartline baseline questionnaire, a Mini- Asthma Quality of Life (M-AQL) questionnaire and a time use diary this study addresses the following three interlinked hypotheses:

1. Individuals with higher periods of reported time spent indoors in the home environment are more likely to report having physician diagnosed asthma than not having asthma.
2. Individuals with physician diagnosed asthma are more likely to report worse symptoms when they spend higher reported periods of time in the indoor home environment than those spending less time at home.
3. Individuals who have visible fungal contamination in their home and spend higher periods of time in that environment are more likely to report worse asthma symptoms than those spending less time at home.

To address hypothesis one, an analysis of the time spent inside individuals' homes is conducted to identify the risk of reporting asthma. To address hypothesis two, the analyses are extended to assess whether having fungal contamination in the home increases the risk of reporting asthma. To address hypothesis three analyses are conducted to assess if time spent in the home increases asthma symptoms, and to test whether the risk of more severe symptoms is observed if the home has visible signs of fungal contamination.

The Chapter is structured as follows; Section 4.2 gives an overview of the Smartline project. Section 4.3 describes the data and methods, before results are presented in Section 4.4. Section 4.5 presents a discussion of the results, with strengths and limitations being identified in Section 4.6. Section 4.7 presents some overall conclusions and recommendations. Section 4.8 provides a summary.

4.2 The Smartline project

Smartline is a European Regional Development Fund collaborative project which started in 2017 between the University of Exeter, Cornwall Council (the local government), Volunteer Cornwall (a local charity working to promote voluntary action throughout the county) and Coastline Housing (an independent Cornish charitable housing association which owns and manages around 5000 homes, whose customers were invited to participate in the project).

The South West Academic Health Science Network also joined the project in the later stages of Smartline and specialize in working with partners across the region in the health and care system to identify, and spread innovative practice, build capability and support evaluation and learning (SWAHSN, 2023).

The relationship between residents and providers of social housing has changed over recent decades with it generally being considered good practice to involve social housing tenants when opportunities arise, to express their views about issues that affect them (Simmons and Birchall, 2007).

Within this context, the Smartline project aims to understand the different challenges social housing residents face regarding their health and wellbeing and their goal for using technology to assist in overcoming these challenges, to facilitate people living healthier and happier lives in homes and communities (Smartline, 2022). Smartline has recruited more than 300 households residing in properties which are owned and managed by Coastline Housing.

To better understand the health and wellbeing of this sub-population a range of research activities have been conducted including qualitative interviews, questionnaire surveys and the installation of sensors to collect internal environmental data. This unique set of validated cross-sectional questionnaire data provides the baseline data utilized by this novel study. This dataset has been used previously to address a range of research questions, including the impact of fuel poverty on health, the impact of COVID-19 lockdowns on utility usage patterns, the impact of mould on health and other issues (Tu et al., 2022, Menneer et al., 2022, Moses et al., 2019b, Walker et al., 2022, Williams et al., 2020a, Williams et al., 2021b, Menneer et al., 2021).

As a sub-population of social housing residents, the Smartline project participants provide a unique insight into the time-use and health and housing needs of a more deprived sub-population who experience a range of health inequalities. This in turn, provides an opportunity for area-level interventions targeting populations living in social housing and wider society to help reduce indoor exposures to physical, chemical and biological agents, and disease onset and/or exacerbation.

4.3 Data and Methods

4.3.1 Recruitment

The Smartline participants were adults (older than 18 years) who were recruited on a convenience basis from residents of Coastline Housing in the towns of Camborne and Redruth and the villages of Illogan and Pool. The Camborne-Pool-Illogan-Redruth area is the largest conurbation in Cornwall, with a population of 47,500 in the census in 2011. A high concentration of Coastline Homes in a location was needed to address the project's focus on communities and individual households, and this area met this need. Coastline Housing conducted participant recruitment street-by-street between September 2017 and November 2018. 649 households were approached; 329 were recruited into the project and completed baseline data collection (329/649, 50.7% response rate) (Williams et al, 2021). The sample was not aiming to be representative of Cornwall or of Coastline Housing, Williams et al (2020) shows that the sample is older and had a higher proportion of females than the Cornwall or England averages.

The participants included in this study exploring time spent inside the home and asthma outcomes were a sub-population of Smartline participants. At the time of the present study 314 households were still active Smartline participants. All

Smartline participants were approached (n=314); 48 during the weekday and 81 during the weekend were recruited during the reporting period in summer (15.3% and 25.8% response rate) and 101 during the weekdays and 102 at the weekend during winter (32.2% and 32.5% response rate).

The Smartline participants who were identified as having asthma at baseline (n=97) were asked to fill in an additional questionnaire on the final day of each study period (n= 36 summer and n= 34 winter) (37.1% and 35% response rate) (Figure 5 and 6).

No power calculations were carried out for either the Smartline project or this follow-on study examining the time spent in the home on asthma outcomes. Instead, the exploratory analyses offer insights into the Smartline cohort and potentially other social housing tenants paving the way for further larger studies, which are needed to verify the findings contained within this thesis.

4.3.1.1 Data Description

An overview of the key available data is presented in Table 9.

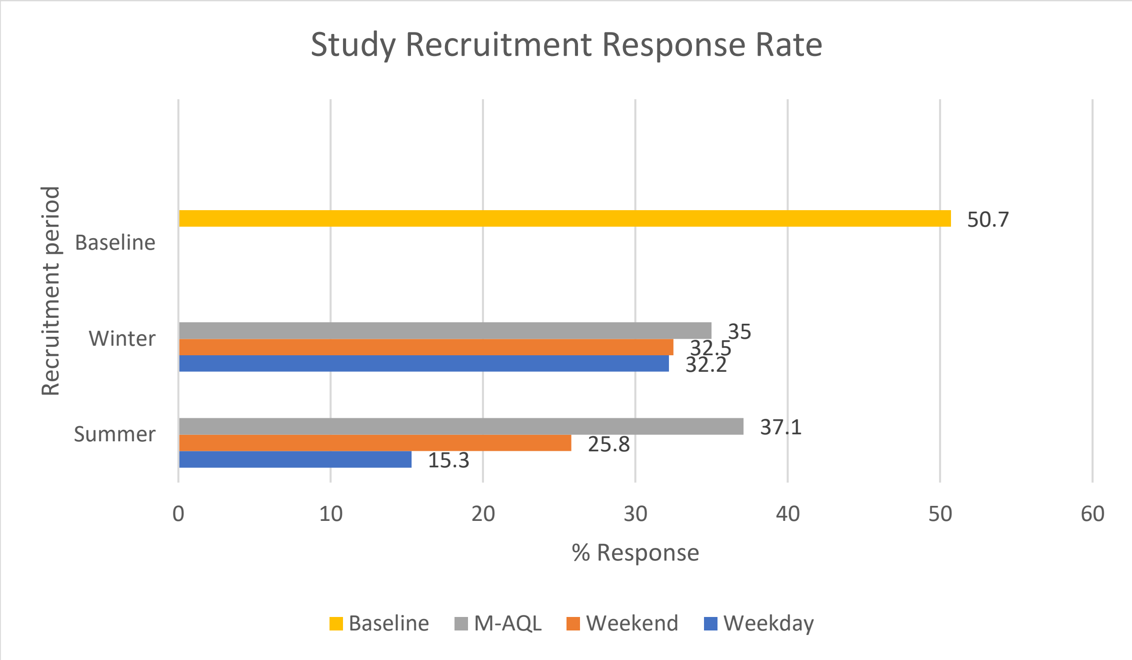
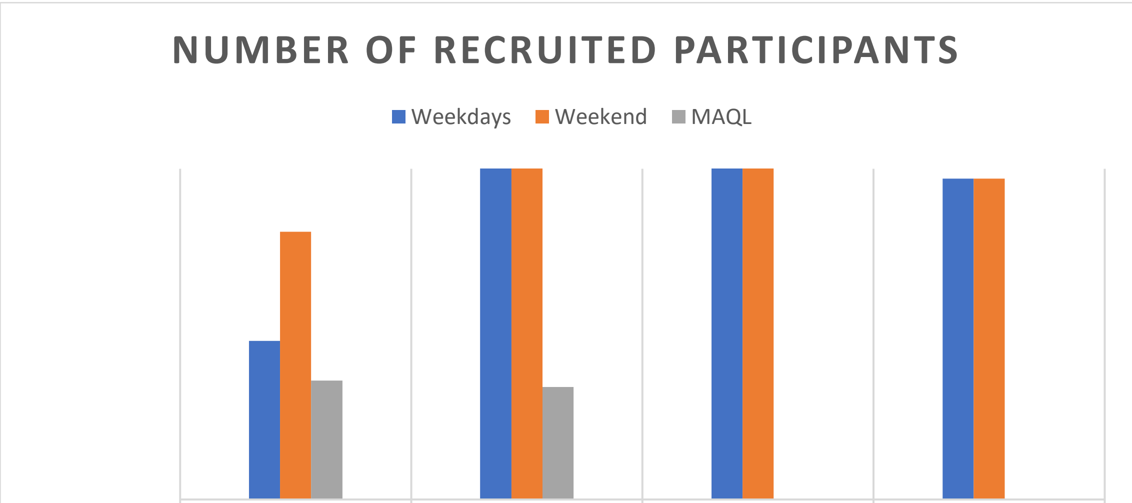


Figure 5 Overview of recruitment response



	Summer	Winter	Baseline	Asthma at baseline
Weekdays	48	101	314	97
Weekend	81	102	314	97
MAQL	36	34		

Figure 6 Summary of Recruited Participants

Table 9 Overview of key available data

Variable	*Details*	*Source*
Doctor diagnosed asthma	Binary variable for both main respondent and partner	Smartline Baseline Questionnaire
ISAAC	Experience of Asthma in year prior to the Smartline Baseline Questionnaire	Smartline Baseline Questionnaire
Mini-Asthma Quality of Life	Experience of Asthma in previous two weeks, conducted on last day of Time Use + M-AQL Questionnaire. (Both winter and summer)	Time Use+M-AQL Questionnaire
Time Use	Hours indoors based on diaries for 7 days in both winter and summer months	Time Use + M-AQL Questionnaire
Time outdoors	Hours indoors (average)	Smartline Baseline Questionnaire
Sex	Binary variable, 1 for Female	Smartline Baseline Questionnaire
Fungal contamination	Self-reported mould through visual inspection	Smartline Baseline Questionnaire
Ventilation Reported	Reported resident action taken to actively prevent mould growth including the use of an extractor fan when cooking and bathing	Smartline Baseline Questionnaire

Pets	Type of pet and number in the property and whether the pet slept in the bedroom of the participant	Smartline Baseline Questionnaire
Smoking status	Past and present smoking status and by how many times per day	Smartline Baseline Questionnaire
Employment status	Current or most recent occupation or retirement status – self reported	Smartline Baseline Questionnaire

4.3.2. Asthma data collection

Data were collected in separate phases for asthma outcomes. First, as part of a baseline questionnaire conducted from October 2017 to February 2018. The baseline questionnaire included ISAAC questions for asthma (ISAAC, 2017):

- Self-reported doctor diagnosed asthma (for both the respondent and their partner, if applicable).
- Self-reported wheezing or coughing (for both the respondent and their partner, if applicable):
    - ever and in last 12 months.
    - over 3 coughing attacks in past 12 months
    - sleep disturbances due to wheezing or coughing in past 12 months.
    - speech limitation due to wheezing or coughing in past 12 months.
    - chest sounding wheezy during or after exercise in past 12 months.
    - dry cough at night (without cold/chest infection) in past 12 months.
- Binary variable for experiencing asthma and having seen a doctor in past 12 months (both respondent and partner).
- Binary variable for taking medicine for asthma in past 12 months (both respondent and partner).

Second, individuals who identified as having experienced asthma in the initial baseline questionnaire were asked to complete the Mini-Asthma Quality of Life questionnaire (M-AQL) in winter (February 2019) and summer

(August/September 2019) (Figure 5). This is because the ISAAC questionnaire that was used in the baseline questionnaire asks about symptoms experienced in the past 12 months. In order to assess any seasonal variability and to reduce recall bias the M-AQL focuses on symptoms over the past two weeks, this is also a useful measurement when analysing the data to see if there are changes in the severity of symptoms at different points throughout the year and whether any potential changes correlate to the amount of time spent within the home or the home environment. Full copies of the questionnaires and consent forms are presented in appendix 3.

4.3.3 Time Use

The study of human time use originated in the late 19th century where studies investigated the life of peasant families by analyzing the one week diaries of housewives in London (Stuart (Robison) "Mrs. Reeves" Magdalen, 2016). Time use studies are intended to monitor an individual's sequential activities through a continuous and defined observation period. A 24-hour self-completed reported daily time diary is an accurate and reliable data collection instrument of recording time use data (Foster et al., 2019). To date, time use data has been used for a variety of analytical purposes including observing consumer behaviour (Glorieux et al., 2010) and urban planning (Harvey, 2002), and more recently understanding potential exposure to COVID-19 (Spooner et al., 2021).

For this study, Smartline participants were asked to fill out a diary indicating how much time they spent inside their own home at four different time points throughout the day each day for seven consecutive days during the summer (August/September 2019) and Winter (February 2019). The timepoints were as follows:

- Morning (before midday)
- Afternoon (midday-5pm)
- Evening 5pm-11pm)
- Night 11pm-6am)

On the final day of the time use diaries, participants who had previously identified as having asthma at Baseline (n=97) were asked to fill out a Mini Asthma Quality of Life (M-AQL) questionnaire. This was to identify whether individuals who had doctor diagnosed asthma were impacted by worsening symptoms and worse overall quality of life with increasing time spent inside the home, and whether the individual reporting visible fungal contamination in the home had any effect on symptom severity.

The same ID protocol was followed for both studies as the initial Smartline project to ensure that the newly collected data could be matched with the baseline questionnaire data. As with the baseline questionnaire, participants were fully informed of the research and their right to withdraw at any time. For this additional study to the Smartline project, ethical consent was approved by the University of Exeter Medical School Research Ethics Committee *REFERENCE NUMBER:* Jan19/B/175.

Table 10 Data collection timeline

	Baseline Survey	Time- use Diaries	M-AQL
Date of collection	*Oct 2017- March 2018*	*Feb 2019 & Aug/Sept 2019*	*Feb 2019 & Aug/Sept 2019*
Season of collection	*Winter*	*Winter & Summer*	*Winter & Summer*

4.3.4 Other control variables

The Smartline baseline questionnaire included a range of questions that can be used as control variables for this analysis. This includes:

- Sex.
- Age.
- Self-reported mobility.
- Time spent indoors (baseline).
- Quality of Life.
- Housing conditions measured subjectively (including indoor presence of fungal contamination).
- Heating and ventilation patterns.
- SF12 questions regarding health and wellbeing.
- Smoking and vaping exposures (both of the individual and in the home).

- Pets in the home.
- Employment status.

Additional data on the property were obtained from Coastline housing including:

- Type of heating.
- Build type.
- Other asset management data.

Data was collected from the person named on the tenancy agreement who is responsible for paying the bills and who had taken receipt of the digital tablet provided by Smartline as well as their partner if applicable. Although for the analyses in this study data was only used from that of the primary participant due to the small sample size

To obtain baseline information about the participating households for the Smartline project, as noted above, project participants were asked to complete a baseline questionnaire. Data collection for the baseline questionnaire was conducted from October 2017 to February 2018. These questionnaires were conducted via face-to-face interviews in participants own homes lasting around 1.5 hours. These were delivered by researchers using a digital tablet and achieving a 100% participation rate.

During the initial baseline questionnaires all participants were informed that as part of the project they may be invited to take part in additional questions at various time points throughout the project prior to giving consent to participate on an entirely voluntary basis.

To examine potential seasonal changes in asthma severity, M-AQL and time use data were, as noted previously collected simultaneously at two time points: February 2019 (winter) and August/September 2019 (summer) (Table 10). Participants were current Smartline participants who were recruited via digital invite through their tablets, at face-to-face events and via letters to reach the maximum number of residents as possible. We aimed to recruit the same people across both timepoints so we could examine any potential changes in their health over time.

This was carried out by asking the participants who agreed to take part, to complete the time-use diaries in both the summer and winter reporting periods (a separate consent and information pack was sent at both timepoints) and participants were reminded via newsletters etc. of the upcoming studies. Those identified as having asthma were asked to fill out the M-AQl in addition to the time-use diary at both time points on the final day of the time diary entry. The recruitment and overview of included participants are summarized in figure 7. Data obtained from each period were linked using the UPRN assigned at baseline and analyzed independently.

A response was classed as complete if all entries on the diary were full in the reporting period for the weekday and or weekend in the summer and winter as analyses for each were conducted separately. If for example the diary had a complete weekend entry but missing data in the week it was still included but only as a weekend entry. This was for two reasons first; the baseline questionnaire had previously asked about time use at the weekends, so it seemed pertinent to directly compare to see if any changes in time use and subsequent health are observed in this population. Second, most other time use studies have evaluated one day at the weekend and one day during the week and the limitations of this have been discussed previously.

By having a continuous 5-day ‘working weeks’ worth of diary entry or a continuous 2-day weekend diary entry a much truer picture of individuals time use can be analyzed, as the way people interact with and within their home inevitable differs between weekdays and the weekend.

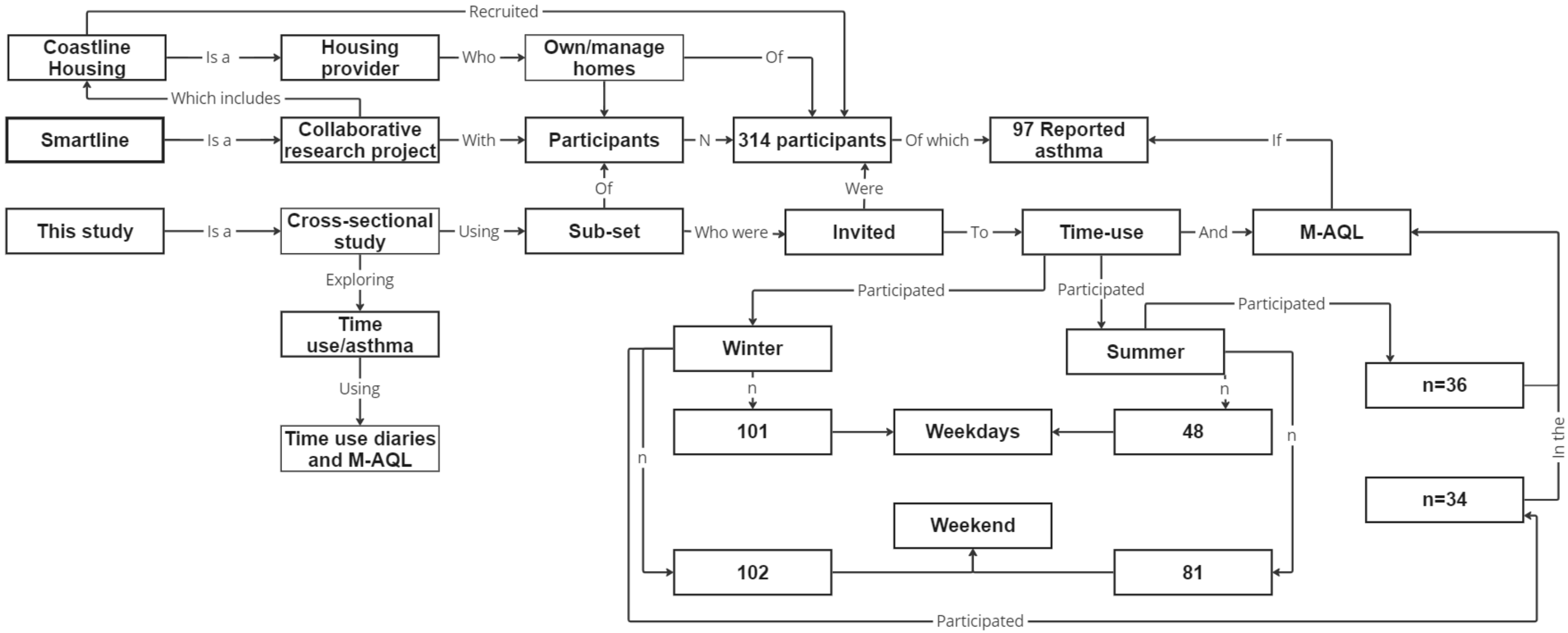


Figure 7 Recruitment and Participation Overview

4.3.5 Data Collected: Baseline Questionnaire

The initial baseline questionnaire (appendix 4) collected data on:

- Self-reported mobility
- Time spent indoors
- Quality of Life
- Housing conditions measured subjectively
- Heating and ventilation patterns
- Pets
- Smoking-status
- Self-reported doctor diagnosed asthma (SF12 (a multipurpose shortform (SF) generic measure of health status)(Ware et al., 2009, Williams et al., 2021b), and the Warwick-Edinburgh Mental Wellbeing Score (Stewart-Brown et al., 2009, Williams et al., 2021b, Moses et al., 2019b)).

In addition, demographic data including:

- Household member ages
- Sex
- Employment status

were recorded for both the main participant and partner (if applicable).

Demographic and environmental exposures understood to influence the risk of asthma were included at baseline and validated in other studies (Moses et al., 2019b, Sharpe, 2015a, Menneer et al., 2022). Data collected included report of visible fungal contamination, report of a fungal contamination or musty odour, whether individuals felt that fungal contamination was impacting on their family's health, cleaning regimes, number of rooms carpeted, pets and heating/ventilation regimes. All of which inform the basis of this analysis.

4.3.6 Data Collected: Asthma

The ISAAC Questionnaire for asthma (a global standardized framework for the measure and comparison of asthma) (ISAAC, 2017) was modified in line with previous studies (Sharpe, 2015a) and also included as part of the baseline questionnaire. This measures self-reported previous diagnosis by a physician of asthma, cough or wheeze in the past 12 months and allergy response providing information in which the M-AQL questionnaire (administered as part of the summer and winter time use) was invoked.

The baseline questionnaire included ISAAC questions for asthma (ISAAC, 2017) included:

- Self-reported doctor diagnosed asthma (for both the respondent and their partner, if applicable).
- Self-reported wheezing or coughing (for both the respondent and their partner, if applicable):
  - ever and in last 12 months.
  - over 3 coughing attacks in past 12 months

    - sleep disturbances due to wheezing or coughing in past 12 months.
    - speech limitation due to wheezing or coughing in past 12 months.
    - chest sounding wheezy during or after exercise in past 12 months.
    - dry cough at night (without cold/chest infection) in past 12 months.
- Binary variable for experiencing asthma and seen doctor in past 12 months (both respondent and partner)
- Binary variable for taking medicine for asthma in past 12 months (both respondent and partner).

Additionally, available asset management data including type of heating, build type, maintenance type and schedule was received from a Smartline partner - Coastline Housing, for all Smartline participants.

4.3.7 Data Collected: Time Use Questionnaire

Given the intensive data, and data collection challenges associated with defining a representative data collection timeframe, (for example do we need to cover the whole year or only part of it?), the regular collection of time diary data has been limited to date, with response rates often much lower than other questionnaire based surveys (Minnen and Rymenants, 2014). Single day observations are standard across many studies however the Eurostat HETUS uses 2 days, a weekday and weekend (Gershuny, 2011).

For our study, Smartline participants (N=314) were asked to fill out a diary indicating how much time they spent inside their own home at four different time points throughout the day (morning, afternoon, evening, night) over seven days (see Table 10). The time use questionnaire was administered twice, once in summer and once in winter to observe any seasonal variability. Data was collected from one participant per household who was the person responsible for paying the bills.

4.3.8 Data Collected: Mini Asthma Quality of Life (M-AQL) Questionnaire

To understand asthma severity in the Smartline population, Smartline participants were asked to participate in the Mini Asthma Quality of Life (M-AQL) questionnaire (Appendix 4). The M-AQL has been used in other studies and demonstrated the ability to determine asthma control with its use indicating clinically relevant effect (minimal clinically important difference = 0.5) (Khusial et al., 2020). Additionally, the modified ISAAC questionnaire that was used in the baseline questionnaire asks about symptoms experienced in the past 12 months. In order to assess any seasonal variability and to reduce recall bias the M-AQL focuses on symptoms over the past two weeks. The M-AQL asks respondents 15 questions relating to four specific domains that form the variables of interest for the asthma severity part of this study:

- *Emotional functioning*: this relates to whether respondents felt frustrated as a result of their asthma, felt afraid of not having their medication available, or felt concerned about having asthma.

- *Environmental Stimuli*: relates to whether individuals felt bothered by or had to avoid dust in their environment; felt bothered by or had to avoid cigarette smoke in the environment or felt bothered by or avoided going outside because of the weather or air pollution.
- *Symptoms*: this domain relates to whether the respondent felt short of breath, bothered by coughing, experienced tightness or heaviness in the chest, had difficulty getting a good night's sleep as a result of their asthma or experienced a wheeze in the chest.
- *Activity Limitation*: this domain focuses the extent to which individuals found limitation in their ability to carry out both strenuous and moderate activities, social activities and work-related activities.

To score the M-AQL questionnaire, responses from each of the 15 questions in the survey are added together and divided by 15 to form an overall score. Responses relating to each domain were added together and divided by the number of items in each domain. All questions in the M-AQL questionnaire ask about issues that arise because of having asthma and the survey is only given to people with asthma so there will therefore be no normal values. Seven is the highest score one can obtain and indicates that the individual is experiencing no impairment from their asthma.

A score below seven represents some degree of impairment with one representing severe impairment. It has been established that when using the M-AQL for interpreting the results the minimal important difference (MID) defined as "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 patients management" (Juniper et al., 1994) is close to 0.5 on the 7-point scale.

4.4 Statistical analysis

Baseline data was linked with the time use diaries, M-AQL survey and asset management records using a unique household identifier (UPRN number). To understand if time use changed between baseline data collection (2017) and the study period (2019), a Spearman's correlation test was used.

Descriptive analysis was performed to describe the participants and overall differences between the participants in terms of time use. Variables used for this analysis were:

- Age range
- Sex
- Household occupancy (how many adults/children/older adults)
- Visible fungal contamination
- Presence of a mouldy odour
  - Whether the individual took preventative measures to stop fungal growth such as regularly opening windows or using an extractor fan when cooking or bathing

Given that a conceptual basis is provided for each analysis, due to the limited sample size and to avoid risk of over fitting the models' multiple cofounders were not corrected for but were available:

- Presence of pets
- Self-reported mobility
- Quality of Life.
- SF12 questions regarding health and wellbeing.
- Smoking and vaping exposures (both of the individual and in the home).
- Pets in the home.
- Employment status.

Additional data on the property were obtained from Coastline housing including:

- Type of heating.
- Build type.
- Other asset management data.

4.4.1 Asthma Prevalence, Time Spent Indoors and Fungal Contamination

To estimate the impact of time spent in the indoor environment on the likelihood of reporting asthma, univariate analyses were conducted on both the baseline questionnaire data and seasonal time use data using a series of logit models as described in figures 8-11. Multiple regression modelling was then applied to analyze the relationship between time spent in the home and the likelihood of reporting asthma for those who had reported fungal contamination at baseline.

4.4.2 Asthma Severity, Time Spent Indoors and Fungal Contamination

For individuals with asthma who took part in the M-AQL, multivariate logistic regression was performed to analyze the relationship between time spent in the home, asthma symptoms and fungal contamination. Associations are expressed as probability values with a statistical significance of ≤ 0.05 and 95% confidence intervals (CI). All statistical analyses were performed using STATA/SE 17.0 (Corporation, 2022).

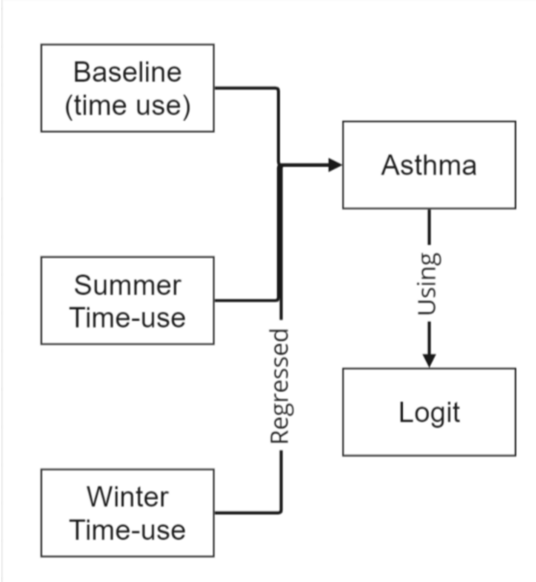


Figure 8 Model 1-Statistical model used to analyse whether increased time in the home increase the risk of reporting asthma.

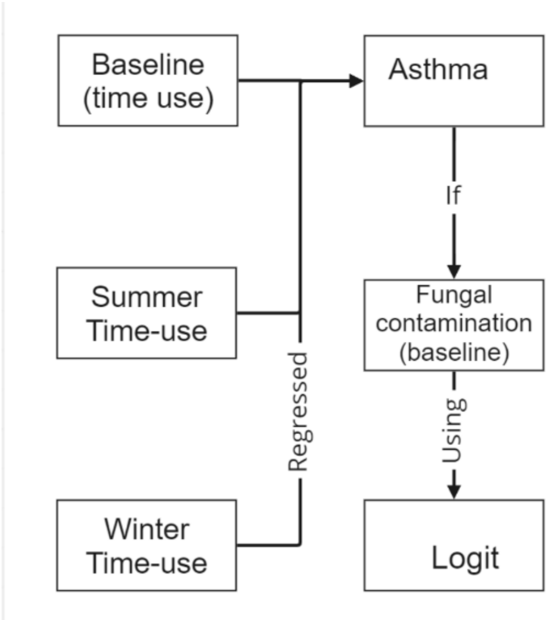


Figure 9 Model 2- Statistical model used to analyse whether increased time spent in the home increases the risk of reporting asthma if the home has fungal contamination.

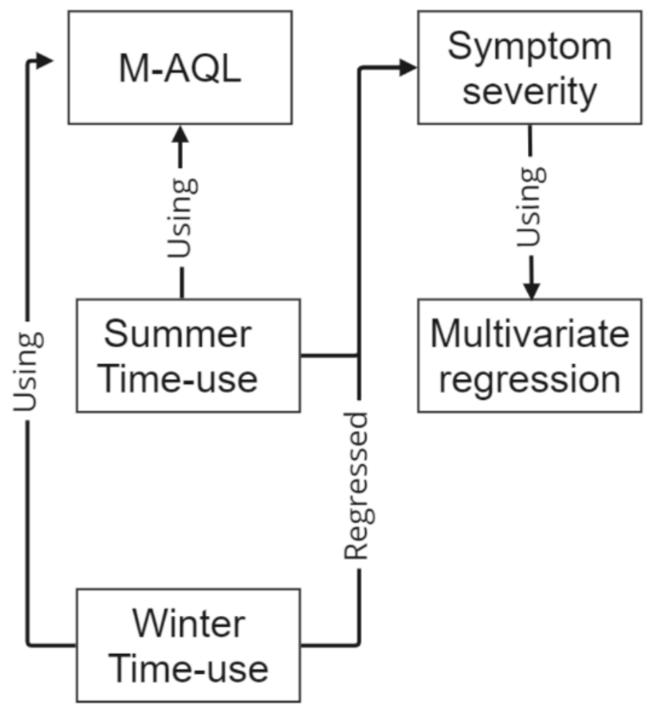


Figure 10 Statistical model used to identify whether increased time spent in the home results in more severe asthma symptoms being experienced.

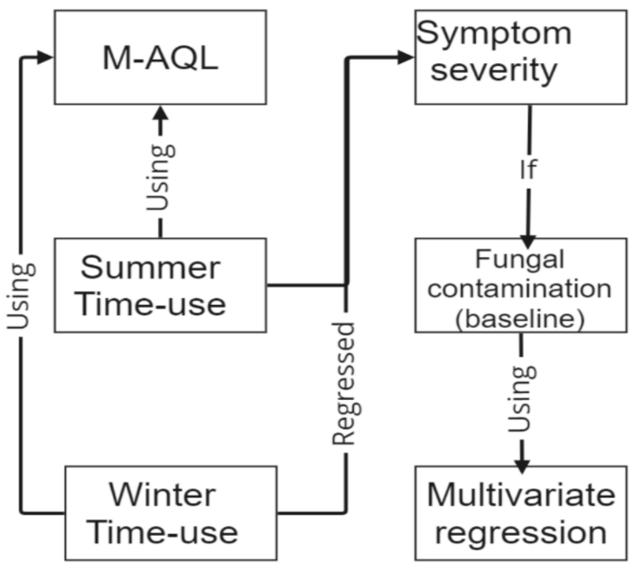


Figure 11 Statistical model used to ascertain whether increased time spent in fungal contaminated homes results in more severe symptoms being experienced.

4.4.3 Ethics

The collection of the Smartline Baseline questionnaire, sensor data and data merger with Coastline Housing data was given ethical approval from the University of Exeter. For the additional study using the M-AQL and time use ethical approval was obtained from University of Exeter Medical School Research Ethics Committee *REFERENCE NUMBER:* Jan19/B/175.

4.5 Results

Table 11 presents an overview of descriptive statistics for the sample population for this study. The average age of participants was 55 years old and 69% were female. 90% of homes were single adult occupancy with only eight percent having two adults in the household. 98% of households who had an adult residing in the property had at least one reported to be an older adult. 76% of homes had one child and 16% of homes had two children.

Forty-four percent of homes reported visible fungal contamination at baseline and 17% reported a mouldy/musty odour with 13% feeling that fungal contamination was impacting on their family's health. Thirty-six percent of the study population reported regularly ventilating their home to actively prevent fungal growth. Other preventative measures to reduce mould reported were the use of an extractor fan when cooking and the use of an extractor fan when bathing, which were reported in 71% on 62% of households respectively.

Table 11 Descriptive Statistics of the Smartline Participants

Descriptive statistics	*Study Participants*	
	Percentage (%)	Number (n = 314)
Mean age (≥18 years) = 55, range = 19- 92 years		
Male	31	98
Female	69	216
Homes consisting of 1 adult	90	209
Homes consisting 0f 2 adults	8	18
Households reporting having at least 1 older adult residing in the property	98	102
Homes with 1 child	76	32
Homes with 2 children	16	7
Reported visible fungal contamination at baseline	44	139
Reported a mouldy odour at baseline	17	55
Felt fungal contamination was impacting on their families health	13	43
Regularly ventilates their property to prevent fungal contamination	36	113
Uses an extractor fan in the bathroom to prevent fungal contamination	71	224
Uses an extractor fan in the kitchen when cooking to prevent fungal contamination	62	196

4.5.1 Time use

Table 12 summaries the average amount of time the study population spend inside their own home during the weekday and weekend of both the baseline reporting period and the study periods during summer and winter. This shows that, on average at baseline, individuals spent around 20 hours per day inside their own home. This did not differ by sex or day of the week.

Examining the time use from Winter 2019 and Summer 2019, at the time of the study periods in summer/winter there were slight differences in time spent in the home by sex and by day of the week. On average, women spent more time inside their homes in both summer and winter than men, regardless of day of the week. Men however, spent less time at home during the weekdays than women, with their average hours per day spent at home during this period being 15 hours per day summer and winter.

As noted, two types of data were collected relating to time use. Data on time use was first collected via the baseline questionnaire, which asked participants to report their time-use on average during a typical weekday and weekend. The second data collected relating to time use was collected as recommended by (Harvey, 2003) via a 7-day time-use diary. The number of respondents replying to the time use diaries was small (summer n=48 weekdays and n=81 weekends, Winter n=101 weekdays and 101 weekends).

To try to optimize the data sample on time use, we explored using the baseline questionnaire data with the asthma severity data. A nonparametric testing was applied to observe whether any differences in time use between baseline and study period existed for the participants. Spearman's correlation (Table 13) analysis identified that there were minor differences in time use between baseline and the study period, however they were not statistically significant. These differences, despite the small sample sizes obtained from the time use diaries, validated the use of the time diary data rather than using the larger data on time-use collected at baseline.

Table 12 Average time spent at home by Smartline participants for both baseline and Study Time-use participants.

Time Period	*Sex*	*Mean hours per day*	*Std.dev.*	*Min*	*Max*	*Season*
Baseline weekday	M (n= 95)	20.87	8.92	8	24	Baseline (Winter)
	F (n= 212)	20.33	7.57	2	24	
Baseline weekend	M (n= 95)	20.14	3.68	8	24	Baseline (Winter)
	F (n=213)	20.32	3.76	1	24	
Summer weekday	M (n= 24)	15.57	2.76	8.6	19.24	Summer
	F (n= 24)	16.09	2.13	12.04	19.24	
Summer weekend	M (n= 29)	20.07	5.35	0.02	24	Summer
	F (n=52)	19.58	5.05	0.12	24	
Winter weekday	M (n= 38)	15.84	2.58	7.61	19.44	Winter
	F (n= 63)	16.31	2.04	10.44	19.24	
Winter weekend	M (n=38)	21.12	3.21	11.22	24	Winter
	F (n=64)	20.53	4.60	0	24.52	

Table 13 Spearman Correlation testing for differences in time use between baseline and study period.

	Weekday Baseline			*Weekend Baseline*		
	Prob > |t|	Spearman's rho	n	Prob > |t|	Spearman's rho	n
Weekday Summer	0.08	0.25	46	-	-	-
Weekend Summer	-	-	-	0.102	0.18	79
Weekend Winter	-	-	-	0.18	0.13	97
Weekday Winter	0.79	0.02	95	-	-	-

4.5.2 Time spent within the home environment and associated risk of reporting adult asthma: Baseline questionnaire.

Estimating the likelihood of reporting asthma with increasing time spent at home using logit models, we found no clear associations between time spent in the home at baseline and increased risk of reporting asthma (n= 307 weekday and n= 308 weekend). However, the presence of a mouldy or musty odour was associated with a 2-fold increased risk of reporting asthma, this was apparent during weekdays and the weekend (OR 2.4, 95% CI 1.34 - 4.4, p= 0.004 and OR 2.4, 95% CI 1.3 - 4.4, p= 0.005 respectively).

Next, to test for associations between increased time spent in the home environment and increased risk of reporting asthma, separate logistic regression analysis using the data from time use diaries during the summer (n= 48 weekdays and n= 81 weekend) and winter (n= 101 weekdays and n= 102 weekends) study period were estimated, however, no such associations were found.

4.5.2 Time spent within the home environment and associated risk of reporting adult asthma: Baseline questionnaire.

Estimating the likelihood of reporting asthma with increasing time spent at home using logit models, we found no clear associations between time spent in the home at baseline and increased risk of reporting asthma (n= 307 weekday and n= 308 weekend). However, the presence of a mouldy or musty odour was associated with a 2-fold increased risk of reporting asthma, this was apparent during weekdays and the weekend (OR 2.4, 95% CI 1.34 - 4.4, p= 0.004 and OR 2.4, 95% CI 1.3 - 4.4, p= 0.005 respectively).

Next, to test for associations between increased time spent in the home environment and increased risk of reporting asthma, separate logistic regression analysis using the data from time use diaries during the summer (n=

48 weekdays and n= 81 weekend) and winter (n= 101 weekdays and n= 102 weekends) study period were estimated, however, no such associations were found.

4.5.3 Time spent within the home environment and associated risk of reporting asthma symptoms if the home has visible fungal contamination: Mini-Asthma Quality of Life questionnaire.

Table 21 summarizes the associations between time spent in the indoor home environment and resultant asthma outcomes for those who were previously identified at baseline as having doctor diagnosed asthma and who subsequently went on to fill in the M-AQL questionnaire on the final day of the time use diaries (n= 36 during summer and n=34 during winter). This is provided as appendix 5. Question responses from the M-AQL are divided into four domains: symptoms, activity limitation, emotional functioning and environmental stimuli. In relation to each domain the results are as follows.

4.5.4 Emotional functioning

To estimate relationships between emotional functioning for asthmatics and time spent in the home environment a linear regression model was run (Table 14). A For each hour increase in time spent inside the home a 1.7-point decrease in emotional functioning was observed. Time spent inside the home during both weekdays and weekends in the winter reporting period were significantly associated with reduced emotional functioning if the home contained visible fungal contamination (F (2,24) = 2.60, p= 0.033, adj. R^2 = 0.10 during weekdays and (F (2,24) = 4.36, p= 0.014, adj. R^2= 0.20 during the weekends). In the summer visible fungal contamination was associated with worse emotional functioning at the weekends, however, these results were not statistically significant (F (2,23), p=0.083, adj.R^2=0.10.

For each hour increase in time spent in the home a 1.7 (winter) point reduction in emotional functioning was observed if the home contained visible fungal contamination, meaning worse symptoms were experienced. No significant relationships were observed for time spent in the home and emotional functioning if the home did not have visible fungal contamination. (β=-.317, p= 0.150 for weekdays in the summer, β=-.243, p= 0.232 for weekends in summer, β=.060, p=0.764 for weekdays in winter, β=-.229, p=0.250 for weekends in winter).

Table 14 The relationship between time spent in the home and emotional functioning.

	Time Spent Inside the Home							
	Summer				Winter			
Health Outcome	Weekdays		Weekends		Weekdays		Weekends	
		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination
Emotional Functioning	-.317	-.333	-.243	-.345	.060	-.436	-.229	-.465
F-ratio	(1, 20) 2.24	(2, 19) 2.45	(1, 24) 1.51	(2, 23) 352 2.47	(1, 25) 0.09	(2, 24) 2.60	(1, 25) 1.39	(2, 24) 4.36
P-value	0.150	0.131	0.232	0.083	0.764	0.033*	0.250	0.014*
95% Confidence Interval	-.811 to .133	-2.755 to .385	-.400 to .101	-2.697 to .176	-.386 to .519	-3.356 to - .150	-.481 to .131	-3.187 to - .393
Coefficient	-.338	-1.185	-.149	-1.260	.066	-1.753	-.175	-1.790
Standard Error	.226	.750	.121	.694	.219	.776	.148	.677
R^2	0.10	0.20	0.05	0.17	0.00	0.17	0.05	0.26
Adj. R^2	0.05	0.12	0.01	0.10	-0.03	0.10	0.01	0.20

4.5.5 Environmental Stimuli

Assessing the relationship between environmental stimuli and time spent inside the home, using a linear regression model, our findings indicate that increased time spent inside the home were associated with more severe asthma symptoms specifically related to environmental stimuli across all time points if the home contained visible fungal contamination (Table 12)($F(2,20) = 3.41$, $p= 0.037$, adj.$R2= 0.17$ for weekdays in the summer, ($F(2,23) = 3.26$, $p= 0.030$, adj. $R2 = 0.15$ for weekends in summer, and $F(2,24) = 2.97$, $p=0.023$, adj. $R2= 0.13$ during weekdays in winter and ($F(2,24) = 4.75$, $p=0.012$, adj. $R2= 0.22$ during weekends in winter). For each hour increase in time spent in the home a 1.6 (summer) and 1.8 (winter) point reduction in environmental stimuli was observed, indicating that worse symptoms were experienced from environmental stimuli. No significant relationships were observed between time spent inside the home and increased asthma symptoms specifically related to environmental stimuli if the home did not have visible fungal contamination ($\beta=-.317$, $p=0.150$ for weekdays in the summer, $\beta=-2.43$, $p=0.232$ for weekends in summer, $\beta= 0.60$, $p= 0.764$ for weekdays in winter, $\beta=-.22$, $p=0.250$ for weekends in winter).

Table 15 The relationship between time spent in the home and environmental stimuli.

	Time Spent Inside the Home							
	Summer				Winter			
Health Outcome	Weekdays		Weekends		Weekdays		Weekends	
		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination
Environmental Stimuli	-.261	-.447	-.199	-.427	.007	-.465	-.251	-.472
F-ratio	(1, 21) 1.55	(2, 20) 3.41	(1, 24) 1.00	(2, 23) 3.26	(1, 25) 0.00	(2, 24) 2.97	(1, 25) 1.69	(2, 24) 4.75
P-value	0.228	0.037*	0.328	0.030*	0.968	0.023*	0.205	0.012*
95% Confidence Interval	-.823 to .207	-3.261 to -.109	-.403 to .140	-3.137 to -.174	-.451 to .469	-3.504 to -.290	-.507 to .114	-3.269 to -.446
Coefficient	-.308	-1.685	-.131	-1.656	.008	-1.897	-.196	-1.858
Standard Error	.247	.755	.131	.716	.223	.778	.151	.683
R^2	0.06	0.25	0.03	0.22	0.00	0.19	0.06	0.28
Adj. R^2	0.02	0.17	-0.00	0.15	-0.03	0.13	0.02	0.22

4.5.6 Asthma Symptoms

To estimate relationships between time spent inside the home and asthma symptoms a linear regression model was run (Table 16). A For each hour increase in time spent inside the home during winter a 1.6-point decrease in asthma symptoms was observed indicating that worse symptoms were experienced during this period.

Time spent inside the home during both weekdays and weekends in the winter reporting period were significantly associated with worse asthma symptoms if the home contained visible fungal contamination (F (2,20) = 5.40, p= 0.018, adj. R^2 = 0.28 during weekdays and (F (2,24) = 3.36, p= 0.016, adj. R^2= 0.15 during the weekends).

In the summer visible fungal contamination was found to be associated with more severe symptoms at the weekend with increased time spent inside the home, however, these results were not statistically significant (F (2,23), p=0.093, adj. R^2=0.11.

No significant relationships were observed for time spent in the home and more severe symptoms if the home did not have visible fungal contamination. (β=.113, p=0.582 for weekdays in the summer, β=-.278, p=0.168 for weekends in summer, β=-.365, p=0.087 for weekdays in winter, β=-.044, p=0.827 for weekends in winter).

Table 16 The relationship between time spent in the home and severity of asthma symptoms.

	Time Spent Inside the Home							
	Summer				Winter			
Health Outcome	Weekdays		Weekends		Weekdays		Weekends	
		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination
Symptoms	.113	-.287	-.278	-.334	-.365	-.484	-.044	-.469
F-ratio	(1, 24) 0.31	(2, 23) 1.06	(1, 24) 2.02	(2, 23) 2.64	(1, 21) 3.23	(2, 20) 5.40	(1, 25) 0.05	(2, 24) 3.36
P-value	0.582	0.192	0.168	0.093	0.087	0.018*	0.827	0.016*
95% Confidence Interval	-.339 to .591	-2.972 to .631	-.527 to .097	-2.869 to .235	-.828 to .060	-2.945 to -.317	-.277 to .224	-2.998 to -.334
Coefficient	.125	-1.170	-.215	-1.316	-.383	-1.631	-.026	-1.666
Standard Error	.225	.871	.151	.750	.213	.629	.121	.645
R^2	0.01	0.08	0.07	0.18	0.13	0.35	0.00	0.21
Adj. R^2	-0.02	0.00	0.03	0.11	0.09	0.28	-0.03	0.15

4.5.7 Activity Limitation

To estimate relationships between time spent inside the home and activity limitation using a linear regression model (Table 17). The regression was statistically significant (F (1,21), p=0.013, adj. R2=0.22 for weekdays in the winter and (F(1,25), P=0.033, adj.R2=0.13 for weekends in winter). The findings indicate that during wintertime spent inside the home during both weekdays and weekends significantly predicted limitation of activity (β= -.509, p=0.013 and β= -.411, p=0.033 respectively).

For each hour increase in time spent inside the home during winter weekdays a .56-point reduction in activity was observed. During winter weekends a .24 decrease in activity was observed indicating that the symptoms experienced during this period were severe enough to limit activity. Fungal contamination in the home was not a significant predictor of activity limitation during this period (β= -.276, p=0.162 and β=-.225, p=0.227 for winter weekdays and weekends respectively). There was insufficient data to test for associations during the summer reporting period.

Table 17 The relationship between time spent in the home and activity limitation.

Time Spent Inside the Home

Health Outcome	Winter				Summer			
	Weekdays		Weekends		Weekdays		Weekends	
		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination
Activity Limitation	-.509	-.276	-.411	-.225	Insufficient data	Insufficient data	Insufficient data	Insufficient data
F-ratio	(1, 21) 7.37	(2, 20) 4.94	(1, 25) 5.11	(2, 24) 3.38	-	-	-	-
P-value	0.013*	0.162	0.033*	0.227	-	-	-	-
95% Confidence Interval	-.996 to -.132	-2.382 to .425	-.472 to -.021	-2.098 to .523	-	-	-	-
Coefficient	-.564	-.978	-.247	-.787	-	-	-	-
Standard Error	.207	.673	.109	.635	-	-	-	-
R^2	0.25	0.33	0.16	0.21	-	-	-	-
Adj. R^2	0.22	0.26	0.13	0.15	-	-	-	-

4.5.8 Overall Score

This domain combines all scores from all domains to give an overall level of asthma quality of life with one representing significantly poor quality with marked impairment and seven representing no impairment and normal functioning. The mean number observed in the study was five during the summer and four during winter. Linear regression modelling was used to test if time spent inside the home predicted lower scores (and therefore worse overall asthma quality of life).

The results show that time spent inside the home environment were associated with significantly lower scores during weekdays in winter ($F(1,21) = 5.96$, $p=0.024$, adj.$R2=0.18$) (Table 18). Lower scores were observed during the weekend in winter, but this failed to reach statistical significance ($F(1,24)$, $p=0.092$, adj.$R2=0.07$. Time spent inside the home during weekdays and weekends in summer did not appear to lower scores ($\beta= -.061$, $p=0.761$ and $\beta= -.320$, $p=0.103$ respectively).

If the home contained visible fungal contamination lower scores were observed during both weekdays and the weekend in winter and weekends in summer (F (2,20=6.42, $p=0.029$, adj.$R2=0.33$ for weekdays, ($F(2,23)$), $p=0.013$, adj.$R2= 0.27$ for weekends in winter and ($F(2,24)= 4.91$, $p=0.019$, adj.$R2=0.23$ for summer weekends). Lower scores were observed during weekdays in summer however these scores did not reach statistical significance ($\beta=-.378$, $p=0.069$).

Table 18 The relationship between time spent in the home and overall asthma quality of life.

	Time Spent Inside the Home							
	Winter				Summer			
Health Outcome	Weekdays		Weekends		Weekdays		Weekends	
		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination
Overall Score	-.470	-.427	-.347	-.461	-.061	-.378	-.320	-.436
F-ratio	(1,21) 5.96	(2, 20) 6.42	(1,24) 3.07	(2, 23) 5.53	(1, 25) 0.09	(2, 24) 1.87	(1, 25) 2.87	(2, 24) 4.91
P-value	0.024*	0.029*	0.092	0.013*	0.761	0.069	0.103	0.019*
95% Confidence Interval	-1.003 to -.080	-2.972 to -.183	-.470 to .038	-3.080 to -.398	-.491 to .363	-2.987 to .117	-.503 to .049	-2.830 to -.280
Coefficient	-.54	-1.578	-.21	-1.739	-.063	-1.434	-.227	-1.555
Standard Error	.221	.668	.123	.648	.207	.752	.134	.617
R^2	0.22	0.39	0.11	0.32	0.00	0.13	0.10	0.29
Adj. R^2	0.18	0.33	0.07	0.27	-0.03	0.06	0.06	0.23

4.6 Discussion

This novel study exploring the impact of the indoor home environment on asthma outcomes for people living in social housing, Cornwall UK, utilizing time use diaries and validated questionnaire data, along with an asthma quality of life questionnaire, has identified that increased time spent inside the home with fungal contamination, suffer more severe asthma symptoms especially in the winter.

4.6.1 Prevalence of Asthma and Asthma Severity

The British Lung Foundation (2018) reported that the South-West of England had a higher-than-average prevalence of newly diagnosed asthma (296 per 100,000) (BLF, 2018). The findings of this study would concur, with 30% of the study population reporting asthma which had previously been diagnosed by a physician. Asthma severity in our study was indicated by the overall asthma quality of life score (based on the four subdomains covering the emotional and physical characteristics of asthma quality of life), increasing quality of life and reduced symptom severity is associated with increasing scores.

We found a one-point difference between each reporting season indicating a clinically meaningful difference between asthma symptoms and control between summer and winter which is an important consideration for asthma management and care planning.

Other studies that have used the M-AQL to evaluate asthma interventions found that a change in score of 0.5 minimal clinically important difference was enough to show clinically significant differences for asthma patients. The findings of their study also showed that the average score in which people had exacerbations (one or more) was between four and five (Khusial et al., 2020). However, the study was evaluating the use of mobile technology to better inform patients so could explain some of our findings. Our study population had an average score of five in the summer and four in the winter, indicating similar levels of risk.

4.6.2 Prevalence of fungal contamination

Forty-four percent of homes reported visible fungal contamination at baseline and 17% reported a mouldy/musty odour with 13% feeling that fungi was impacting on their family's health. Thirty-six percent of the study population reported regularly ventilating their home to actively prevent fungal growth. Prior research has shown that indoor fungal contamination is influenced by a complex interaction between the built environment and occupant behaviours (Sharpe et al., 2014a). A mouldy odour is indicative of more severe fungal contamination in the home and thought to influence different age groups such as in older adults (Moses et al., 2019b).

Declining mobility associated with ageing and other health related comorbidities, could have a considerable impact on the individual’s ability to adequately maintain the home which can lead to elevated dampness, increased fungal contamination and corresponding increased exacerbation of asthma symptoms. Conversely, other research suggests that the risk of asthma due to fungal contamination in the home was higher in younger adults (Sharpe et al., 2015). Other differences in time use have been attributed to age, sex, employment status and season (Matz et al., 2014).

4.6.3 Time-Use

Previous studies have explored daily time-spent in different environments, finding it to be affected by several factors including sex, which day of the week it was (weekday/weekend) and age. In the present study, increased periods of time spent in the home could be explained by an older population who may naturally spend longer indoors due to retirement, declining health or poor mobility. Older adults’ vulnerability due to the related health risks associated with age, and because of exposure risk (in relation to indoor allergens/pollutants) which their vulnerability makes them especially susceptible to, make them an important demographic to study.

98% of homes in this study had at least one older adult residing in the property. Prior research indicates that women spend more time in the home than men (Hussein et al., 2012, Brasche and Bischof, 2005); however our findings noted little difference in the time spent at home between men and women generally, with only minor differences during the weekdays. We hypothesize that our findings may be explained by our older population, who have higher than average time spent at home and lower household income.

However, despite much societal change over the past decades, women are still responsible for most household cleaning, childcare and other caring responsibilities (Cerrato and Cifre, 2018). As women tend to do more household chores they could be adversely affected by the home environment; not just by the build quality or air quality within it, but also by the products used to maintain it (Zock et al., 2007). This could be especially concerning if the products used are highly volatile, such as those used to treat commonly occurring household fungal contamination, as volatile organic compounds are also associated with increased risk of asthma in adults (Paterson et al., 2021). Therefore, there is potential for interaction of and between other exposures (reactive chemistry between individual chemical compounds and to other biological and chemical agents found in homes) in this population, given the high number of reported homes experiencing visible fungal contamination.

Given therefore, that only one exposure (fungal contamination) was analyzed in our study it is impossible to draw any conclusions on development and/or exacerbation of asthma in this population given the high probability of other exposures in the home of which the interaction is largely unknown.

Furthermore, the timing and extent of exposure to multiple indoor allergens can result in variable outcomes of allergic diseases, and sensitization may play a different role in children and adults (Sharpe et al., 2015h).

4.6.4 The prevalence of asthma, fungal contamination and time spent at home: Baseline Time Use

We found no associations between the amount of time spent in the indoor home environment at baseline and increased risk of reporting asthma, even if the home had reported visible fungal contamination. However, if the home reported a mouldy or musty odour there was a 2-fold increase in the likelihood of reporting asthma with increased time spent indoors, at baseline. This concurs with prior findings (Sharpe et al., 2015f).

Increased fungal spores during summer and autumn are common (Hughes et al., 2022). Research (Sharpe et al., 2015b) indicates that one potential driver of fungal growth is fuel poverty, regardless of occupant risk perception and use of ventilation. Research indicates that 23.2% of fuel poor households are in social housing (Minnen and Rymenants, Tu et al., 2022). This is a key consideration in our study as the study population were social housing tenants which, by their very eligibility for housing, make them vulnerable to fuel poverty.

Previous research has reported that households affected by fuel poverty did not adequately ventilate their homes due to the cost (Sharpe et al., 2015b).However, social housing properties are managed according to the Decent Homes Standard and generally have higher levels of energy efficiency improvements that can make homes more affordable to heat (Sharpe et al., 2015f).

Importantly, other studies regarding social housing tenants suggest that when people are experiencing fuel poverty and the associated outcomes it brings, that often amongst other factors it is embarrassment and stigma that have prevented them from seeking assistance or support with their housing need (Longhurst and Hargreaves, 2019).

It is therefore vital that housing associations and health authorities work more collaboratively to ensure that the needs of the population are being met. For example, fungal growth can be modelled from indoor air relative humidity and temperature (Menneer et al., 2022); understanding when fungal growth could occur allows for preventive measures to be taken as well as remedial works when required before the fungal growth becomes prolific enough to cause adverse health effects.

Innovative ways of monitoring the indoor environment could provide social landlords with real time data to alert them of households that require intervention rather than solely relying on residents reporting fungal contamination related issues independently. It is important to consider that once landlords receive information in this way the onus to act upon it would be invoked. This could have implications for both the resident and the landlord.

4.6.5 Asthma severity, fungal contamination and time spent in the home.

It is widely accepted that fungal contamination in the indoor environment increases the risk of asthma across the life course (NHS, 2021, WHO, 2009, Asthma, 2022). Other studies have reported that visible fungal contamination in indoor environments is associated with increased risk of asthma (Caillaud et al., 2018, Hughes et al., 2022, Jie et al., 2011, Sharpe et al., 2015a). This study demonstrates that fungal contamination, identified by fungal patches in the property, was associated with overall worse asthma outcomes. We find that although time spent at home affects asthma severity in the winter, symptom severity (such as feeling frustrated, fear of lack of medication availability or feeling concerned about having asthma, wheeze, cough, shortness of breath etc.) was worse across all domains regardless of season if the home reported visible fungal contamination.

We found some seasonal variability between symptom severity with worse symptoms being experienced during the winter, this concurs with prior research (Bauer et al., 2019). It is important to note that although worse symptoms were noted in the winter, symptoms significant enough to reduce quality of life were observed in both seasons.

When scoring the M-AQL, 0.5 MID is indicated as sufficient change of score in which a change in a patient's management would be warranted. With a whole point score difference between the seasons of summer and winter different strategies may need to be employed to help individuals better manage their condition.

Other potential explanations for our results could be, that people know that fungi is their trigger and therefore when fungi is visible in the home (which was previously identified as more likely to occur in winter and produce asthma exacerbations) (Bauer et al., 2019, Canova et al., 2013), they then actively try and treat the fungal contamination, potentially causing further impact.

The "Why Asthma Still Kills Report" by the Royal College of Physicians (2015) noted that most people who died were not under any specialist care in the 12 months prior to death and nearly half died without seeking medical assistance or before care could be provided. Exacerbating factors or triggers were noted for nearly half of patients and included viral infection, drugs, and allergy as well as psychosocial factors such as depression and mental health issues (Royal College of Physicians, 2015).

For this study population who are older and therefore more prone to health-related issues associated with age, extended periods of time indoors due to reduced mobility for example, could naturally enhance their frustration at their condition especially if they lack capacity to access services either physically (GP surgeries, pharmacies etc.) or digitally (online access to health information, benefits, medication ordering etc.). This is important to consider as nearly two million older adults (over 75) are still digitally excluded (AgeUk, 2021). With more services moving online (medication ordering, telemedicine, benefits etc.) there is potential for some individuals to slip through the cracks.

Our findings indicate that increased time spent inside the home during the winter was associated with more severe asthma symptoms specifically related to environmental stimuli (dust, cigarette smoke, weather, air pollution) when the home had visible fungal contamination. Asthma has been reported to be worse during colder months especially when an individual is exposed to allergens or pollution known to cause exacerbations previously (Asthma.UK, 2020b). However, other studies that have examined asthma severity, found that admissions to hospital for asthma exacerbations were reduced during the coronavirus pandemic despite that being a period when individuals were spending more time at home (Fischell et al., 2022). Nonetheless, consideration must be given to the lack of reporting of health problems during this period (Anderson et al., 2021). Conversely, other research points out that seasonal variation in asthma exists in individuals who are sensitive to pollen and fungi, the effect is not modified by sensitization to feline allergens or house dust mite (Canova et al., 2013), which could explain some of the findings of this study.

Previous studies have reported that both extremes of hot and cold temperatures (Han et al., 2023) and inadequate ventilation in a property can increase moisture and therefore fungal growth which is known to exacerbate asthma (Sharpe et al., 2014). We found a high number of individuals reporting fungal contamination despite many reportedly taking active measures to prevent fungal growth, such as ventilating the home by opening windows and using an extractor when cooking or bathing.

It is possible that the severity of symptoms could be related to individuals' management of their condition and the property as well as environmental factors such as climate and fungal growth rates. Cornwall's climate is mild and temperate which experiences around 1000 mm of rainfall per year (Cornwall Council, 2022) making it ideal growth conditions for fungal spores such as Aspergillus (a known allergen and exacerbator of asthma) during both the summer and winter season (Atherton, 2020).

Prior research has examined fungal concentrations in house dust and find that allergenic fungal species were most prolific in the spring months in New York City and that indoor relative humidity and temperature could be a mediator in seasonal trends of fungi (Cochran et al., 2022). These vary by region too, so it could seem reasonable that as concentrations of fungal spores increase seasonally, any additional enhancing growth conditions (indoors) could function as an additional vector enhancing the exposure load.

4.7 Strengths and Limitations

There are several strengths to this study, baseline questionnaires were completed by trained enumerators ensuring all questions were adequately explained to participants therefore reducing bias through misunderstanding of the questions and as such received a 100% response rate. Although response rates were lower for the time use/M-AQL, results show strong associations and offer a unique insight into this sub population of the impact the home has on social housing residents.

Much research to date around asthma and homes has focused on children (Patelarou et al., 2015, Dick et al., 2014), this paper offers new innovative insights into the relationship between adults (with attention to women and the elderly as these groups are known to be more at risk of adverse health effects) and how time spent in their home, and agents found within it, effect asthma symptoms.

The time use diaries and M-AQL were conducted at two time points throughout the year to check if there were seasonal differences in the way people spend their time, and the interactions with their own home environment, and to observe any changes in their asthma symptoms over this period. This was advantageous as the M-AQL asks respondents about any symptoms that they may have experienced over the past two weeks. Many other asthma and respiratory related health questionnaires ask about symptoms that have been experienced over the past 12 months, making recall bias a significant issue.

There are however limitations to this study, only having one timepoint for the baseline questionnaire and two timepoints for the study data restricts the possibility of deriving conclusions on causality. Further, due to the sample size of the time use and M-AQL questionnaires, confidence in the effect sizes is reduced despite strong effects being observed in some domains.

There is potential for bias because of asthmatic individuals being more likely to report fungal contamination in the first place due to being more informed of environmental triggers relating to asthma, therefore more selective when responding to the M-AQL questions. There are a number of reasons why increased time in the home can elicit more severe asthma symptoms, this study only examined one known asthma trigger (fungal contamination). Future studies could address this by monitoring the indoor environment in a more inclusive manner to capture any other potential interactions and associations that could be impacted by prolonged exposure. Medication usage could also be monitored directly using sensors on asthma inhalers, building on the work of Moore and colleagues, which could be linked to data on exposures (Moore et al., 2021).

4.8 Conclusions and Recommendations

In this study we found that individuals with asthma who spend more time in homes with visible fungal contamination show worse asthma symptoms than individuals living in non-fungal contaminated homes. This is likely the result of the complex interaction between external influences as described in Figure 10 (outdoor air pollution, fungi, pollen etc.), indoor conditions (presence of visible fungal contamination and other indoor pollutants), building fabric and resident individual actions and lifestyles.

Housing condition and home management have a significant impact on fungal growth and respiratory health, therefore housing managers and residents need to improve the condition of stock and be better informed of the potential hazards of fungi, which must include how best to combat it, to preserve both the health of the occupants and the building fabric.

Further steps could be taken to carefully monitor homes using smart sensors to accurately inform and predict deleterious environmental related issues such as fungi in a proactive manner and ensure information relating to mitigation reaches all members of society including those difficult to access.

This research was conducted in social housing properties, caution would be offered when applying the findings to the wider population. Nonetheless, other agencies, services and providers should consider the findings when designing new treatment plans and contracts to ensure that the public health needs of the population are met and to reduce some of the economic and societal burden that asthma remains.

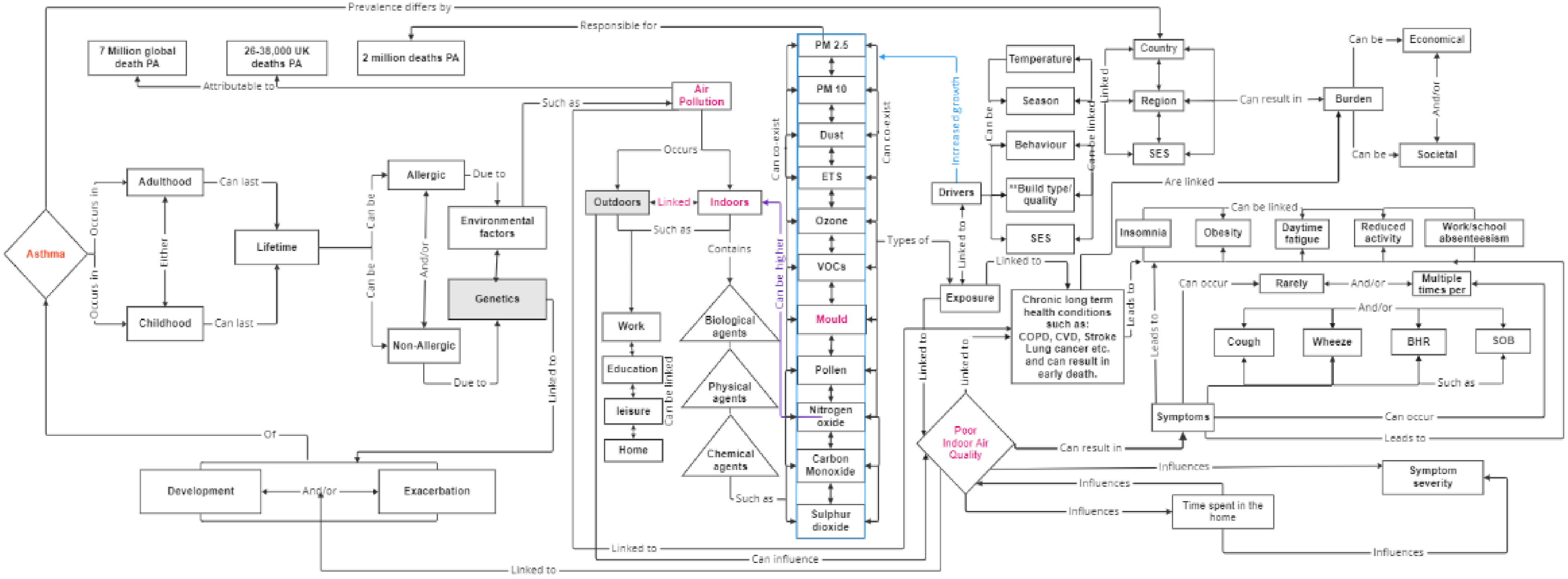


Figure 12 Model describing the complexities of asthma and time spent in the home.

4.9 Summary

Individuals spend significant periods of time in their own home. The indoor environment and the exposures contained within it can be heavily influenced by a range of factors including the interaction of outdoor and indoor air pollution, mould and pollen spore production and growth and human activities within the home. Social housing tenants may be disproportionately affected by exposure to indoor air pollution due to this sub population being older with lower income. Previous studies have highlighted the importance of fungal contamination on asthma development and/or exacerbation, however little research has examined the impact of time spent inside the home on asthma outcomes for this sub population.

The findings of this study indicate that individuals residing in homes with fungal contamination show worse asthma symptoms than individuals residing in homes without fungal contamination. This is likely due to the complex interaction between indoor and outdoor air, indoor conditions, housing quality and individual action and lifestyles. Housing providers and individuals should take actionable steps to reduce in-home fungal exposure to better protect health and reduce the economic, societal and physical burden of asthma.

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Chapter 5: Analysing the Impact of Indoor Air Pollution on Asthma Outcomes: A protocol Paper.

5.1 Introduction

This protocol paper sets out the process that will be used to extend the research presented in Chapter 4 to include objective measures of air quality collected as part of the Smartline project. Prior studies have used similar statistical methods in analyzing the impact of indoor air on asthma outcomes. For example, the studies included in the systematic review of PM and VOC exposure which was described in Chapter 3. These studies and their associated methodologies are summarized in Table 19. However, these studies have not explored the impact of time spent inside the home environment in combination with objective measures of environmental pollution.

As briefly outlined in Chapter 4, on being recruited to the Smartline project, participants had a range of sensors installed in their homes to measure indoor environments, air quality and utility usage. By combining validated questionnaire/time activity surveys, indoor environmental sensors, and collecting data about time spent inside the home environment we attempt to objectively address the following hypotheses:

1. The association between self-reported asthma and residential indoor air conditions is stronger amongst individuals with higher periods of time spent indoors.
2. Using environmental sensor data as measures of air quality, the association between self-reported asthma symptoms and the indoor environment is stronger amongst women than men.
3. The stronger association is explained by differences in time spent indoors in the home environment between women and men.

This Chapter is organised as follows. First, the methods are described, including the design of the questionnaire. Then a description of the data is presented before an analysis plan is provided. As mentioned in Chapter 1, this chapter is a protocol for further research, due in part to the COVID-19 pandemic. It is hoped that the protocol provided in this chapter will form the basis for future research on this topic.

Table 19 Statistical methods of prior studies which have measured indoor exposures and asthma outcomes in adults.

Author	*Name of Paper*	*Study Design*	*Statistical Analysis Applied*
Arif and Shah, (2007b)	Association between personal exposure to volatile organic compounds and asthma among US population	Cross- sectional	Chi- square, exploratory factor analysis and multiple regression
Balmes et al. (2014)	Annual average ambient particulate matter exposure estimates, measured home particulate matter, and hair nicotine are associated with respiratory outcomes in adults with asthma	Cross- sectional	Multivariable regression modelling
Bentayeb et al. (2013)	Higher prevalence of breathlessness in elderly exposed to indoor aldehydes and VOCs in a representative sample of French dwellings.	Cross sectional	X^2 test, ANOVA
Billionnet et al. (2011)	Quantitative assessment of indoor air pollution and respiratory health in a population-based sample of French dwellings	Cross sectional	Regression modelling
Dales and Cakmak (2019)	Is residential ambient air limonene associated with asthma? Findings from the Canadian Health Measures Survey	Cross-sectional	Linear and logistic mixed-effects models

Frisk et al. (2009)	Can aa housing environmental index establish associations between indoor risk indicators and clinical tests in persons with asthma?	Cohort	Linear regression
Hulin et al. (2013a)	Positive associations between respiratory outcomes and fungal index in rural inhabitants of a representative sample of French dwellings	Cross- sectional	Mann Whitney two samples test, Pearson $X^{2,}$ exact Fischer test, logistic regression modelling,
Levesque et al. (2001)	Wood-burning appliances and indoor air	Case-control	X^2, Fischer test
Norback et al. (1995)	Asthmatic symptoms and volatile organic compounds, formaldehyde and carbon dioxide in dwellings	Cross-sectional epidemiological	Mann-Whitney U test, X^2, Fischer's exact test, Kendal rank correlation (Tau-beta), Multiple logistic regression, Logarithmic values.
Sharpe et al. (2015g)	Variable risk of atopic disease due to indoor fungal exposure in NHANES 2005-2006	Cross sectional	Multivariate logistic regression models
Simoni et al. (2002)	The po river Delta (north Italy) indoor epidemiological study: Effects of pollutant exposure on acute respiratory symptoms and respiratory function in adults	Cross-sectional epidemiological survey	Logistic regression modelling

Simoni et al. (2004)	Indoor exposures and acute respiratory effects in two general population samples from a rural and urban area in Italy	Cross-sectional	Logistic regression
Triche et al. (2005)	Indoor heating sources and respiratory symptoms in non-smoking women	Prospective Cohort	Repeated measures Poisson regression analysis using log-linear model
Wieslander et al. (1997)	Asthma and the indoor environment: The significance of emission of formaldehyde and volatile organic compounds from newly painted indoor surfaces	Cross-sectional	Multivariate linear and logistic regression modelling

5.2 Methodology

Data Description

An overview of the key available data is presented in Table 20.

5.2.1 Sensor data collection

All the participants consenting to be part of the Smartline project received environmental sensors in both the living room, and main bedroom of their homes, to monitor indoor air pollutants and provide objective measurements for particulate matter, volatile organic compounds, air temperature, and relative humidity with a maximum frequency of every 3 min, from October 2017 to August 2022 as these particular pollutants are known asthma triggers. Additional sensors were placed on utilities (gas, water, electricity) where possible to monitor usage, although these were not used in this Chapter. Sensors were installed between October 2017 and April 2018 by Blue Flame, a company that provides maintenance services to Coastline Housing (Blue-Flame, 2022). Sensors were ISL 067 radio ultra-RF (reference: QC0160) which were manufactured by Invisible Systems Limited (Invisible-Systems, 2022, Menneer et al., 2022).

Outdoor air quality, temperature and humidity sensors were also installed in areas around the houses in the study – located based on characteristics of the area. Air quality, temperature and relative humidity sensors were placed in the main living room and in the main bedroom, to give estimates of exposures both at day and night. All respondents were given access to their survey data through an app on a tablet device that was provided as part of the Smartline project. Despite having been given training, very few accessed this data.

5.2.2 Asthma data collection

Data were collected in different stages for asthma outcomes as described in Chapter 4. First, as part of a baseline questionnaire conducted from October 2017 to February 2018. The baseline questionnaire included ISAAC questions for asthma (ISAAC, 2017):

- Self-reported doctor diagnosed asthma (for both the respondent and their partner, if applicable).
- Self-reported wheezing or coughing (for both the respondent and their partner, if applicable):
    - ever and in last 12 months.
    - over 3 coughing attacks in past 12 months
    - sleep disturbances due to wheezing or coughing in past 12 months.
    - speech limitation due to wheezing or coughing in past 12 months.
    - chest sounding wheezy during or after exercise in past 12 months.
    - dry cough at night (without cold/chest infection) in past 12 months.

- Binary variable for experiencing asthma and having seen a doctor in past 12 months (both respondent and partner).
- Binary variable for taking medicine for asthma in past 12 months (both respondent and partner).

Second, individuals who identified as having experienced asthma in the initial baseline questionnaire were asked to complete the Mini-Asthma Quality of Life questionnaire (M-AQL) in winter (February 2019) and summer (August/September 2019). This is because the ISAAC questionnaire that was used in the baseline questionnaire asks about symptoms experienced in the past 12 months. In order to assess any seasonal variability and to reduce recall bias the M-AQL focuses on symptoms over the past two weeks, this is also a useful measurement when analysing the data to see if there are changes in the severity of symptoms at different points throughout the year and whether any potential changes correlate to the sensor data and the amount of time spent within those environments. Full copies of the questionnaires and consent forms are presented in appendix 4.

5.2.3 Time Use

As described in Chapter 4, all Smartline participants were asked to fill out a time use diary which asked how much time individuals spend in their own home environment over seven days at two intervals throughout the year (summer/winter). This survey was conducted in the week prior to the M-AQL questionnaire.

For the time spent indoors diary, all Smartline participants were invited to take part (N=314). This is because it is important to see how much time people spend in their own home environments, so it is possible to examine whether the indoor air quality is affected by the amount of time an individual spends in the home environment, and to see if the indoor home environment has an impact on their health.

5.2.4 Other control variables

The Smartline baseline questionnaire included a range of questions that can be used as control variables for this analysis. This includes:

- Sex.
- Age.
- Self-reported mobility.
- Time spent indoors.
- Quality of Life.
- Housing conditions measured subjectively (including indoor presence of fungal contamination).
- Heating and ventilation patterns.
- SF12 questions regarding health and wellbeing.
- Smoking and vaping exposures (both of the individual and in the home).
- Pets in the home.
- Employment status.

Additional data on the property were obtained from Coastline housing including:

- Type of heating.
- Build type.
- Other asset management data.

5.2.6 Recruitment

As described in Chapter 4, participants for the M-AQL and time use study were current Smartline participants who were recruited via digital invite through their tablets, at face-to-face events and via letters to reach the maximum number of residents as possible. Participants were fully informed of the research and their right to withdraw at any time. We aimed to recruit the same people for consistency and so we can examine any potential changes in their health over time.

5.3 Ethics

The collection of the Smartline Baseline questionnaire, sensor data and data merger with Coastline Housing data was given ethical approval from the University of Exeter. For the additional study using the M-AQL and time use ethical approval was obtained from University of Exeter Medical School Research Ethics Committee *REFERENCE NUMBER:* Jan19/B/175.

5.4 Data Linkage

Sensor data were linked with the baseline questionnaire, M-AQL questionnaire and asset management records using a unique household identifier (UPRN number). This data linkage was conducted through a system maintained by UrbanTide, a company which has been subcontracted to manage the data of the Smartline project in a secure manner (Urban-Tide, 2022).

Transformation of the sensor data is required to enable comparison. For example, variables around average indoor environments for both PM and VOCs will need to be constructed from the 3-minute annual datasets as previously demonstrated by Meneer et al (2022). Indeed, it may be necessary to consider constructing a novel indicator of indoor environmental quality combining readings for PM and VOCs – given the likely interactions between these variables in driving asthma outcomes.

Table 20 Key Data Available

Variable	Details	Source
Doctor diagnosed asthma	Binary variable for both main respondent and partner	Smartline Baseline Questionnaire
ISAAC	Experience of Asthma in year prior to the Smartline Baseline Questionnaire	Smartline Baseline Questionnaire
Mini-Asthma Quality of Life	Experience of Asthma in previous two weeks, conducted on last day of Time Use + M-AQL Questionnaire. (Both winter and summer)	Time Use+M-AQL Questionnaire
Time Use	Hours indoors and outdoors based on diaries for 7 days in both winter and summer months	Time Use + M-AQL Questionnaire
Time outdoors	Hours indoors (average)	Smartline Baseline Questionnaire
Sex	Binary variable, 1 for Female	Smartline Baseline Questionnaire
PM	Particulate matter readings for every 3 minutes over the two weeks previous (for comparison to M-AQL) and for the year after installation of sensors (for comparison to asthma data from	House Sensors – both living room and bedroom

	Baseline Questionnaire)	
VOCs	VOCs readings for every 3 minutes over the two weeks previous (for comparison to M-AQL) and for the year after installation of sensors (for comparison to asthma data from Baseline Questionnaire)	House Sensors – both living room and bedroom
Outdoor PM	Particulate matter readings for every 3 minutes over the two weeks previous (for comparison to M-AQL) and for the year after installation of sensors (for comparison to asthma data from Baseline Questionnaire) – for the outdoor sensor which is considered closest (according to several characteristics – not just distance from the house, but also distance from road and other geographical characteristics)	Outdoor Sensors
Outdoor VOCs	VOCs readings for every 3 minutes over the two weeks previous (for comparison to M-AQL) and for the year after installation of sensors (for comparison to asthma data from Baseline Questionnaire) – for the outdoor sensor which is considered closest (according to several characteristics – not just distance from the house, but also distance from road and other geographical characteristics)	Outdoor Sensors

5.5 Statistical Analysis

Assessing the links between indoor air pollutants and asthma presents multiple analytic challenges that must be solved to provide robust findings. The methodology employed must control for the effects of multiple correlated air pollutants (Shook et al., 2017). Structural equation modeling (SEM) is a statistical technique for testing and estimating causal relationships amongst the variables, some of which may be latent using a combination of statistical data and qualitative causal assumptions. Latent variables (also known as unobserved variables, hypothetical variables, or hypothetical constructs) are variables that are not directly observed but are reflected from other variables that are observed and directly measurable. Air quality, comprising multiple, single measure variables that are highly correlated may be modelled best as a latent variable. Modelling air quality as a latent variable overcomes the methodological challenges associated with modelling multiple correlated variables.

In addition, SEM allows the relationship between specification of the regressions not only from predictors to outcome variables to be modelled but also between multiple predictor variables. This is important for our analysis as one can assume that time spent indoors will have an impact on the latent variable air quality, which will have in turn an indirect impact on asthma, but time spent indoors will also have a separate direct relationship with asthma. Please see Figure 13 for an example of one such specification. Within this context, to assess the relationship between indoor air quality and asthma outcomes among participants of the Smartline project, a structural equation modeling (SEM) framework is proposed. The next section outlines the analysis plan.

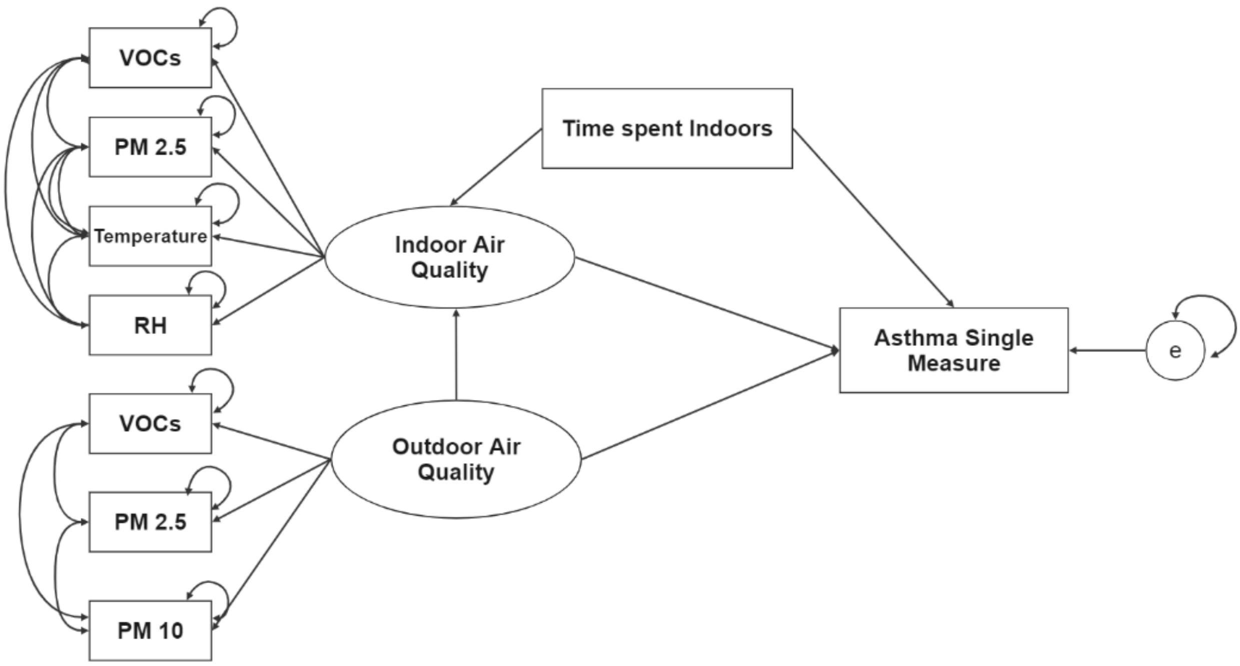

Figure 13 Proposed path analysis for asthma and indoor air quality.

5.6 Analysis Plan

To examine the overall hypotheses outlined in the Introduction, three research questions are tested. First, we hypothesize that the association between self-reported asthma and residential indoor air conditions is stronger amongst individuals with higher periods of time spent indoors (RQ 1). Initially, analysis of the means of asthma outcomes for those spending different lengths of time indoors will be estimated and compared to see if they are statistically different.

Next, three separate logistic regression models will be run for each of the asthma variables of interest; (doctor diagnosed asthma from ISAAC and asthma severity from M-AQL) controlling for time spent indoors (directly estimated from the time use data for the small sample of M-AQL, estimated as 1-time indoors for the ISAAC and doctor diagnosed data). Due to the small sample size, selected control variables will be added where possible including respondents age. An overview is shown in Figure 14.

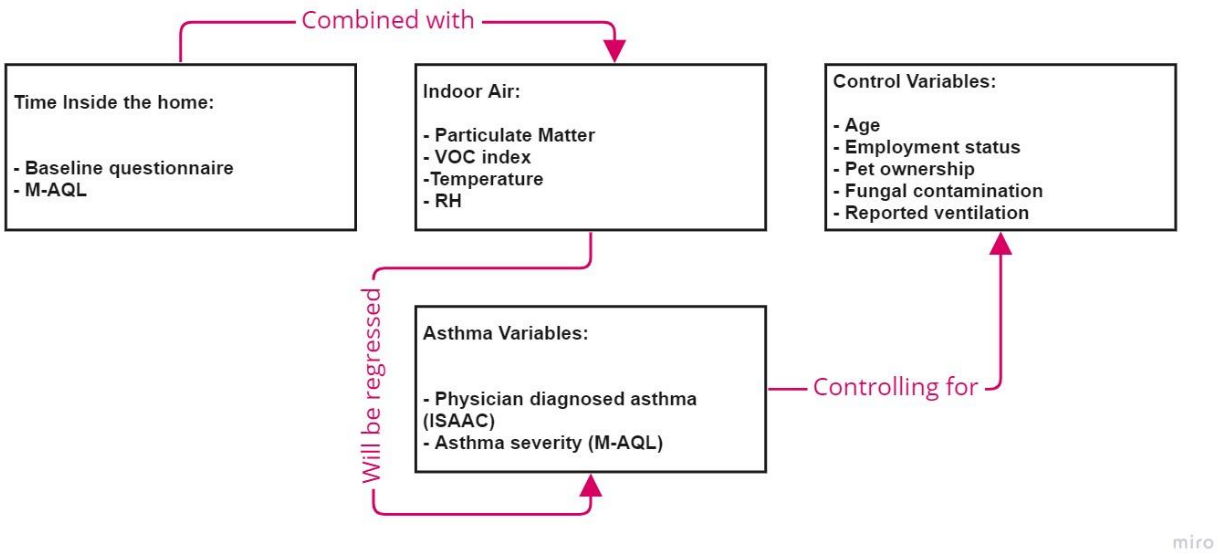

Figure 14 Overview of analysis of impact of time spent indoors and indoor air quality on asthma.

Using the environmental sensor data as measures of air quality, RQ2 and RQ 3 seek to understand the association between self-reported asthma symptoms and its potential gendered impact. Initial analysis involves the calculation of the mean ISAAC and M-AQL scores for men and women for high, medium, or low levels of the indoor environmental pollutants. Where possible these relationships will be tested for statistical significance. Here we expected that the impact of air quality will be higher for women given the difference in time spent indoors in the home environment between women and men (Brasche and Bischof, 2005).

Next, SEM will be used to analyse the relationship between indoor and outdoor air quality defined as two discrete latent variables **(see Figure 13)** on each of the three asthma outcome variables of interest, controlling for time spent indoors. The impact of time spent indoors, and fungal containment will also be included as a predictor of indoor air quality.

Due to the small sample size of the Smartline project, stratification between men and women is not possible using a SEM. Data will be analysed using STATA SE 17 statistical software.

5.6 Conclusion and next steps

This chapter has provided a planned data analysis protocol which aims to explore the impact of time spent inside the home environment on asthma for tenants living in social housing in Cornwall, UK, using real-time novel sensor data, time use diaries and validated cross-sectional survey data, status and fungal contamination. From a public health perspective, understanding the distinction and contributing magnitude of the household environment versus the outdoor environment on asthma outcomes is important as it will allow policy makers to target the required mix of housing and community-based health strategies. This is particularly important as although outdoor air pollution is regulated in terms of what levels of pollution are classed as risky, indoor pollution however is not, and relies heavily on resident behaviours to modify risk.

Regarding the Smartline project, having a clear understanding of what is happening in terms of indoor air pollution and respiratory outcomes of its tenants, Coastline housing will see direct benefit as it will identify opportunities to improve indoor air quality, inform resident behaviours and other national policy/practice. The potential for next steps is discussed in Chapter 6 in full. For individual participants, having a better understanding of the home environment allows for actionable negative health mitigation.

Chapter 6: Conclusions and Recommendations

6.1 Introduction

As outlined in Chapter 1, the central aim of this thesis was to examine the relationship between the indoor microenvironment, time spent indoors and poor indoor air quality on asthma outcomes for individuals residing in social housing in Cornwall. This relationship is summarized in a series of models throughout this thesis with the empirical evidence and new findings identified within the scientific field highlighted in yellow in the final model found in Figure 15.

This thesis critically and systematically examined selected indoor exposures (particulate matter 2.5, volatile organic compounds, fungal contamination) and their impact on asthma, as well as evaluating the impact of spending longer periods of time in the home on asthma and asthma symptoms. Section 6.1 of this chapter summaries the research that has been carried out as part of this thesis. Section 6.2 outlines several advantages and limitations associated with the research conducted as part of this thesis. Finally, Section 6.3 discusses future research possibilities and discusses a health in homes information communication research agenda.

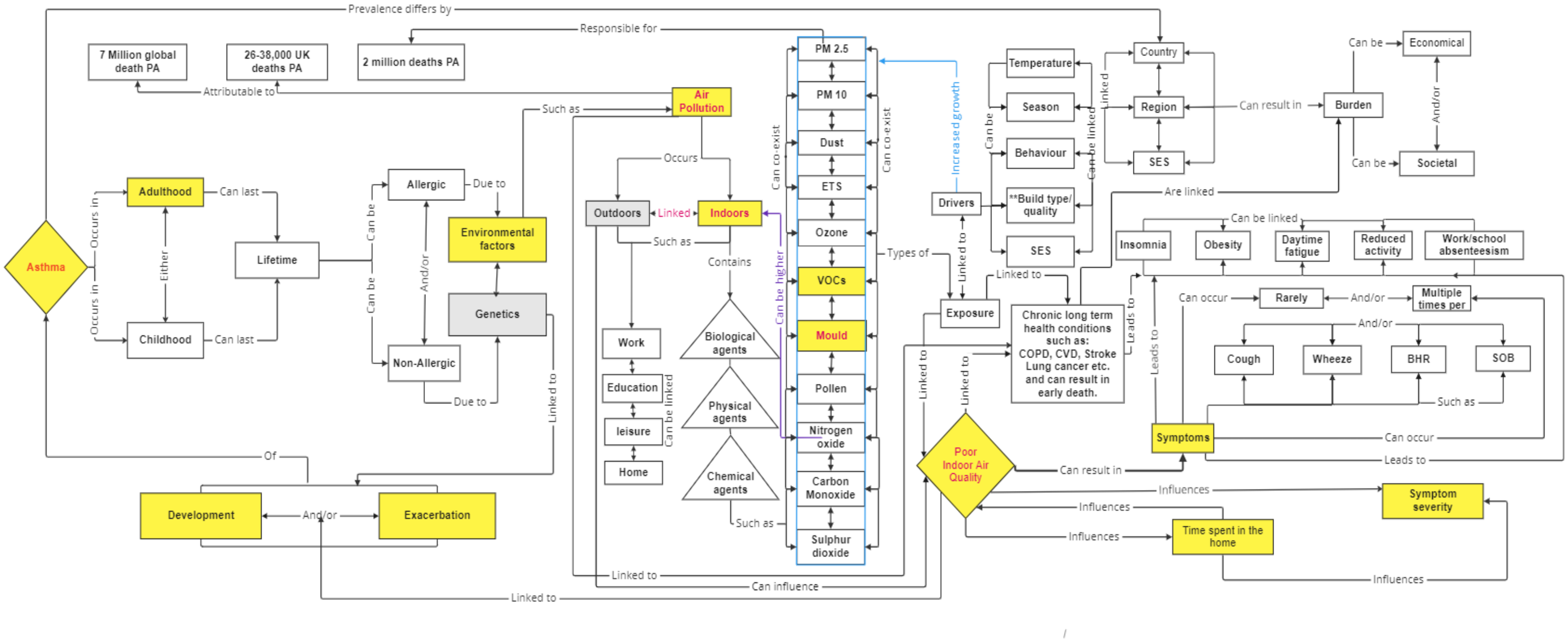

Figure 15. The relationship of asthma and the indoor environment as identified throughout this thesis.

6.1.1 Research Summary

The health risks associated with exposure to air pollution both indoors and outdoors are significant, especially in vulnerable individuals. With new sources of pollution being identified that have deleterious health effects, air quality monitoring standards have been implemented, changed, and updated as the knowledge base of harmful pollutants, and their resultant impacts on health has expanded. However, these standards are often breached, whilst indoor air quality standards remain much less developed than for outdoors, are harder to both implement and monitor, they are largely modifiable by human individual action in, and interaction with, the indoor home environment.

The indoor home environment is unique as are the exposures contained within it. Exposures to a range of pollutants including $PM_{2.5}$, VOCs and fungi inside the home have a significantly increased risk in the development and exacerbation of asthma. Asthma is a chronic respiratory condition which affects millions of individuals around the globe.

Asthma has been responsible for more than 12,700 deaths in the past decade with 1,400 deaths in 2018 alone in England and Wales. Lack of asthma care impacting an estimated 2.9 million people, and non-identification of triggers may have contributed to what were potentially avoidable deaths, had better mitigation and management been in place.

As a modifiable micro-environment, heavily influenced by individual action, a better understanding of the indoor environment and its components can help both individuals and policymakers to better plan and manage health and homes. As such, identifying the pollutants and allergens in the home which are responsible for the development of and or exacerbation of asthma, and understanding the relationship with both other exposures, and the resultant asthma related health impacts, is critical to enable better mitigation, regulation, population health, healthier environments and better patient care.

In the context of this thesis systematic and cross-sectional analyses were implemented to evaluate the impact of the indoor environment at an individual, household and area level on asthma outcomes. Firstly, Chapter 1 provided an overview of air pollution, attributable to around seven million deaths per year, air pollution is a major global public health concern. The major sources of pollution, the standards and monitoring, and the associated respiratory health risks were highlighted. This chapter therefore provided the context for the remainder of this thesis.

Chapter 2 reviewed the literature regarding indoor air pollution and asthma. People spend around 70% of their time in the indoor home environment. Pollutants in the home are complex and diverse and have been associated with major chronic long term health problems including asthma. Asthma costs around £1.1 billion to treat each year in the UK, and still kills approximately 1400 people per year, despite being a completely treatable disease.

Asthma is complex but can be linked to environmental stimulus including poor air quality, temperature extremes and fungal spores, poor building quality, thermal quality, damp and fungal contamination, ventilation patterns, furnishing, use of cleaning products and personal interaction within the environment which have all been found to function as moderating factors to overall indoor air quality.

Understanding exactly what people are exposed to in the home (given complex interaction between outdoor and indoor air, geographical location etc.), in what environment they are exposed, for how long and to what extent the exposure causes harm was identified as an area of need with focus on asthma and the home environment. Identifying and understanding health risk exposures, as demonstrated in this thesis, allows policymakers to target resources to areas with the greatest need.

To synthesize current evidence Chapter 3 systematically reviewed literature on the relationship between $PM_{2.5}$ and volatile organic compounds in the indoor home environment and the associated risk of asthma development or exacerbation. The results indicated that VOCs such as aromatic and aliphatic compounds in the indoor home environment are associated with an increased risk of asthma and asthma like symptoms including wheeze in adults.

The larger the concentration of exposure to these chemicals the worse the health outcome. It was previously identified that indoor exposure to pollutants can be causative in asthma development and/or exacerbations, these exposures were mainly identified as formaldehyde, house dust mite, pet and pollen allergies and fungal contamination. Studies in children had explored particulate matter 2.5 and VOCs but no comprehensive review had been conducted in adults. This thesis therefore provides collective new evidence which can provide the starting point for an increased understanding of such exposure for policy makers and individuals, as asthma effects many throughout the life course. This chapter also provided insights into evidence gaps relating to asthma risk and sex.

Chapter 4 employed a repeated multi-season cross sectional analysis exploring the impact of time spent in the home on asthma, and the severity of asthma symptoms in a subpopulation of social housing tenants. The prevalence of asthma has been increasing rapidly over the past two to three decades (the South-West of England having a higher-than-average increase in newly diagnosed asthma), and incidence rates in more deprived communities are much higher. Thus, understanding the asthma related risk associated with increasing time spent in the home, as demonstrated through this research will be important for health and housing authorities across the region for future mitigation planning.

For individuals, understanding their risk can help them adapt their individual action to better manage their health and their home environment. This adds to the existing literature on mould and asthma (Sharpe et al., 2014b, Sharpe et al., 2015a, Moses et al., 2019b, Caillaud, 2018, Choi and Bornehag, 2011) by explicitly considering the time spent indoors and fills part of the research gap identified by the Chief Medical Officer of the UK’s report on indoor air pollution.

Finally, Chapter 5 is a protocol paper, this sets out the planned analysis exploring the interaction between the time spent in the indoor home environment and asthma outcomes for a subpopulation of social housing tenants in Cornwall, UK. Utilizing validated cross-sectional questionnaire and real time environmental sensor data, along with time use diary data a nested multilevel regression and structural equation modelling approach is described. The use of multi-level modelling is an innovative step in understanding the relationship between socio-economic factors, home environment and time spent indoors on asthma outcomes. It is the hope that this work will be taken forward in the future.

This thesis found that exposure to VOCS such as aromatic and aliphatic compounds in the indoor home environment are associated with an increased risk of asthma and asthma like symptoms including wheeze in adults. The greater the concentration of exposure to these chemicals the worse the health outcome. It was also identified that individuals with physician diagnosed asthma who spend more time in homes with fungal contamination show worse asthma symptoms than individuals living in non-mouldy homes. This brings novel and important data to the scientific field and will provide individuals, health and housing providers with key information to help them better manage their homes and their health.

6.2 Limitations of the results

There are four main limitations to consider when examining the results of this thesis. First, the thesis was limited in the number of indoor exposures that could be explored. Although some new evidence was found in Chapter 3 linking indoor VOC exposure to poor asthma outcomes in adults, and a known exposure was analyzed in relation to length of exposure on asthma outcomes in Chapter 4, the indoor environment contains a complex range of biological, physical and chemical agents which individuals are rarely exposed to in isolation. Nevertheless, it could be argued that the central aim of this thesis was to examine the relationship between the indoor environment, time spent indoors and poor indoor air quality on asthma outcomes for individuals residing in social housing in Cornwall, and the protocol detailed in Chapter 5 provides a modelling framework for future analysis that encompass real time sensor monitoring to better understand this relationship.

Second, the Smartline sample are a unique subset of participants that differ from the local population in relation to age and sex mix, making validity external to social housing tenants limited. Chapter 2 highlighted how socioeconomic status can be a major confounding factor in the type and quality of housing an individual may reside in, with low-income families and those with poor health often being forced into health-risky homes, so there is a risk that this population would naturally be disproportionately affected by poor health.

Whilst we followed a strict and robust scientific method throughout our evidence synthesis in Chapter 3, the number of volatile organic compounds are vast and there is limited knowledge to the extent in which inhalation of each pollutant can cause harm. The knowledge base is continually evolving as new exposures are identified, therefore there is potential for some studies to have been missed. Further, limited high quality evidence availability relating to indoor home $PM_{2.5}$ and asthma outcomes in adults, limits the ability to sufficiently assess the associated risk in this population and thus further research, such as detailed in Chapter 5, will be needed to address this going forward.

Finally, due to the sample size of the time use and M-AQL questionnaires, confidence in the effect sizes is reduced despite strong effects being observed in some domains and will require larger studies to validate the findings. In section 6.3 several areas for future research are outlined relating to indoor environments and asthma that would mitigate some of the limitations discussed above.

6.3 Future research

The work contained within this thesis has provided collective new evidence that increased periods of time spent inside individuals own homes which contain air pollution, VOCs and fungal contamination increases their asthma symptom severity. Based on the empirical evidence presented in this thesis, future research should focus on the impact of housing and indoor exposures on respiratory health, particularly with our increasing population and demand for decent homes. Whilst much literature exists exploring specific health effects of the indoor environment on asthma in children, much less has been explored in adults or in reactive chemistry between individual compounds.

Given the evidence of the relationship between indoor air pollutants and asthma outcomes, further mitigation measures need to be implemented that inform housing occupants on individual actionable behaviour modification, which could go some way to improving the indoor air quality in home environments. There are several research areas which the novel data obtained from this thesis could address, to reduce the health and economic burden associated with asthma.

For individuals, understanding the biological, physical and chemical agents found in the home can help them to both better manage their home and their health. Delivering the knowledge gained through this thesis in relation to indoor exposures and asthma is important. A variety of communication platforms could be utilized (e.g., social media, radio, world wide web, leaflets, influencers etc.) to evaluate information uptake and subsequent behaviour change, as well as any possible resultant health outcomes is a future research interest.

This type of analysis would be of benefit to individuals to help them mitigate health risks in their own home but also to policy makers and health care providers as it would allow decision makers to tailor specific resources to those who need it most. This type of study should also explore non-technological ways of delivering public health information in those populations who are typically hard to reach (elderly, disabled, rural etc.) to ensure that their home environment is as safe and healthy as possible.

This thesis has highlighted that fungal contamination is associated with poor asthma outcomes and demonstrates the serious health effects of living with fungal contamination in the home. However, it is plausible that those households with high levels of fungal contamination use products to combat the fungi that are just as harmful.

Previous studies have shown the risk for lung health of exposure to cleaning products (Svanes et al., 2018). Further, the information given to tenants currently, generally only informs them to remove fungal contamination but often fails to adequality inform them of how to do this. For example, in social housing providers customer handbook, advice is given to tenants to take reasonable steps to take of the home ensuring there is adequate ventilation and that the home is regularly cleaned, however there is no advice as to what to clean the property with or how best to do it (Coastline-Housing, 2022). Moreover, the improper use of household products and their mixing is potential for further health problems, including skin conditions and further lung issues (Koksoy Vayisoglu and Oncu, 2021). Again, the use of different communication platforms to provide evidence-based health in the home information allows for powerful messaging to be disseminated across a large platform which could improve population health.

In response to the death of Awaab Ishak, who died of a respiratory condition caused by prolific fungal contamination in his home, the UK Government recently published correspondence to all registered housing providers (private and local authority) to ensure that any homes they supply are well-maintained and of a decent standard (MacGregor, 2022).

The Government have pledged to take appropriate action on any provider failing to meet the standards they have outlined, addressing damp and fungal contamination in their stock, and assessing risk to tenants and their health (MacGregor, 2022). They note the importance of listening to tenants' concerns, understanding their populations diverse range of needs, and the need to remove barriers to prompt access to services.

Given our findings which indicate that increased time spent in homes with fungal contamination increases asthma symptoms especially in winter, improved measures need to be put in place to combat fungal contamination in homes as well as enhancing indoor air quality.

A future research interest would therefore involve a multisectoral approach to better managing asthma and the home by ensuring a home environment (to include air quality and fungal contamination) risk assessment is implemented as part of ongoing asthma care. This would allow health authorities and housing associations to identify those most at risk of adverse health effects and ensure that the appropriate treatment is given as timely as possible.

Digital health apps allow greater efficiency and accessibility of health care. The NHS app which provides health advice is an example of such app (NHS, 2022). The ANTICIPATE (Actively anticipating the unintended consequences on air quality of future public policies) project (which assesses the capacity for producing real time notifications, linked to the NHS app, to deliver targeted advice about how to mitigate exposure to indoor and outdoor air pollution) developed and published a policy briefing, providing suggestions about how to mitigate the air quality related impacts regarding the NHS app. Among others, they recommend the inclusion of patient advice regarding the health impacts related to indoor and outdoor air pollution within the NHS App (ANTICIPATE, 2022, ANTICIPATE, 2020). As well as exploring the feasibility of the app being able to deliver advice relating to the health impacts of indoor and outdoor air pollution. In the context of this thesis, a clear area for further research would be to test a subpopulation of asthmatic individuals' readiness for integrated health in homes, by asthma alerts delivered via the NHS app.

Whilst there is a clear societal drive for digital health tech, how this is achieved across all populations will no doubt require a tremendous effort and skillset because despite all Smartline participants being given digital tablets at the start of the project very few engaged with the technology making an already hard to reach population even more remote.

In comparison to the current disparate system, this could pave the way for better integrated healthcare that proactively prevents some of the adverse health effects of living in homes with poor air quality. These alerts could be derived from linking real time sensor data with the NHS app so that when indoor pollutants reach a pre-determined threshold the user would be alerted to the risk of increased symptoms.

The sensor data could also feed back to the housing association to enable real time housing stock condition alerts. This type of interagency, inter-systems approach could offer a number of opportunities for improved health including real-time knowledge of indoor air pollution (potentially leading to more immediate mitigation when air quality is poor), improved patient education, identification of exposure thresholds in which asthma exacerbations are likely to occur and reduced footfall within clinical setting. Such an analysis would also help reduce overall emissions related to transportation. If successful, the data collected could prove useful in the formation of a similar model to the DAQI (outdoor) to forecast predicated indoor air pollution levels based on historic data and real time monitoring with assigned health risk.

6.4 Final comments and recommendations

Exposure to toxic chemicals such as those found in VOCs and $PM_{2.5}$, as well as hazardous organic material such as fungal spores in the air, have dangerous and sometimes fatal consequences for individuals. Exposure to these types of pollutants is variable and largely modifiable in the home environment. However, the field of indoor air pollution is still in its infancy compared to outdoor air pollution, making evidence limited but desperately needed. Worryingly, exposure is largely unavoidable and comes at a significant cost to treat the resultant health outcomes.

To facilitate a speedy reduction in exposure, a unified measurement at the component level is urgently required should a reduction in air pollution-related health outcomes be achieved. An integrated and evidenced based approach across all sectors in regard to future building, design and management will have multiple benefits for public health.

Further, research should focus on the mechanistic insights gained through both human and animal subject studies to gain a better understanding of exactly how exposure to such respirable pollutants may affect individuals not only during short exposure periods but also across the life course. With an ageing population and increased industrial loads, measures will need to be put in place to protect future generations as well as ensure the health and well-being of the current population.

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8. Appendices.

Appendix 1 Research article

Changes in Domestic Energy and Water Usage during the UK COVID-19 Lockdown Using High-Resolution Temporal Data

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Abstract

In response to the COVID-19 outbreak, the UK Government provided public health advice to stay at home from 16 March 2020, followed by instruction to stay at home (full lockdown) from 24 March 2020. We use data with high temporal resolution from utility sensors installed in 280 homes across social housing in Cornwall, UK, to test for changes in domestic electricity, gas and water usage in response to government guidance. Gas usage increased by 20% following advice to stay at home, the week before full lockdown, although no difference was seen during full lockdown itself. During full lockdown, morning electricity usage shifted to later in the day, decreasing at 6 a.m. and increasing at midday. These changes in energy were echoed in water usage, with a 17% increase and a one-hour delay in peak morning usage. Changes were consistent with people getting up later, spending more time at home and washing more during full lockdown. Evidence for these changes was also observed in later lockdowns, but not between lockdowns. Our findings suggest more compliance with an enforced stay-at-home message than with advice. We discuss implications for socioeconomically disadvantaged households given the indication of inability to achieve increased energy needs during the pandemic.

Keywords: sensors; electricity usage; gas usage; water usage; COVID-19

1. Introduction

The COVID-19 pandemic has been associated with 3.1 million deaths worldwide (Dong et al., 2020, John Hopkins University, 2020), as of 26 April 2021, and has caused significant disruption to individuals, societies and economies (Rozanova et al., 2020). In an effort to reduce the spread of the virus, the UK Government provided public health guidance, from 3 March 2020 onwards, to stay at home and to increase the frequency and duration of handwashing (The Health Foundation, 2020, UK Government, 2020, Wikipedia, 2020). People were formally *advised* by the UK Prime Minister to stay at home from the evening of 16 March 2020 (advice period) (The Health Foundation, 2020). A week later, the first full lockdown came into force on the evening of 23 March 2020, when people were *instructed* to stay at home (instruction period).

Reduction in virus transmission rates is reliant on individuals' compliance with the government guidance. Other than a reduction in transmission rates, there are few sources of evidence of compliance. However, changes in domestic utility usage patterns can be used to test for evidence of behavioural changes in response to the government guidance to stay at home.

Public compliance with guidance in a disaster scenario depends on perception of personal risk and trustworthy communications of consistent public information (Manuell and Cukor, 2011). Specific to virus outbreaks, loss of income is a common concern for not wishing to comply with voluntary quarantine (DiGiovanni et al., 2005). For COVID-19, compliance increases with fear of the virus (Harper et al., 2020) and with the stringency of government actions (Götz et al., 2021). It therefore seems likely that public compliance will increase following the instruction to stay at home, given a growing number of COVID-19 cases implying higher personal risk, repetition of consistent public guidance, the announcement of the furlough scheme (20 March 2020) (ATT, 2020a) and the closure of more activities, such as social venues and schools (20 March 2020) (Wikipedia, 2020).

More time indoors provides more time for appliance and water use and an increased need for heating, leading to increased electricity, gas and water usage when the house is occupied than when unoccupied (Adeyeye and She, 2015, Baker and Rylatt, 2008, Buchberger and Wells, 1996, Domene and Sauri, 2006, Fuerst et al., 2020, Harold et al., 2015, Kavousian et al., 2013, Wijaya and Tezuka, 2013). During the containment measures in response to COVID-19 across a range of countries, national electricity consumption rates decreased overall, particularly on weekdays, due to lack of commercial demand (Abu-Rayash and Dincer, 2020, Bahmanyar et al., 2020, International Energy

Agency, 2020). However, studies of large cities have shown that domestic electricity distribution increased in the COVID-19 lockdown in spring 2020 in Lagos, Nigeria (Edomah and Ndulue, 2020), and in New York's lockdown, usage increased in the middle of the day (Meinrenken et al., 2020) and self-reported usage shifted to later in the day (Chen et al., 2020). During the UK lockdown, self-reported domestic activities shifted to later in the day, and revealed an increase in housework and food-related activities (Grünewald, 2020b, Grünewald, 2020a).

Detection of changes in utility usage would have implications for utility supply networks and on household expenditure. In the short-to-medium term, leading health organisations predict that COVID-19 will remain an active threat (World Health Organisation, 2020). Further lockdowns have already been implemented in the UK since the first in spring 2020 and could also be used in the future. After the pandemic has passed, increased home-working is predicted to continue (Office for National Statistics, 2020a, ATT, 2020b, BBC, 2020, CBI, 2020), thereby reducing energy demand in office settings and increasing or shifting domestic demand. With regards to household expenditure, increased energy poverty is seen as an unintended consequence of COVID-19 that requires targeted financial support (Mastropietro et al., 2020). The impact is likely to be greater in socioeconomically disadvantaged areas, such as the area for our study, which can have lower energy consumption than other areas (Elnakat et al., 2016, Đurišić et al., 2020), and are already experiencing a greater impact of COVID-19 more generally in terms of mental health, education and digital inequality (Abbs and Marshall, 2020, BBC Panorama, 2020, Beaunoyer et al., 2020). Evidence for meaningful differences in utility usage during lockdown is therefore important in understanding the wide range of impacts of the COVID-19 lockdown (Betsch et al., 2020).

The purpose of this study is to test whether domestic utility usage data changed as a result of the COVID-19 UK outbreak in spring 2020, by comparing the data during that time with data from the same dates in 2019. In contrast to previous research, reported above, our study uses data measured directly from the home, and includes gas and water usage, from a cohort of participants that spend a high proportion of time at home normally, and live in a semi-rural, deprived area of England. Data from 280 sensored homes are used, providing high temporal resolution, allowing us to test for changes in usage patterns across the day, as well as overall differences.

Primarily, we test for changes in spring 2020, in two time periods under different levels of Government guidance. The *advice period* is defined as 17 to 23 March 2020, when people were advised by the UK Government to stay at home, prior to the full lockdown in the UK. The *instruction period* is defined as the first month of full lockdown, from the 24 March to the 23 April 2020, when people were instructed to stay at home (The Health Foundation, 2020).

Our hypotheses are as follows: (1) As a result of the UK Government guidance, there should be an increase in the time spent indoors and the amount of handwashing in 2020 compared with 2019, which we expect to detect through increases in energy and water usage. We expect any changes to be stronger in the instruction period than the advice period. (2) We also expect energy and water usage to vary over different times of day; for example, lower usage at night than in the morning. Variation across the course of the day is expected regardless of behavioural responses to the COVID-19 guidance. In other words, we should see variation in 2019 as well as 2020. (3) We expect that changes as a result of COVID-19 guidance may differ at different times of day, for two reasons. Firstly the home would generally be occupied equally at certain times of the day (e.g., night-time, evening), so there may be no change due to stay-at-home guidance at those times. Secondly, there may be shifts in daily behaviour patterns, as people’s behaviours adjust to more time at home.

In addition to the primary investigation of the first lockdown in spring 2020, we also repeat the analyses to test for changes throughout the course of the pandemic, including further lockdowns in November 2020 and January 2021, as well as periods when the restrictions were relaxed.

2. Study Background and Data

2.1. The Smartline Project

The Smartline and Smartline Extension projects are a six-year interdisciplinary research programme that began in 2017, funded by the European Regional Development Fund, Southwest Academic Health Science Network, Cornwall Council and HM Government. The project involves collaboration between the University of Exeter, Coastline Housing (a social housing provider), Volunteer Cornwall (a charity that supports individuals and communities through voluntary action), Cornwall Council and the Southwest Academic Health Science Network.

Smartline has recruited over 300 households in properties that are owned and managed by Coastline Housing in the Camborne and Redruth area of Cornwall, Southwest UK. The overarching aim of the project is to explore and trial opportunities for technology to support people to live healthier and happier lives in their homes and communities (Smartline, 2020, Moses et al., 2019a, Walker et al., 2020, Williams et al., 2020b, Williams et al., 2021a).

2.2. Data Collection

As part of the Smartline project, survey, sensor and housing data were collected from 280 homes, following informed written consent. The large dataset was a completely unique combination of cross-sectional and time-series data, including household characteristics, health measures, environmental readings and utility usages.

2.2.1. Survey Data

Face-to-face surveys were conducted in participants' homes in September 2017 to November 2018. Questions covered a range of topics, such as digital technology in the home, health and wellbeing and community cohesion.

2.2.2. Sensor Data

Electricity meters were installed in 280 Smartline homes, gas meters in 52 homes and water meters in 22 homes. Readings were recorded at a maximum frequency of every 3 min for electricity, and every 7.5 min for gas and water, dependent on transmission success from the sensor to the host system. Homes for installation of gas and water meters were previously selected using cluster analysis on factors that can influence utility usage, in order to capture a representative sample of homes (Menneer et al., in preparation).

Sensors were also installed in 281 homes to measure temperature in the living room and main bedroom, with readings recorded at a maximum frequency of every 3 min. External air sensors were placed outside some homes, including measurements of temperature, with readings at a maximum frequency of every 30 min.
All sensors were manufactured by Invisible Systems Limited (Invisible Systems Ltd., 2020) and installed by the Blue Flame company (Blue Flame, 2020) from October 2017 onwards, and will be in place until August 2022. See Table S1 in the Supplementary Materials for sensor models and accuracy information.

3. Materials and Methods

We may expect overall differences between utility usage between 2019 and 2020; however, given that the home would generally be occupied equally between the two years at certain times of the day (e.g., night-time, evening), we also examined the 24 h profiles. Identification of any changes across different times of day is only possible given the high temporal resolution in the Smartline sensor data.

Data for all sensors were linearly interpolated to a sampling rate of 60 min, providing a value for each hour in each period. The means of hourly values across the days in the advice period and instruction period were calculated for each home to provide a 24 h usage profile for each outcome measure. (Times of day were adjusted for changes between Greenwich Mean Time and British Summer Time.)

We used mixed linear regression for our analyses. In the following sections, we describe the variables, followed by the analysis method details.

3.1. Predictor and Outcome Variables

Predictor variables were year (2019 and 2020), period (advice and instruction) and hour of the day (0–23). Outcome variables were the mean electricity (kWh), gas (m^3) and water (m^3) usages per hour in each home, with separate regressions conducted for each measure.

3.2. Covariates

The survey, sensor and housing data allow us to include factors in our analysis that may affect utility usage in addition to increased time spent indoors. Table 1 summarises the factors identified by previous research and provides the Smartline survey, sensor or housing data used to create the covariate measures for inclusion in the analyses. For the homes used in the energy analyses, we also considered heating type (Đurišić et al., 2020), but it was not included as a covariate because all except six homes had gas-powered heating. The remaining six homes had air source heat pumps and were included in the electricity analysis. All homes with gas monitoring had gas heating.

The following covariates were included where possible: household size, presence of occupants under 18 years of age or in employment, time normally spent indoors, presence of a smart meter, number of rooms, property type, fuel poverty survey score, mean indoor temperature, and IMD rank. Mean indoor temperature was calculated from time-series data sets for homes with corresponding utilities data sets. The electrical appliances measure was also included for the electricity analysis. IMD rank was excluded from the water analysis, given a variance inflation factor of 38.8 in combination with the other factors, and the water smart meter was not included, given all 'No' responses for those homes with a Smartline water meter. For the gas analysis, given the small sample size, only the repeated measures (year, period and hour) were included due to low numbers for the different levels of the independent measures. Variance inflation factors for all included covariates were below 3.9.

Table 1. Factors that can affect domestic utility usage, and the covariate measure created from the survey, sensor or housing data.

Factor Affecting Utility Usage and Supporting Literature	*Survey Question or Source of Data*	*Survey Response Options (All Questions Also Had the Option to Not Answer)*	*Measure(s) Created*	*Missing Data*
The number of the people in the household (Kavousian et al., 2013, Wijaya and Tezuka, 2013, Baker and Rylatt, 2008, Fuerst et al., 2020, Harold et al., 2015, Domene and Sauri, 2006, Makki et al., 2015, Thatcher and Layton, 1995).	Please tell us the number of people in your household.	Numbers of males and females in the following age ranges: 0–12, 13–17, 18–65, 65+ years.	The total number of people living in the home.	No missing responses.
The UK lockdown would have particularly affected people under the age of 18 and those in employment due to closures of schools and places of work, thereby increasing the time spent at home. In particular, children and adolescents in the home can affect utility usage (Fuerst et al., 2020, Makki et al., 2015).	Please tell us the number of people in your household.	Numbers of males and females in the following age ranges: 0–12, 13–17, 18–65, 65+ years.	Set to 1 if the response for 0–12 or for 13–17 is greater than zero.	No missing responses for number of children and adolescents. For employment, cases with missing responses were excluded from the analyses. The two factors were summed to give a value of 0, 1 or 2, reflecting the potential effect of the lockdown on the individuals in the household.
	Last week, were you: (Include any paid work, including casual or temporary work, even if only for one hour.)	Working as an employee? Self-employed or freelance? Working paid or unpaid for your own or your family's business? Away from work ill, on maternity leave, on holiday or temporarily laid off. Doing any other kind of paid work? On a government sponsored training scheme. Waiting to start a job you have already obtained? Actively looking for work? Retired (whether receiving a pension or not)? A student? Looking after home or family? Long-term sick or disabled? None of the above?	Employment was 1 if 'working as an employee', and 0 for all other non-missing responses.	
Time normally spent inside the home (see Section 1).	On average, about how many hours per day do you spend indoors at home during an average weekend day (including sleeping)? Question repeated for weekday, and for your partner.	0 to 24	Mean time spent indoors, across the main respondent and his/her partner, and across weekday and weekend day, weighted to give the average time spent at home each day.	Cases with missing responses were excluded from the analyses.
Electrical appliances (Kavousian et al., 2013).	Which of these pieces of technology	Internet connection, Television, TV decoder (e.g., Sky, Virgin Media),	A measure of the electrical devices in the home. Count of the number of	The survey question comprised a list with

	do you have in your home and are they connected to the internet? (Select all that apply.)	Mobile phone, Computer, Tablet, Wearable technology (e.g., Fitbit), Smart watch, other technology.	technology devices in the home, including those connected to the internet.	options to select, so missing responses were treated as a 'No' response.
Smart meters (Faruqui et al., 2010, Kappel and Grechenig, Strengers, 2011, Willis et al., 2010, Murtagh et al., 2014, Rausser et al., 2018, Thomas, 2012).	Does your home have smart meters for your energy/water supply?	No, Electricity, Gas, Water.	Whether or not the home has a smart meter for the relevant utility.	No missing responses.
The number of rooms in the home or floor area (Baker and Rylatt, 2008, Đurišić et al., 2020, Fuerst et al., 2020, Harold et al., 2015, Kavousian et al., 2013, Wijaya and Tezuka, 2013).	Please tick all the rooms that you have in your home.	Kitchen, Dining room, Utility room, Bathroom, Living room, Bedrooms 1 to 4, Other room.	Count of the number of rooms in the home.	No missing responses, except for 'Other', which was counted if it contained any text.
The building type (Domene and Sauri, 2006, Harold et al., 2015, Kavousian et al., 2013).	Flat or house (including bungalow) obtained from Coastline Housing records.		Property type (flat or house).	No missing information.
Fuel poverty (Anderson et al., 2012, Lomax and Wedderburn, 2009, Sharpe et al., 2015d, Lister, 1995, Makki et al., 2015, Shan et al., 2015).	Do you think your home is adequately heated?	Yes/No	Combined to provide an indicator of fuel poverty. A score of 1 was assigned to 'No', 'Yes' and 'Yes', respectively, and summed to provide a score of 0 to 3. The fuel poverty measure was based on the definition "the state of being unable to afford to heat one's home adequately" (Collins Dictionary, n.d.) (page: definition of fuel poverty), and on research showing that families suffering fuel and water poverty will change their behaviours, for example restricting heating and ventilation, to save energy and water (Anderson et al., 2012, Lister, 1995, Lomax and Wedderburn, 2009, Makki et al., 2015, Shan et al., 2015, Sharpe et al., 2015d).	Cases were excluded from the analyses if any response was missing.
	Do you avoid turning on the heating because of cost?	Yes/No		
	Do you avoid ventilating your home to save heat/energy?	Yes/No		
In addition to the fuel poverty measure constructed from the survey data, mean indoor temperature (World Health Organisation, 2018) and IMD	Temperature data from Smartline living room and bedroom sensors.		The mean temperature over both rooms. Calculated from the mean of hourly values across the lockdown time period in both years to provide one value per home.	If sensor data was not present for both years, the case was excluded from the analyses.

rank (Department for Communities and Local Government, 2015) were also included as an indicators of fuel poverty (Markus, 1994).	IMD rank using the postcode for the home.	606 to 19,024, with a lower rank indicating higher deprivation.

3.3. Datasets

Homes were excluded from the analysis if the relevant survey responses for covariates were missing, the participant withdrew from the study before 24 April 2020, the sensor had been removed for practical reasons or the data indicated a recording error. Specifically, homes were excluded if either year mean (2019 and 2020) was zero (5%), the year mean had either doubled or halved from 2019 to 2020 (28%), or data were missing from a given hour across all days in the period (32%). For electricity, three homes were also excluded due to a mean hourly usage below 0.08 kWh. Only a subset of Smartline homes were monitored for gas and water usage, as described in the Study Background, Section 2.2.2. Complete datasets comprised 50 homes for electricity, 8 for gas and 14 for water, with a minimum of 33,644, 13,457 and 13,014 original recordings per home, respectively.

3.4. Regression Method

The year, period and hour of the day provide repeated measures within each home, while the survey factors and mean indoor temperature are independent measures. We therefore used a linear mixed effects regression to test for changes in usage with year (from 2019 to 2020). We also included the following interactions between variables, to test whether any changes with year differed over the different periods (advice and instruction) or hours of the day: year × period, year × hour and year × period × hour. The unique property reference number (UPRN) for all homes was included as a random effect to represent the change within each home, and to capture the repeated measures. Models were implemented using R version 4.0.2 (R Core Team, 2020) and the lmer function from R's lmerTest package library (Kuznetsova et al., 2020), which uses the lme4 package (Bates et al., 2015).

For each outcome variable and each time period combination (both periods together, advice period separately and instruction period separately), three models were fit. The null model comprised an intercept and the UPRN random factor. The main effects model comprised all factors but not the interaction terms. The interaction model included all factors and the year × hour interaction term, and the model using data for both periods also included the year × period, period × hour and year × period × hour interaction terms.

The plots of residuals against fitted values showed evidence of heteroscedasticity for all utilities and regression models. These plots became more evenly distributed when electricity data were natural-log transformed and gas and water were square-root transformed (see Figure S1 in the Supplementary Material). The results of the analyses with transformed data are therefore reported. The patterns of results with non-transformed data are similar, with differences noted in Section 4. The quantile–quantile plots of the residuals revealed generally symmetric and sufficiently normal distributions. For all outcome variables and period combinations, the main effects model was a significantly better fit than the null model (all $\chi^2 > 95$, $p < 0.001$), and the interactions model was a significantly better fit than the main effects model (all $\chi^2 > 79$, $p < 0.001$). The results of the interaction models are therefore reported. For each regression, a reference hour was defined as the hour in which the absolute difference between 2019 and 2020 was the smallest. This hour of the day represents the minimum change that occurred during lockdown, and acts as a comparison to test whether changes during lockdown are larger at other hours of the day.

Even in cases of no significant interactions with period, separate analyses were also conducted for the advice and instruction periods. There were two reasons for planned stratification of the analyses. Firstly, the reference hour differed between the two periods for all utilities (see Tables S3–S5 in the Supplementary Material). Secondly, there was evidence for changes in all utility usages between the advice and instruction periods (see Section 4).

4. Results

Figure 1 provides an overview of the sensor data from February to April. Average hourly usage rates in the UK are 0.2–0.8 kWh for electricity, 0.08–0.18 m^3 for gas and 0.008–0.016 m^3 for water (UKPower, 2020, South West Water, 2020).

Table S2 in the Supplementary Material provides descriptive statistics for each covariate for each group of homes with electricity, gas and water usage measurements. Tables S3–S5 provide the detailed regression model outputs reported in the following subsections.

The survey data, taken prior to the COVID-19 pandemic, show that the Smartline participants normally spend a high proportion of time at home. Of the Smartline participants, 59% responded that they were retired or long-term sick or disabled, while 17% were in full-time employment, and the mean time normally spent inside the home per day was 19.5 h.

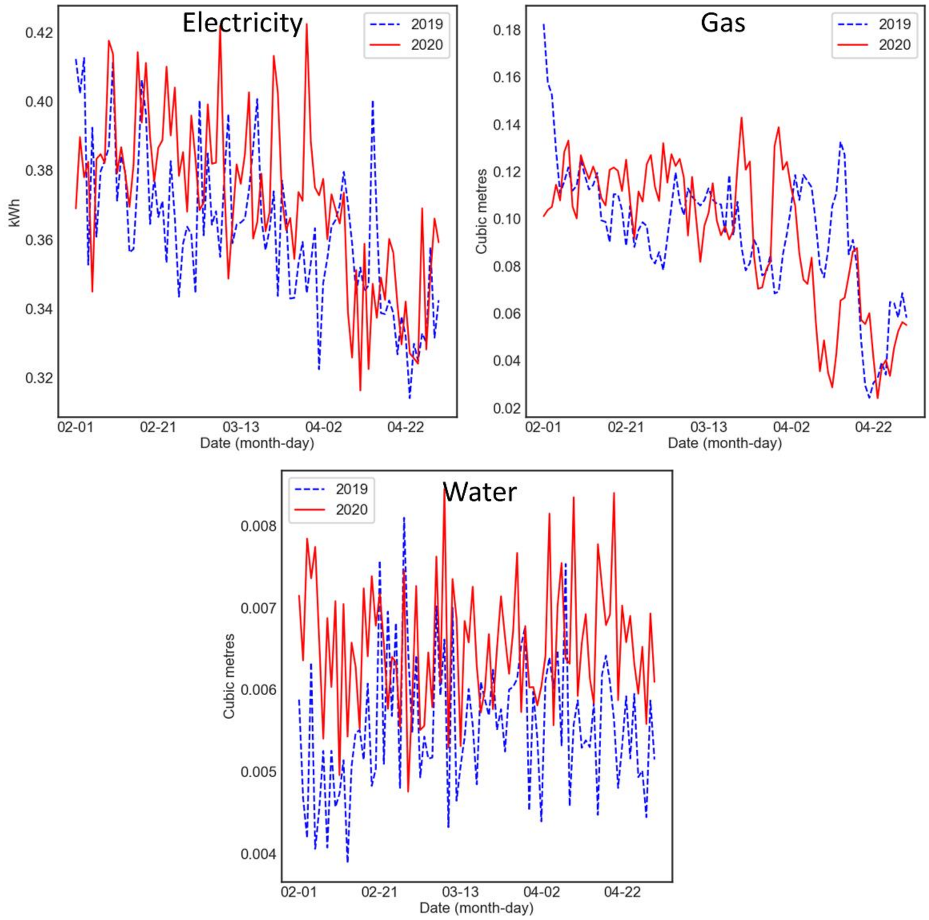

Figure 1. Mean hourly usage per day over all homes from February to April in 2019 and 2020 for electricity (**upper left**), gas (**upper right**) and water (**lower panel**).

The 24 h profiles, averaged across homes, are shown in Figure 2. As anticipated, the pattern of the 24 h profiles indicates that there are differences across years, and that they may only be apparent at certain times of the day. These patterns indicate that rather than utility usage necessarily increasing among the Smartline cohort, the timing of everyday activities linked to utility usage shifted. Given the high temporal resolution of the Smartline sensor dataset, it was possible to identify any changes in usage across the time of day, by splitting the day into hourly sections for the analyses.

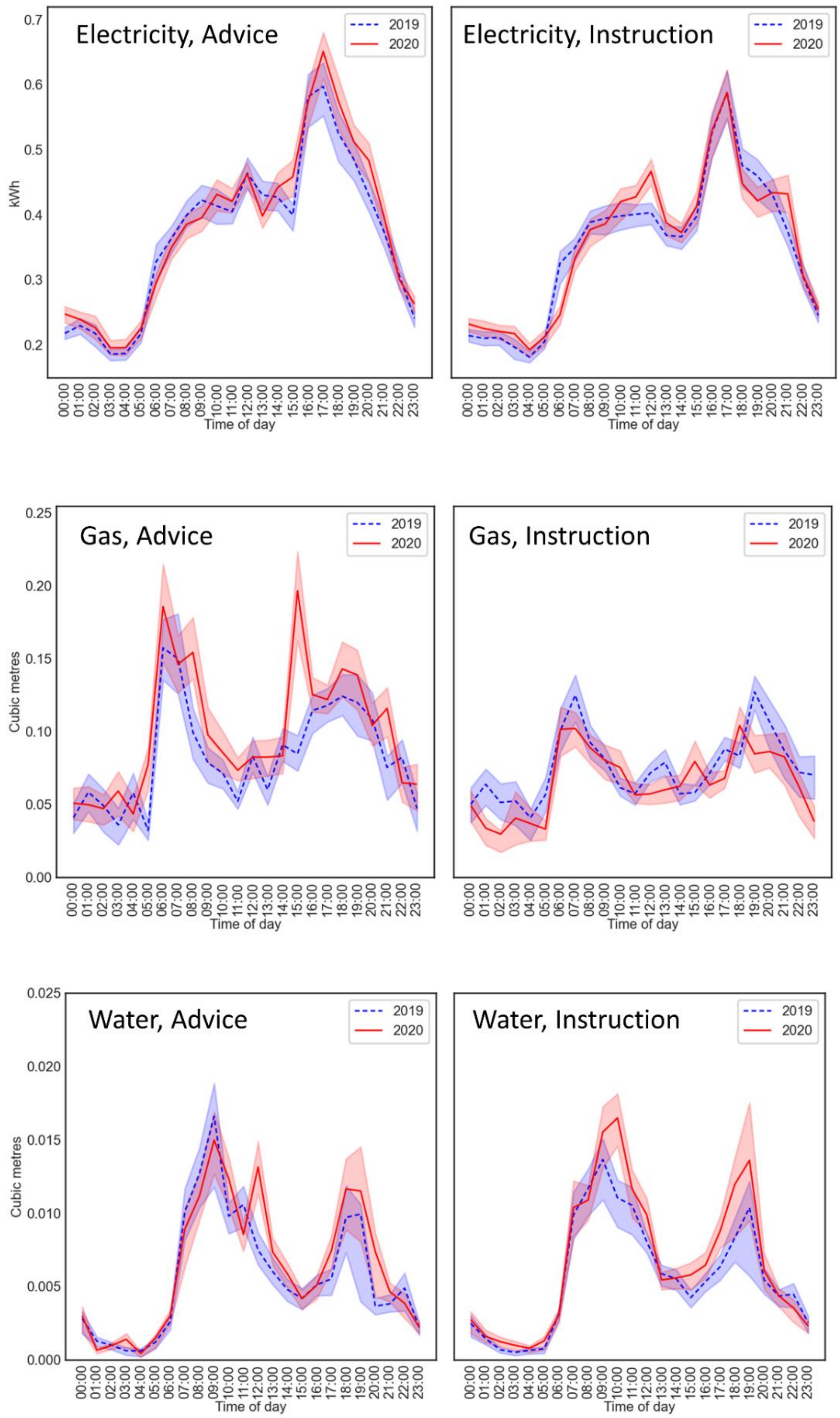

Figure 2. Electricity (**upper panels**), gas (**middle**) and water (**lower**) usage during the advice (**left**) and instruction (**right**) periods. Error bands represent 0.5 standard errors. The scale on the vertical axis applies to both panels of the same measure.

4.1. Electricity

In the overall analysis, containing data from both periods, there was no significant relationship between electricity usage and year ($p = 0.200$), and no interaction with period ($p = 0.169$). The year × hour interaction was significant ($p = 0.010$), but the difference across years at each hour was not significantly different from the difference at the reference hour (all $p > 0.117$). Electricity usage decreased from the advice period to the instruction period ($p = 0.006$), and period interacted with hour ($p = 0.008$). The three-way interaction, year × period × hour, was not significant ($p = 0.276$).

Electricity usage changed with hour of the day ($p < 0.001$), as would be expected. Hourly electricity usage increased by 23% with each extra person in the household ($p = 0.030$) and increased by 59% with a change from flat to house ($p = 0.002$). No other factors were significant predictors of electricity usage (all $p > 0.182$).

With non-transformed data, the year × hour interaction only approached significance ($p = 0.054$), and compared with the reference hour, there was some evidence of an increase in electricity usage from 2019 to 2020 at 15:00, 17:00 and 20:00 (p = 0.058, 0.079 and 0.082, respectively).

The results for the overall analysis provide little evidence for a change in electricity usage between 2019 and 2020, nor for differences between the advice and instruction period. However, given the interactions with hour and a different ideal reference hour for the two periods, we examined the two periods separately, which did reveal differences.

During the instruction period there was a significant interaction of year × hour ($p = 0.001$), which was not significant during the advice period ($p = 0.375$). Compared with the reference hour (17:00), following the government's instruction to stay at home, there was an increase in electricity usage from 2019 to 2020 at 12:00 ($p = 0.023$), and a decrease at 06:00 ($p = 0.005$). All other relationships held as for the overall analysis (see Table S3 for details).

We also examined the change in electricity usage from 2019 to 2020 using binary splits according to the values of the covariates. Figure 3 shows visual increases during the middle of the day for larger households, households with occupants under 18 years of age or in employment, households that normally spend less time indoors and houses or bungalows. Table S8 in the Supplementary Material shows the mean overall change from 2019 to 2020 for each covariate group. The largest increases between groups occurred for households without a smart meter, not suffering fuel poverty and with the highest IMD rank (least deprivation). Despite numerical and visual differences between the covariate groups, overall differences were not statistically significant (all $p > 0.088$; Table S8).

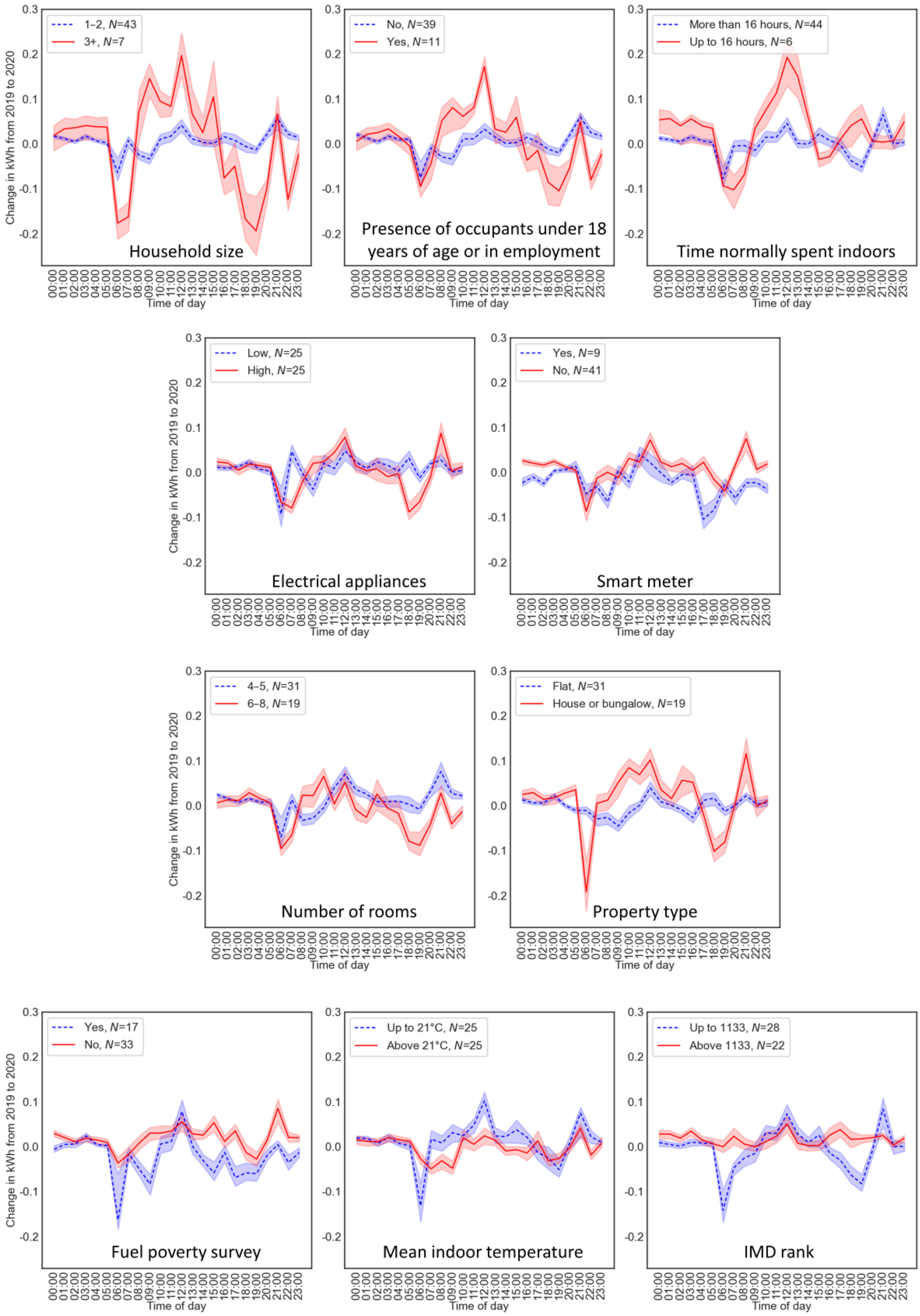

Figure 3. The change in electricity usage from 2019 to 2020 for households split into binary categories according to the values of the covariates. The group represented by the red line was considered more likely to be affected in terms of electricity usage by lockdown. Error bands represent 0.5 standard errors. See also Table S8 in the Supplementary Material.

4.2. Gas

In the overall analysis, there was no difference between years ($p = 0.732$), but there was a significant year × period interaction ($p < 0.001$), which is explored below, when the advice period and instruction periods were analysed separately. There was a trend towards decreased gas usage from the advice period to the instruction period ($p = 0.068$), and changes in gas usage with hour of the day ($p < 0.001$). All other interactions were not significant (all $p > 0.173$). With non-transformed data, the decrease with period was significant ($p = 0.018$) and the period × hour was significant ($p = 0.014$).

During the advice period, hourly gas usage increased with year ($p = 0.003$) by 20% from 0.083 m^3 in 2019 to 0.100 m^3 in 2020, but there was no significant change in the instruction period ($p = 0.136$). Hour remained a significant predictor in both periods.

4.3. Water

In the overall analysis, hourly water usage increased between years ($p = 0.046$) by 17% from 0.006 m^3 in 2019 to 0.007 m^3 in 2020 and increased from the advice period to the instruction period ($p = 0.012$). No interactions were significant (all $p > 0.557$). Water usage changed across hours of the day ($p < 0.001$). There was a trend towards a significant increase in water usage with each extra person in the household ($p = 0.059$). No other factors were significant predictors of water usage (all $p > 0.228$). With non-transformed data, period was not a significant predictor of water usage ($p = 0.417$) and the relationship with household size was significant ($p = 0.013$).

The results for the overall analysis show increased water usage in 2020 compared with 2019. Examination of the two periods separately revealed a trend towards year being a significant predictor of water usage in the advice and the instruction periods ($p = 0.088$ and 0.096, respectively). All other relationships were similar to the patterns in the overall analysis (see Table S5 for details). With non-transformed data, year was only a significant predictor of water usage during the instruction ($p = 0.040$), not the advice period ($p = 0.162$), and household size was a significant predictor of water usage in both periods (both $p < 0.017$).

The regression coefficient estimates for the difference between years at each level of hour reflected the shifts in the morning peaks in both periods in Figure 2, with weak evidence for a greater increase at 12:00 in the advice period ($p = 0.082$), and a greater increase at 10:00 in the instruction period ($p = 0.003$). However, the year × hour was not significant for either period (both $p > 0.543$).

4.4. After the First Lockdown

The focus of this Special Issue is on the first responses to COVID-19 in March to April 2020. However, the data allow us to test for evidence of behaviour change in later lockdowns in England, and of sustained behaviour change between lockdowns.

We repeated the analyses for the second lockdown from 5 November to 2 December 2020, the first month of the third lockdown from 5 January to 4 February 2021 and the time between lockdowns, from 1 September to 31 October 2020, during which many stay-at-home restrictions were lifted and most schools had reopened. Data from the 2021 lockdown were compared with data from the same dates in 2020. Data are presented in Figure 4. Outputs from the regressions are provided in Tables S6 and S7 in the Supplementary Material. Given the withdrawal of participants from the study and the removal of sensors in order to install smart meters, the sample sizes were smaller than for the first lockdown, with at least 21 for electricity, 6 for gas and 11 for water. We therefore do not statistically analyse the gas data. For homes with water meters, the presence of occupants under 18 years of age or in employment and the fuel poverty survey score were no longer included in the analyses due to raised variance inflation factors.

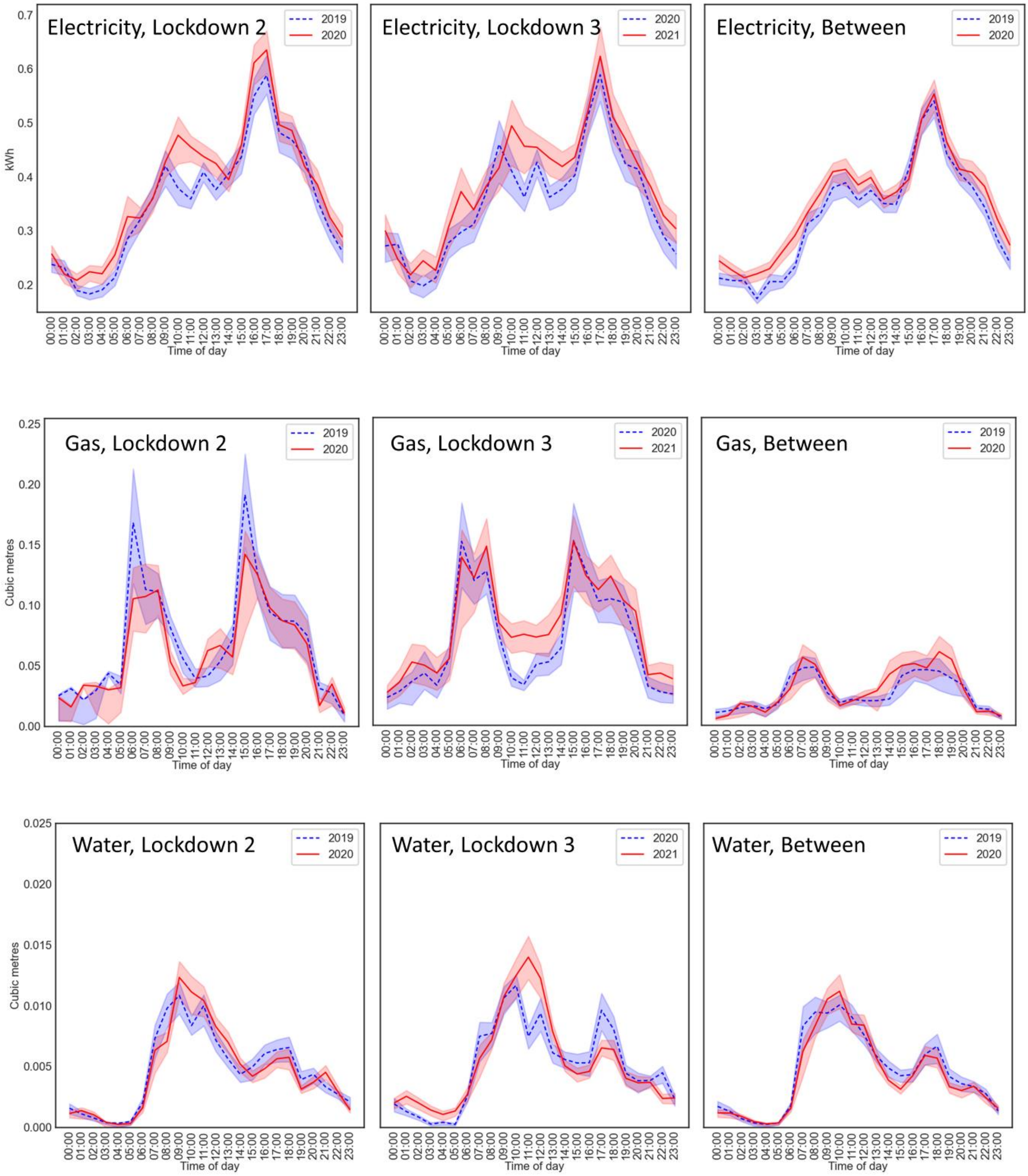

Figure 4. Electricity (**upper panels**), gas (**middle**) and water (**lower**) usage during the second lockdown (**left**), third lockdown (**middle**) and between lockdowns (**right**). Error bands represent 0.5 standard errors. The scale on the

vertical axis applies to all panels of the same measure.

4.4.1. Second and Third Lockdowns

Unlike the first lockdown, electricity usage increased overall in both the second and third lockdowns compared with the previous year (both $p < 0.039$). There were no overall changes in water usage (both $F < 1$).

As for the first lockdown, there was evidence that electricity and water morning usage shifted later in the day. For electricity, in the second lockdown, there was a stronger increase between years at 10:00 and 11:00 compared with the reference hour (08:00). However, the year × hour interaction was not significant ($F < 1$). For water, in the third lockdown, the interaction was significant ($F = 1.857$, $p = 0.012$), with a stronger increase at 11:00 ($p = 0.023$) and decrease at 22:00 ($p = 0.041$), compared with the reference hour (00:00).

Visually, for gas, in Figure 4, there is some indication of reduced usage during the second lockdown compared with 2019 at some times of day, and for increased usage overall in the third lockdown.

4.4.2. Between Lockdowns

There was a trend towards increased electricity usage in 2020 compared with 2019 ($F = 3.549$, $p = 0.067$), and no significant difference for water ($F < 1$). The regression coefficients showed evidence for an increase in electricity from 02:00 to 05:00 (all $p < 0.037$, compared with the reference hour of 16:00). However, the year × hour interactions were not significant ($F = 1.232$, $p = 0.207$). For gas, Figure 4 shows slightly more gas usage in the afternoon in 2020 compared with 2019, although gas usage was lower at this time of year than in any of the lockdowns.

5. Discussion

Utilising the Smartline Project network of 280 sensored homes, the purpose of this study was to test for changes in electricity, gas and water usages during the COVID-19 outbreak in the UK. We examined data from the week following advice to stay at home and from the month following the instruction to stay at home in 2020, and compared them with data from the same periods in 2019. Our hypotheses were: (1) increases in utility usages in 2020 compared with 2019, with any changes being smaller in the advice period than the instruction period; (2) differences in utility usage at different times of day, regardless of behavioural responses to the COVID-19 guidance; and (3) changes across years to interact with hour of the day. We found evidence to support all hypotheses, except that changes in gas usage were stronger during the advice than instruction period, perhaps due to changes in the weather condition. The changes in energy usage (gas and electricity) are discussed in the context of temperature, followed by the changes in water usage.

Gas usage increased during the advice period, suggesting people were acting on the government advice to stay at home. However, there was no change in gas usage during the instruction period. All homes with gas sensors have gas-powered heating, so the change between these two periods could reflect weather conditions at the time of year becoming warmer, when there was decreased need for heating. Heating requirements would account for the difference between 2019 and 2020 being apparent earlier in March (advice) but not later (instruction).

External sensor data (see Figure 5) showed that the mean temperature during the advice period was lower in 2020 than in 2019 (9.3 and 10.6 °C, respectively), but was slightly higher during the instruction period (12.0 and 11.1 °C), which could also have contributed to increased gas usage in the advice period during 2020 when compared to 2019, but not during the instruction period in 2020 when compared to the equivalent time period in 2019.

There was no evidence that electricity usage was affected in the advice period. However, during the lockdown instruction period, morning electricity shifted later in the day with no change in the evening. These shifts, together with the visible shifts in morning water usage to later in the day, suggest that more time at home leads to people getting up later in the day or being more leisurely, with delayed activities such as morning showers or breakfast. There is also a visual increase in usage during off-peak hours (see Figure 2: 1–4 a.m.).

Differences between the advice and instruction period were also supported by the indoor temperature (Figure 5), with temperature being generally lower in 2020 than 2019 during the advice period, and higher during the instruction period in the living room, consistent with people spending more time at home during the instruction period. The rise in living room temperature from 2019 to 2020 seems unlikely to be due to external temperatures, given the similar mean daily temperatures in 2020 (12.0 °C) and in 2019 (11.1 °C), and a smaller difference in bedroom temperature between 2019 and 2020. In addition, the indoor difference between 2019 and 2020 was fairly constant throughout the day, while the external difference varied, with similar minima at night and a larger difference between maxima during the day.

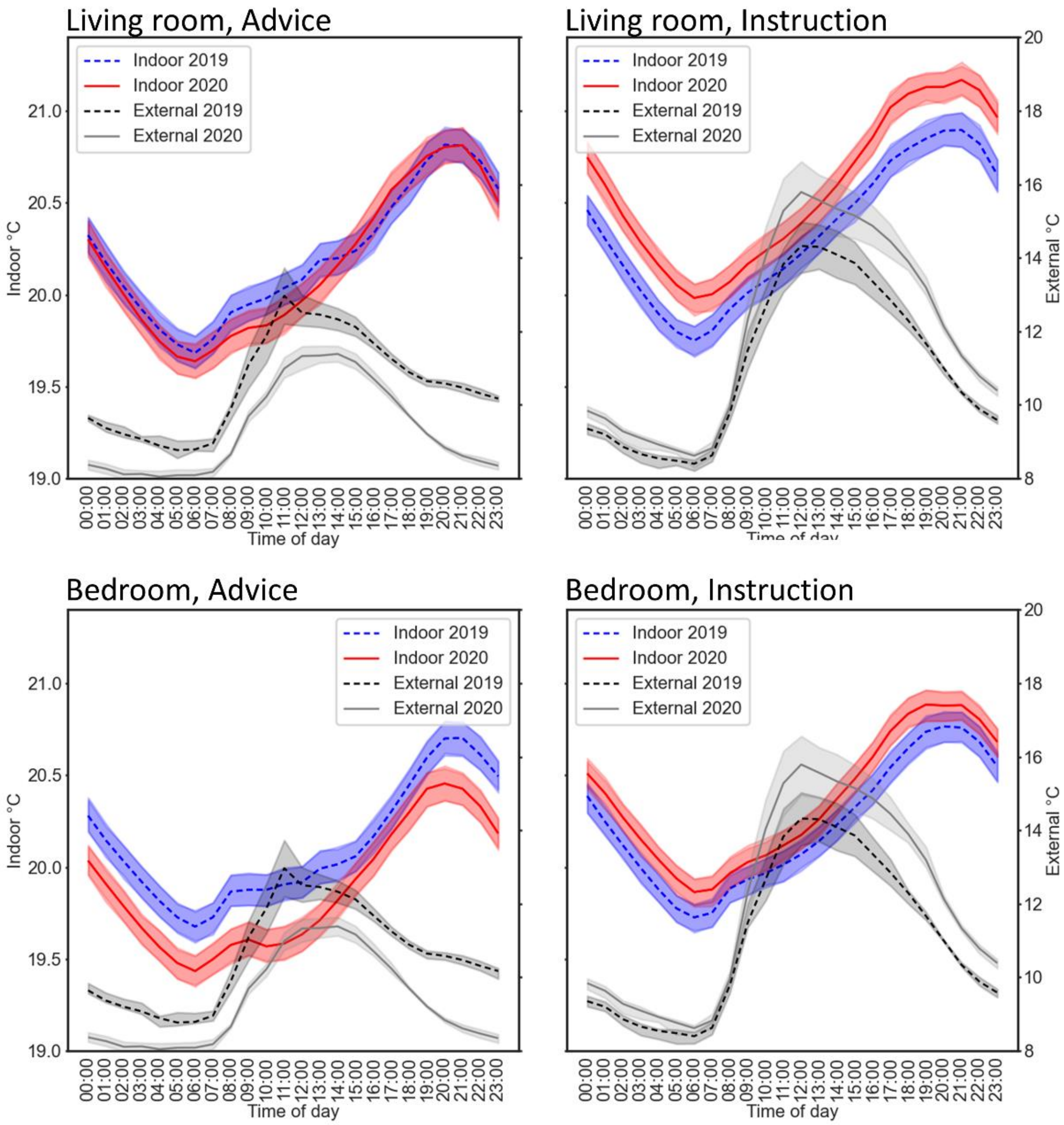

Figure 5. Red and blue lines show the indoor temperature in the living room (**upper panels**) and bedroom (**lower panels**) during the advice (**left**) and instruction (**right**) periods in 2019 and 2020. Grey lines show the external temperature during the same periods. Error bands represent 0.5 standard errors, and the number of homes included for indoor temperature was 162 to 170. The scales on the vertical axes apply to both left and right panels.

Patterns in water usage provide further evidence that people were spending more time at home. Overall water usage increased, consistent with people following the guidance to stay at home and increase handwashing. One reason for increased water usage could be more gardening (Grünewald, 2020b), which would be reflective of people staying at home, particularly with an extended period of warm, settled weather in the UK in spring 2020. Precipitation data show more rain in 2019 than 2020 (approximately 71 and 13 mm, respectively) (Weather Online, 2020). Other possible reasons for the increase include people undertaking more cooking, eating and drinking at home, as also observed in self-reports of activities (Grünewald, 2020b), especially with alternative venues such as cafes being closed. Self-reported activities during lockdown suggest a decrease in washing and showering (Grünewald, 2020b), but people may have been taking more time in the shower (Adeyeye and She, 2015), or having time for a bath instead of a shower, and using the lavatory more. With particular response to COVID-19, people should also be undertaking more handwashing and cleaning.

Overall, there were differences in utility usages during the advice and instruction periods in March to April 2020 compared with the same periods in 2019. These changes may be less apparent than they might be in a general population given that a large proportion of the Smartline cohort, as an older demographic, spend a lot of their time inside the home, regardless of COVID-19. The findings for electricity are in line with previous research from large cities in countries other than the UK (Edomah and Ndulue, 2020, Meinrenken et al., 2020, Chen et al., 2020), and with self-reports of activities in the context of national electricity consumption in the UK during the spring 2020 lockdown (Grünewald, 2020b, Grünewald, 2020a). Our results show that delayed or increased electricity usage is also observed in the UK, in a semi-rural area with above-average levels of deprivation.

The delayed morning electricity and water usage suggest that people exhibited more compliance given the instruction to stay at home than given the advice to stay at home in the week prior to the full lockdown. Such behavioural change supports findings from previous research that compliance increases with fear of the virus and with stringency of the government guidance (Götz et al., 2021). Behavioural changes indicated by the changes in utility usage patterns also appeared in the second and third lockdowns in England, with continued evidence for morning usage of electricity and water shifting to later in the day and increased overall electricity usage. The overall increase in these lockdowns, but not the first lockdown, could be due to these later lockdowns occurring in winter months, as opposed to the first lockdown occurring in spring 2020 with notably fine weather. The patterns observed in the lockdowns were not present in the data between lockdowns. These further analyses suggest people were complying with the stay-at-home message during the second and third lockdowns, but that this behaviour was not sustained between lockdowns despite the continued threat of COVID-19 and general government advice to limit outdoor activities.

We provide evidence that there were meaningful increases and temporal shifts in energy and water usage in the home following the UK Government COVID-19 guidance to stay at home.

These findings are important for the wider impacts of the COVID-19 lockdown, particularly given predictions that COVID-19 will remain an active threat in the population in the short-to-medium term (World Health Organisation, 2020). Our future research will examine the time course of effects throughout the pandemic in relation to the COVID-19 case rates reported by the media and the UK Government. We wish to determine whether there was increased compliance with government guidance at times of high case rates. Such a finding would support work showing that perceived risk increases compliance with instructions during disasters (Manuell and Cukor, 2011).

In addition, this study shows that behaviour change can be identified in time-series sensor data, which allow examination of the temporal shifts. In future developments, changes and anomalies could be identified to detect behaviour change relating to health, for example, someone becoming unwell or having a fall, or fuel poverty, with restricted energy usage.

This study also has implications for other areas of research. Increased costs associated with higher levels of domestic utility usage may be seen as an unintended consequence of COVID-19 lockdowns. Here, we did not assess the impacts on expenditures, but in other assessments bills were predicted to increase by 10 to 30% while working at home (BBC News, 2020a, Grünewald, 2020b). The Smartline cohort resides in social housing and in a region with higher than average rates of deprivation, with all but three of the participating homes being in the lowest 40% of the most deprived areas in England (Index of Multiple Deprivation (IMD) ranks) (Department for Communities and Local Government, 2015). Our findings indicate that within our cohort of households, economic and wider socioeconomic factors were observed in utility usage, with less deprived households, as measured by fuel poverty, using more electricity during the first lockdown (Figure 3). These patterns suggest that the increase required by other households during lockdown was not achievable by these homes. The impact of increased utility bills, or of the ability to afford required energy, could be greater on those in socioeconomically disadvantaged areas. These homes are already suffering other inequitable impacts from COVID-19 and the UK lockdown, such as an increased impact on mental health due to lack of space at home (Abbs and Marshall, 2020), future consequences of reduced school contact for pupils in state-funded versus privately funded schools (BBC Panorama, 2020) and digital inequalities (Beaunoyer et al., 2020).

In the context of energy savings and potential solutions for mitigating increased energy usage, Figure 3 shows that, without an electric smart meter, there are visual increases from 2019 to 2020 during the instruction period at 12:00 and 21:00, as also seen in Figure 2. The presence of a smart meter, including shower water use displays, can encourage reductions in energy consumption and water consumption (Kappel and Grechenig, Strengers, 2011, Willis et al., 2010). Spending more time at home would increase the accessibility of usage information, thereby facilitating responses to it. While the effects are varied (Strengers, 2011), with maintained engagement with the smart meter depending on several factors, one of the strongest motivations appears to be financial

benefits (Murtagh et al., 2014, Rausser et al., 2018), which would be relevant to homes struggling with the financial effects of locked-down time at home.
More broadly, these changes in utility usage have implications for the supply and pricing of energy and water, and for consideration of the environmental impact from domestic usage. Changes in the temporal demands for domestic energy could affect peak loads and time-of-use or dynamic pricing (Dutta and Mitra, 2017), or encourage off-peak pricing policies for low-income households. This research supports proposals for considering the future sustainability of home domestic energy sources (Tokazhanov et al., 2020), especially given that time spent at home is likely to remain above the levels before the COVID-19 pandemic. In the short-to-medium term, time at home will be impacted by future lockdowns, and record-level job losses (Office for National Statistics, 2020b). In the longer term, increased time at home will continue, with home working predicted beyond COVID-19 restrictions (Office for National Statistics, 2020a, ATT, 2020b, BBC, 2020, CBI, 2020). Energy demand is therefore likely to decrease in offices and increase or shift in domestic settings (BBC News, 2020b).

6. Conclusions

During the time that people were advised (17 March 2020) and then instructed (24 March 2020) to stay at home during the COVID-19 lockdown in 2020 in the UK, gas, electricity and water usage patterns changed, compared with the same time periods in 2019. Gas usage increased following the advice to stay at home, prior to the full lockdown instruction, which may in part reflect a change in the external air temperature. Following the lockdown instruction to stay at home, electricity usage shifted from morning to midday, while evening usage remained the same. Water usage increased overall, and peak usage shifted to at least one hour later in the day. The changes are consistent with people getting up later, spending more time at home and washing more. These findings provide evidence for behaviour change in response to the UK Government's instruction to stay at home during the COVID-19 outbreak, but only weak evidence for people following the advice to stay at home prior to the instructed lockdown.

Electricity and water usage data also provide evidence for such behavioural change during the second and third lockdowns in England, but virtually no evidence of sustained change during the time between these lockdowns. We show meaningful increases in utility usage during the UK COVID-19 lockdown, even though our participants normally tend to spend a high proportion of time at home. Such increases in utility usage will have an economic impact on households or could be unachievable for those already in fuel poverty. These impacts seem particularly likely to affect those in socioeconomically disadvantaged areas, which are already suffering other inequitable impacts from the virus and unintended consequences of the lockdown.

Supplementary Materials:

The following are available online at www.mdpi.com/xxx/s1, Table S1: Sensor information for each type of utility usage and air measurement, Table S2: Descriptive statistics for each relevant covariate, for each group of homes with electricity, gas and water usage measurements in the first lockdown, Table S3: Electricity usage regression model outputs for the first lockdown, Table S4: Gas usage regression model outputs for the first lockdown, Table S5: Water usage regression model outputs for the first lockdown, Table S6: Electricity usage regression model outputs for periods after the first lockdown, Table S7: Water usage regression model outputs for periods after the first lockdown, Table S8: Mean change in electricity usage from 2019 to 2020 in the instruction period of the first lockdown, split by binary categories according to the values of the covariates, Figure S1: Residuals as a function of the values fitted by the interaction regression model containing both periods, for non-transformed and transformed electricity, gas and water usage.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the University of Exeter Research Ethics Committee (eUEBS002996 v2.0 on 16 June 2017 and 5 December 2019).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The majority of Smartline data are available by registering interest at www.smartline.org.uk/main-content-area/data-access (accessed on 8th January 2021).

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Appendix 2 Certificate of ethical approval

UNIVERSITY OF EXETER

COLLEGE OF MEDICINE AND HEALTH

University of Exeter Medical School
Research Ethics Committee

Certificate of Ethical Approval

Research Institute/Centre: European Centre for Environment and Human Health

Title of Project: Examining the impact of cold homes, time spent indoors and individuals' microenvironment on asthma among adults in social housing in Cornwall

Name(s) of Project Research Team member(s): Cheryl Paterson
Dr Tim Taylor
Dr Karyn Morrissey
Dr Richard Sharpe

Project Contact Point: Cheryl Paterson

This project has been approved for the period

From: 22 January 2019

To: 28 February 2020

University of Exeter Medical School
Research Ethics Committee approval reference: Jan19/B/175

Signature: RGarside.

Date: 22 January 2019

Name of Chair
Ruth Garside, PhD

Your attention is drawn of the attached paper "Guidance for Researchers when Ethics Committee approval is given", which reminds the researcher of information that needs to be observed when Ethics Committee approval is given.

Application Reference Number 18/06/175

Appendix 3 Participant cover letter

Date: 22 January 2019

Smartline

Smart wellbeing inspired by the community

Cheryl Paterson

European Centre for Environment and Human Health

University of Exeter Medical School

Knowledge Spa

Royal Cornwall Hospital

Truro

Cornwall

TR1 3HD

Dear Smartline Participant

Please find enclosed details of the second part of the additional study being offered to you as part of the Smartline project. This study is looking at relationships between the indoor environment and respiratory health. Please read through the information carefully prior to taking part. We thank you for your ongoing help and support in our research.

Yours sincerely

Cheryl Paterson

Research Associate/ PhD student

Examining the impact of cold homes, time spent indoors and individuals' microenvironments on respiratory health

CONSENT FORM FOR PARTICIPANTS

VERSION NUMBER [6] : DATE [17.12.18]

Participant Identification Number: UPRN:
Name of Researcher: Cheryl Paterson

Please carefully read and initial the statements below if you are happy to take part in this study. There are two copies enclosed (one for you to keep yourself and one to send back to the researcher).Once completed this form can be returned to the researcher in the pre-paid envelope provided along with your survey responses

1) I confirm that I have read the information sheet dated [17.12.18] version no [6] for the above project. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2) I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without my legal rights being affected.	
3) I understand that relevant sections of the data collected during the study, may be looked at by members of the research team, individuals from the University of Exeter, Cornwall Council, Coastline Housing or Volunteer Cornwall and regulatory authorities where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.	

4) I understand that taking part involves identifiable questionnaire and time use diary responses to be used for the purpose of research and the anonymised data collected will be: • Included in the PhD thesis of the student undertaking the project • Published in an academic publication • Shared with the wider Smartline group • Made available to businesses to support the development of ideas and products to support health and wellbeing issues.	

5) At the end of the project, anonymised data will be stored in a secure repository and may be shared with other researchers for use in future research projects/will be made publicly available as required by the funder	
6) I agree that my contact details can be kept securely and used by researchers from Smartline to contact me about future research projects	
7) I understand that I can decline to answer any particular question(s).	
8) I consent to completing a Mini Asthma Quality of Life survey which includes questions about my respiratory health and other respiratory symptoms I may experience	
9) I consent to completing a time use diary for a period of 2 weeks over two occasions	
10)I am aware I can withdraw from this study at any time without any disadvantage If I withdraw from this study I can still remain in the overall Smartline project.	
11)I understand that if I withdraw from the study, the data collected up to the point of withdrawal may be retained and used by the project, but my identity will be protected (the data will be anonymised)	

.... ………………………….. ....

(Printed name of participant) (Signature of participant) (Date)

Cheryl Paterson 7.8.19

(Printed name of researcher taking consent) (Signature of researcher) (Date)

This project has been reviewed and approved by the University of Exeter Medical School Research Ethics Committee

***UEMS REC REFERENCE NUMBER:* Jan19/B/175**

When completed: 1 copy for participant; 1 copy for researcher/project file

European Union
European Regional Development Fund

Smartline
Smart wellbeing inspired by the community

Examining the impact of cold homes, time spent indoors and individuals' microenvironments on respiratory health.

INFORMATION SHEET FOR PARTICIPANTS VERSION NUMBER [6] : DATE [17.12.18]

Thank you for showing an interest in this project. Please read this information sheet carefully before deciding whether or not to participate.

What is the aim of the project?

This is an additional study being undertaken as part of the Smartline project, and it aims to explore any potential relationships between housing and indoor air pollution on respiratory health.

This study is being undertaken as part of the requirements for the Postgraduate Doctor of Philosophy (PhD).

Description of participants required.

This study is open to all participants who are already part of Smartline and over the age of 18 years old.

What will participants be asked to do?

Should you agree to take part in this project, you will be asked to complete a time use diary for 7 consecutive days. This will happen on two occasions: once in the summer and once in the winter (February/March 2019 and September 2019).

We ask that this is filled in on the diary provided in this pack.

The time use diary will require you to record how much time you spend inside your house at 4 different time intervals during the day (morning, afternoon, evening, night). As the time use diary will require you to record your activities every day, to reduce any fatigue or disruption to your day, this can be filled in once per day and should only take a minute or two.

If you suffer from asthma, on the last day of the time use diary, you will also be asked to complete an additional Mini Asthma Quality of Life survey that asks about your asthma and other respiratory symptoms you may have had over the past 2 weeks, this is a short survey which should take no more than a few minutes of your time to complete. It is anticipated that there would very little risk of any harm or discomfort to you as a result of taking part in this study.

Time commitment

It is estimated that those taking part in this study will need around 5 minutes per day to fill out the time use diary each day for 7 days, over two occasions (summer/winter). The additional survey will take around 5 minutes to complete and will only need to be completed once on each occasion (summer/winter).

Can participants change their mind and withdraw from the Project?

Participation in the study is completely voluntary and participants should be aware that this study is an additional extra to the Smartline project. If for any reason you no longer wish to be involved in this extra study, you may withdraw from taking part at any time without having to give a reason and without any disadvantage to yourself of any kind, withdrawal from this study will not affect your participation in the Smartline project in any way. Should you wish to withdraw any information you have already provided us up to the time of withdrawal will still be used as it will be fully anonymised and therefore no longer linked to your name. The anonymised information will be securely stored at the University of Exeter and destroyed in 2032 as required by our funder. If you wish to withdraw simply email or phone Cheryl Paterson or Dr Tim Taylor, you will not be required to provide any reason for your withdrawal.

What data or information will be collected and what use will be made of it?

The University of Exeter processes personal data for the purposes of carrying out research in the public interest. The University will endeavor to be transparent about its processing of your personal data and this information sheet should provide a clear explanation of this. If you do have any queries about the University's processing of your personal data that cannot be resolved by the research team, further information may be obtained from the University's Data Protection Officer by emailing dataprotection@exeter.ac.uk or at www.exeter.ac.uk/
data protection

For this study information about how you spend your time at 4 time points in the day (morning, afternoon, evening, night) will be collected via a time use diary (see attached). Also, information will be collected about any asthma symptoms (if you suffer from asthma) you might have experienced over the past 2 weeks via a short questionnaire (attached). After the survey, your information will be anonymised and processed and coded with study numbers so no names will be retained. The anonymised and processed data will be stored in a repository and destroyed in 2032 as required by the funder. Only the research team will have access to a list containing identifiable information such as your name, address, phone number, study number,
so we can contact you during the study if needed. This list will be securely stored on the university

server with access limited to the core research team. This information will be destroyed on completion of the larger Smartline project in February 2020 in accordance with University of Exeter's document retention polices.

To comply with the law, the project requires your permission to collect and share the following ***Personal information****. You are able to withdraw your consent at any time.*

Name

Address DoB

Gender

Postcode

General asthma survey questions Activity

record

The study will collect some of this information from the information you have already told us about during the initial baseline surveys. This information and any further information you give us (time use diary/Mini asthma quality of life survey) will then be put together and studied to identify patterns and help with Research.

In order to do this, the **personal information** you provide will be shared with a small number of people from Coastline Housing, The University of Exeter, Volunteer Cornwall and Cornwall Council but will not be shared with anyone else.

Your information will then be **anonymized** so you will not be able to be identified. The information will then be made available to businesses to support the development of ideas and products to support Health and wellbeing issues.

Your Personal information will not be shared with these businesses.

The results of this project may be published but any data included will not be individually identifiable. Should you wish, you will be provided with a summary of the study's findings.

The personal data collected will be securely stored so that only those mentioned above will be able to gain access to it.

After the project is finished, the anonymised data will be stored in a secure repository and may be analysed by other researchers/will be publicly available as required by the funder.

European Union
European Regional Development Fund

Smartline
Smart wellbeing inspired by the community

Why me?

As you are already a Smartline participant and a resident in either Camborne, Poole, Illogan or Redruth we are approaching you to see if you would be interested in taking part in this addition- al study.

When should I start?

We would like you to start your time use diary as soon as possible, once you have logged your activities for 7 days please return in the stamped addressed envelope provided. We would like all responses returned by 9th September 2019.

What if participants have any questions?

If you have any questions about our project, either now or in the future, please feel free to contact either:-

Ms Cheryl Paterson
University of Exeter
Telephone Number: *01872 258167*
Email: c.b.paterson@exeter.ac.uk

or

Dr Tim Taylor
University of Exeter
Telephone Number: 01872 258146
Email:timothy.j.taylor@exeter.ac.uk

Complaints

If you have any complaints about the way in which this study has been carried out please con- tact the Chair of the University of Exeter Medical School Research Ethics Committee:-

Ruth Garside, PhD
Chair of the UEMS Research Ethics Committee
Email: uemsethics@exeter.ac.uk

This project has been reviewed and approved by the University of Exeter Medical School Research Ethics Committee

UEMS REC REFERENCE NUMBER: Jan19/B/175

SMARLINE SURVEY
VERSION NUMBER 12: DATE August 2017

Thank you for agreeing to participate in the SMARTLINE project. We are excited about this opportunity to work with you.

The questions below are intended to help us to get to know you, your household and to give us some information about your health, wellbeing and community before the sensors are installed.

This form is to be completed on behalf of the household with a household member who can take responsibility for the household (the person named on the tenancy agreement with Coastline, or who pays the bills).

We hope that you will answer all the questions. However, if there are any questions you don't want to answer we can select the 'Not answered' box and continue with the rest of the questionnaire.

The questionnaire should take approximately 30-60 mins to complete, we are very grateful for you giving us your valuable time. The data you provide will not be shared outside the project team without having any identifying information removed (anonymised).

Personal details

1. First Name

2. Middle name

3. Family name/Surname

4. Address:

   Unique property reference number (from Coastline Housing)

5. Postcode:

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

Household

6. Please tell us the number of people in your household (people who sleep at the house regularly)

D Not answered

	Male	Female	Other
Child (0-12 years)			
Adolescent (13-17 years)			
Adult (18-65 years)			
Older adult (65+ years)			

7. What is your relationship status?

D Not living in a long-term relationship, marriage or civil partnership (single, divorced, widowed or separated)

D Living with spouse/partner in a long-term relationship, marriage, or civil partnership

D Not answered

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

8. Which of these pieces of technology do you have in your home and are they connected to the internet? (*select all that apply*)

D	Not answered		
D	Internet connection? Television		
D		connected to the internet?	D
D	TV decoder (e.g. Sky, Virgin Media)	connected to the internet?	D
D	Mobile phone	connected to the internet?	D
D	Computer	connected to the internet?	D
D	Tablet	connected to the internet?	D
D	Wearable technology (e.g. fitbit)	connected to the internet?	D

9. Does your home have smart meters for your energy/water supply? (*select all the apply*)

D No D Electricity D Gas D Water D Not answered

10. Please tick all the rooms that you have in your home;

Not answered	Kitchen	Dining room	Utility room	Bathroom	Living room	Bedr/m 1 (main)	Bedr/m 2	Bedr/m 3	Bedr/m 4	Other room, please specify below
D	D	D	D	D	D	D	D	D	D	D

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

11. Please tick all the rooms that are carpeted and/or have a rug in your home;

Not answered	Kitchen	Dining room	Utility room	Bathroom	Living room	Bedr/m 1 (main)	Bedr/m 2	Bedr/m 3	Bedr/m 4	Other room, (Already specified)
c	c	c	c	c	c	c	c	c	c	c

12. How many times a month do you vacuum clean your home? ______________________________ c Not answered

13. Do you have any pets that live indoors, and if so how many? (*select all that apply*)

c No (**Skip to question 15**) c Not answered

c Dog – how many? ____________

c Cat – how many? ____________

c Bird – how many? ____________

c Other – what type? ______________________, how many? ________

14. If yes, please select which rooms in your home your pets stay in?

Not answered	Kitchen	Dining room	Utility room	Bathroom	Living room	Bedr/m 1 (main)	Bedr/m 2	Bedr/m 3	Bedr/m 4	Other room, (Already specified)
c	c	c	c	c	c	c	c	c	c	c ____________

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

15. Which methods do you use to dry clothes indoors?

Not answered	Clothes hanger	Clothes horse	Vented/ condenser dryer	Unvented dryer	On the radiator / heater	Other indoors, please specify below	Elsewhere (i.e. not indoors)
c	c	c	c	c	c	c	c

16. In which of the following rooms do you use heating through the winter?

Not answered	Kitchen	Dining room	Utility room	Bathroom	Living room	Bedr/m 1 (main)	Bedr/m 2	Bedr/m 3	Bedr/m 4	Other room, (Already specified)
c	c	c	c	c	c	c	c	c	c	c

17. Do you avoid turning on the heating because of cost? c Yes c No c Not answered

18. Do you think your home is adequately heated? c Yes c No c Not answered

19. Does your home have visible mould patches? c Yes c No **(Skip to question 22)** c Not answered

20. What is the average size of the mould?

Not answered	One or two spots (..........)	Several small patches (postage stamp)	Bigger than a post card	Up to an arm's length (1m)	Bigger than an arm's length
c	c	c	c	c	c

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

21. Which of the following rooms have mould patches?

Not answered	Kitchen	Dining room	Utility room	Bathroom	Living room	Bedr/m 1 (main)	Bedr/m 2	Bedr/m 3	Bedr/m 4	Other room, , (Already specified)
c	c	c	c	c	c	c	c	c	c	c ______________-_

22. Has your home suffered from a mouldy/musty odour in last 12 months?

c Yes c No **(Skip to question 24)** c Not answered

23. Which rooms were affected?

Not answered	Kitchen	Dining room	Utility room	Bathr/m	Living room	Bedr/m 1 (main)	Bedr/m 2	Bedr/m 3	Bedr/m 4	Other room, please specify
c	c	c	c	c	c	c	c	c	c	c

24. Do you think damp/mould is impacting your or your family's health? c Yes c No c Not answered

25. Which of the following rooms do you regularly open windows (e.g. more than once per week) to ventilate your home?

Not answered c	Kitchen	Dining room	Utilit y room	Bathroom	Living room	Bedr/m 1 (main)	Bedr/m 2	Bedr/m 3	Bedr/m 4	Other room, (Already specified)
Open window	☐	☐	☐	☐	☐	☐	☐	☐	☐	c
Not able to be opened	☐	☐	☐	☐	☐	☐	☐	☐	☐	c
Room has no window	☐	☐	☐	☐	☐	☐	☐	☐	☐	c

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

26. Do you ventilate your home to minimise damp and mould? c Yes c No c Not answered

27. Do you use the extractor fan when cooking? c Yes c No c Not answered

28. Do you use the extractor fan when having a bath/shower? c Yes c No c Not answered

29. Do you avoid ventilating your home to save heat / energy? c Yes c No c Not answered

30. Do you use? c Dehumidifier(s) c Fan(s) c Air conditioning unit(s)

31. On average, about how many hours per day do you/ your partner spend indoors at home during an average **weekend** day (Saturday or Sunday including sleeping)?

You__________ Your Partner______________ c Not answered

32. On average, about how many hours per day do you/your partner spend indoors at home during an average **week** day (Monday – Friday including sleeping)?

c Not answered You__________ Your Partner______________

33. Do you smoke? *Please select the most applicable statement* c Not answered

c Never

c Used to smoke (*Please also tick the quantity you used to smoke*)

c Smoke tobacco less than 5 times per day

c Smoke tobacco 5-15 times per day

c Smoke tobacco more than 15 times per day

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

34. Does your partner smoke? *Please select the most applicable statement*

c Never

c Used to smoke (*Please also tick the quantity you used to smoke*)

c Smoke tobacco less than 5 times per day

c Smoke tobacco 5-15 times per day

c Smoke tobacco more than 15 times per day

c Not answered

35. Does anybody smoke inside your home?

c Yes c No c Not answered

36. Does anybody 'vape' (use e-cigarettes) inside your home?

c Yes c No c Not answered

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

Community

37. This question contains eight statements about your relationship with your community. Please select how much you agree or disagree with each statement.

Not answered		Strongly agree	Agree	Neither agree / nor disagree	Disagree	Strongly disagree
c	I visit my friends in their homes	☐	☐	☐	☐	☐
c	The friendships and associations I have with other people in my neighbourhood mean a lot to me	☐	☐	☐	☐	☐
c	If I need advice about something I could go to someone in my neighbourhood	☐	☐	☐	☐	☐
c	I believe my neighbours would help in an emergency	☐	☐	☐	☐	☐
c	I borrow things and exchange favours with my neighbours	☐	☐	☐	☐	☐
c	I would be willing to work together with others on something to improve my neighbourhood	☐	☐	☐	☐	☐
c	I rarely have a neighbour over to my house to visit	☐	☐	☐	☐	☐
c	I regularly stop and talk with people in my neighbourhood	☐	☐	☐	☐	☐

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

38. In the last 12 months, that is, since [DATE ONE YEAR AGO], have you/your partner given unpaid help (excluding donating money or anything related to you work) to any groups, clubs or organisations?

c No **(Skip to question 41)** c Not answered

c Yes *please specify type of groups, clubs or organisations e.g. community group school/charity/sports/environment/campaigning/political party*

39. What sort of unpaid help have you/your partner given to groups, clubs or organisations in the last 12 months (e.g. fund raising, committee membership, campaigning, befriending etc.)? *Please specify*

40. Over the last 12 months, how often have you/your partner helped [this/these] group(s), club(s) or organisation(s)?

c Not answered

c At least once a week

c Less than once a week but at least once a month

c Less often than once a month

41. In the last 12 months, that is, since [DATE ONE YEAR AGO], have you/your partner helped or done any unpaid work for someone who was not a relative? (For example: kept in touch to make sure they are alright, given them a hand round the house or garden, helped them get out and about, given advice or help with forms or finances, looked after children or pets)

c No **(Skip to question 43)** c Not answered

c Yes *please describe types*

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

42. Over the last 12 months, that is, since [DATE ONE YEAR AGO], about how often have you/your partner done [this/these things]?

c At least once a week　　c Less than once a week but at least once a month　　c Less often than once a month

c Not answered

43. Do you look after, or give help or support to family members, friends, neighbours or others because of either:

- long-term physical or mental ill-health/disability?
- Problems related to old age?
- Do not count anything you do as part of paid employment. Please choose only one of the following:

c No

c Yes, 1-2 hours per week

c Yes, 3-5 hours per week

c Yes, 5-10 hours per week

c Yes, 10-19 hours per week

c Yes, 20-34 hours per week

c Yes, 35 or more hours per week

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

Wellbeing

44. Below are some statements about feelings and thoughts.
Please tick the box that best describes your experience of each over the **last 2 weeks**

Not answered	STATEMENTS	None of the time	Rarely	Some of the time	Often	All of the time
c	I've been feeling optimistic about the future	c	c	c	c	c
c	I've been feeling useful	c	c	c	c	c
c	I've been feeling relaxed	c	c	c	c	c
c	I've been dealing with problems well	c	c	c	c	c
c	I've been thinking clearly	c	c	c	c	c
c	I've been feeling close to other people	c	c	c	c	c
c	I've been able to make up my own mind about things	c	c	c	c	c

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

SF-12v2® HEALTH SURVEY (FOUR-WEEK RECALL) SCRIPT FOR INTERVIEW ADMINISTRATION

This first question is about your health now. **Please try to answer as accurately as you can.**

1. **In general, would you say your health is . . .** *[READ RESPONSE CHOICES]*

(Circle one number)

Excellent 1

Very good.. 2

Good 3

Fair 4

or Poor 5

Now I'm going to read a list of activities that you might do during a typical day. **As I read each item, please tell me if your health now limits you a lot, limits you a little, or does not limit you at all in these activities.**

2a. **. . . moderate activities, such as moving a table, pushing a vacuum cleaner, bowling, or playing golf. Does your health now limit you a lot, limit you a little, or not limit you at all?** *[READ RESPONSE CHOICES ONLY IF NECESSARY]*

[IF RESPONDENT SAYS S/HE DOES NOT DO ACTIVITY, PROBE: Is that because of your health?]

(Circle one number)

Yes, limited a lot.. 1

Yes, limited a little 2

No, not limited at all.. 3

2b. .... **climbing several flights of stairs. Does your health now limit you a lot, limit you a little, or not limit you at all?** *[READ RESPONSE CHOICES ONLY IF NECESSARY]*

[IF RESPONDENT SAYS S/HE DOES NOT DO ACTIVITY, PROBE: Is that because of your health?]

(Circle one number)

Yes, limited a lot.. 1

Yes, limited a little 2

No, not limited at all.. 3

The following two questions ask you about your physical health and your daily activities.

3a. **During the past 4 weeks, how much of the time have you accomplished less than you would have liked as a result of your physical health?** *[READ RESPONSE CHOICES]*

(Circle one number)

All of the time 1

Most of the time.. 2

Some of the time 3

A little of the time.. 4

or None of the time 5

3b. **During the past 4 weeks, how much of the time were you limited in the kind of work or other regular daily activities you do as a result of your physical health?**
[READ RESPONSE CHOICES]

(Circle one number)

All of the time 1

Most of the time.. 2

Some of the time 3

A little of the time.. 4

or None of the time 5

The following two questions ask about your emotions and your daily activities.

4a. **During the past 4 weeks, how much of the time have you accomplished less than you would have liked as a result of any emotional problems, such as feeling depressed or anxious?** *[READ RESPONSE CHOICES]*

(Circle one number)

All of the time 1

Most of the time.. 2

Some of the time 3

A little of the time.. 4

or None of the time 5

4b. **During the past 4 weeks, how much of the time did you do work or other regular daily activities less carefully than usual as a result of any emotional problems, such as feeling depressed or anxious?** *[READ RESPONSE CHOICES]*

(Circle one number)

All of the time 1

Most of the time.. 2

Some of the time 3

A little of the time.. 4

or None of the time 5

5. **During the past 4 weeks, how much did pain interfere with your normal work, including both work outside the home and housework? Did it interfere..***[READ RESPONSE CHOICES]*

(Circle one number)

Not at all.. 1

A little bit 2

Moderately 3

Quite a bit.. 4

or Extremely 5

The next questions are about how you feel and how things have been with you during the past 4 weeks.

As I read each statement, please give me the one answer that comes closest to the way you have been feeling; is it all of the time, most of the time, some of the time, a little of the time, or none of the time?

6a. **How much of the time during the past 4 weeks . . . have you felt calm and peaceful?** *[READ RESPONSE CHOICES]*

(Circle one number)

All of the time 1

Most of the time.. 2

Some of the time 3

A little of the time.. 4

or None of the time 5

6b. **How much of the time during the past 4 weeks . . . did you have a lot of energy?**
[READ RESPONSE CHOICES]

(Circle one number)

All of the time 1

Most of the time.. 2

Some of the time 3

A little of the time.. 4

or None of the time 5

6c. **How much of the time during the past 4 weeks.................................. have you felt downhearted and low?** *[READ RESPONSE CHOICES ONLY IF NECESSARY]*

(Circle one number)

All of the time 1

Most of the time..2

Some of the time 3

A little of the time..4

or None of the time 5

7. **During the past 4 weeks, how much of the time has your physical health or emotional problems interfered with your social activities like visiting with friends or relatives? Has it interfered** *[READ RESPONSE CHOICES]*

(Circle one number)

All of the time 1

Most of the time.. 2

Some of the time 3

A little of the time.. 4

or None of the time 5

Health [Questions 45-50 are from the Twelve Item Short Form Survey (SF-12v2[TM]) copyright Optum]

51. Compared to one year ago how would you rate your health in general now?

Not answered	Much better	Somewhat better	About the same	Somewhat worse	Much worse
D	D	D	D	D	D

52. In the last 12 months, have either you/your partner stayed in a hospital due to ill-health?

	Yes	No	Not answered	(if both No/NA Skip to question 54)
You	D	D	D	
Partner	D	D	D	

53. If yes, what was your/your partner's health concern / problem?

You ____________________

Your partner ____________________

D Not answered

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

54. Have you / your partner had any of the following health problems?

Not Answered		You Yes	No	Your partner Yes	No
D	Have you/your partner **ever** had **wheezing or a dry cough** at any time in the past, but not including having a cold or chest infection?	D	D	D	D

If not answered or the answer is no for both you and your partner, please skip to question 55

D	Have you/your partner had wheezing or dry coughing in the chest in the last **12 months**?				
D	In the last **12 months** have you/your partner had over 3 wheezing or coughing attacks?				
D	In the last **12 months**, has sleep been disturbed due to wheezing or coughing?				
D	In the last **12 months**, has wheezing/coughing ever been severe enough to limit your/your partner's speech between breaths?				
D	In the last **12 months**, have you/your partner's chest sounded wheezy or coughed during or after exercise?				
D	In the last **12 months**, have you/your partner had a dry cough at night, apart from a cough associated with a cold or a chest infection?				

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

55. In the last 12 months have you/your partner suffered any of the following health problems and seen a doctor? (No/NA skip to question 57)

Not answered		You Yes	You No	Your partner Yes	Your partner No
D	Asthma	D	D	D	D
D	Allergy Please specify	D	D	D	D
D	Chronic bronchitis, emphysema or COPD (Chronic Obstructive Pulmonary Disease) please specify	D	D	D	D

56. If you ticked yes to question 55, do you take medication for asthma, allergy or emphysema?

You:	D Asthma	D Allergy	D Emphysema/COPD	D Not answered
Partner:	D Asthma	D Allergy	D Emphysema/COPD	D Not answered

57. Think about any physical activity you engage in. This may include sport, exercise, and brisk walking or cycling for recreation or to get to and from places, please include housework or physical activity that may be part of your job.

During the last 7 days, on how many days have you done a total of 30 minutes or more of physical activity, which was enough to raise your breathing rate? **days per week** D Not answered

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

58. Now think about walking in particular, which can include walking for recreation or to get to and from places, please include walking that may be part of your job.

During the last 7 days, on how many days did you walk for at least 10 minutes at a time?

days per week D Not answered

59. During the **last 7 days**, about how much time did you spend **sitting** on a **week day**?

hours **minutes per day** D Not answered

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

Further Personal Details

60. Gender: Male D Female D Other D Not answered D

61. Date of birth: DD/MM/YYYY Not answered D

62. What is your national identity and ethnic group? (*please select all that apply*) D Not answered

D Cornish	D British	D White
D English	D Irish	D Mixed/multiple ethnic groups
D Welsh	D Any other national identity	D Asian
D Scottish		D Black
D Northern Irish		D Any other ethnic group

63. Which levels of education and/or qualifications have you completed? (please *select all that apply*)

D Primary education (4-11 years of age)

D Secondary education (11-16 years of age)

D Secondary/further education (16-18 years of age)

D Undergraduate university education

D Postgraduate university education

D Other (please specify) ______________________________

D None of the above

D Not answered

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

64. Last week, were you? (include any paid work, including casual or temporary work, even if only for one hour)

D working as an employee?

D self-employed or freelance?

D working paid or unpaid for your own or your families business

D away from work ill, on maternity leave, on holiday or temporarily laid off?

D doing any other kind of paid work? ____________________

D on a government sponsored training scheme?

D waiting to start a job you have already obtained.

D actively looking for work

D retired (whether receiving a pension or not)?

D a student?

D looking after home or family?

D long-term sick or disabled?

D none of the above

D Not answered

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

65. Have you ever worked? (only ask if not working from answer above)

D Yes, write in the year that you last worked ___________________________

D No (Skip to end of questionnaire)

D Not answered (Skip to end of questionnaire)

66. What is or was your job title? ____

D Not answered

67. Which of these best describes your most recent job?

D Managerial and professional occupations (e.g. Lawyers, Architects, Medical doctors, Chief executives, Economists, Social workers, Nurses, Journalists, Retail Managers, Teachers)

D Intermediate occupations (e.g. Armed Forces up to Sergeant, Paramedics, Nursery Nurses, Police up to Sergeant, Bank staff, Farmers, Shopkeepers, Taxi drivers, Driving instructors, Window cleaners,)

D Routine and manual occupations (e.g. Mechanics, Chefs, Train drivers, Plumbers, Electricians, Traffic wardens, Receptionists, Shelf-stackers, Care workers, Telephone Salespersons, Bar staff, Cleaners, Labourers, Bus drivers, Lorry drivers)

D Not answered

END OF THE QUESTIONNAIRE

Thank you for your time

For office use only:

Date received:		Date recorded on IT system:	
Household ID:		Participant ID:	

European Union
European Regional Development Fund

Smartline
Smart wellbeing inspired by the community

Dear Participant

This is your time use diary. Please complete this diary **each day** for one week.

Please indicate how much time you spent inside your home today during the morning, afternoon, evening and night. Time spent indoors includes any activity inside ***your own*** home, this **does not** include time spent in other houses/buildings or any time spent travelling inside a vehicle.

We would like you to start the diary as soon as possible. Once you have completed the diary please return to the researcher in the stamped addressed envelope provided by 22nd March. Thank you once again for your continued support.

Start Date:

Day of the Week	**Morning** (before midday)		**Afternoon** (midday-5pm)		**Evening** (5pm-11pm)		**Night** (11pm-6am)	
How much time did you spend inside your home?	**Hours**	**Minutes**	**Hours**	**Minutes**	**Hours**	**Minutes**	**Hours**	**Minutes**
Monday								
Tuesday								
Wednesday								
Thursday								
Friday								
Saturday								
Sunday								

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Appendix 5 Supplementary statistical tables

Table 21 Overview of the relationship between time spent indoors and asthma.

	Time Spent Inside the Home							
	Winter				Summer			
Health Outcome	Weekdays		Weekends		Weekdays		Weekends	
		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination		Visible Fungal Contamination
Overall Score	-.470	-.427	-.347	-.461	-.061	-.378	-.320	-.436
F-ratio	(1,21) 5.96	(2, 20) 6.42	(1,24) 3.07	(2, 23) 5.53	(1, 25) 0.09	(2, 24) 1.87	(1, 25) 2.87	(2, 24) 4.91
P-value	0.024*	0.029*	0.092	0.013*	0.761	0.069	0.103	0.019*
95% Confidence Interval	-1.003 to -.080	-2.972 to -.183	-.470 to .038	-3.080 to -.398	-.491 to .363	-2.987 to .117	-.503 to .049	-2.830 to -.280
Coefficient	-.54	-1.578	-.21	-1.739	-.063	-1.434	-.227	-1.555
Standard Error	.221	.668	.123	.648	.207	.752	.134	.617
R^2	0.22	0.39	0.11	0.32	0.00	0.13	0.10	0.29
Adj. R^2	0.18	0.33	0.07	0.27	-0.03	0.06	0.06	0.23
Activity Limitation	Insufficient data	Insufficient data	Insufficient data	Insufficient data	-.509	-.276	-.411	-.225
F-ratio	-	-	-	-	(1, 21) 7.37	(2, 20) 4.94	(1, 25) 5.11	(2, 24) 3.38
P-value	-	-	-	-	0.013*	0.162	0.033*	0.227
95% Confidence Interval	-	-	-	-	-.996 to -.132	-2.382 to .425	-.472 to -.021	-2.098 to .523
Coefficient	-	-	-	-	-.564	-.978	-.247	-.787
Standard Error	-	-	-	-	.207	.673	.109	.635

R^2	-	-	-	-	0.25	0.33	0.16	0.21
Adj. R^2	-	-	-	-	0.22	0.26	0.13	0.15
Symptoms	-.365	-.484	-.044	-.469	.113	-.287	- .278	-.334
F-ratio	(1, 21) 3.23	(2, 20) 5.40	(1, 25) 0.05	(2, 24) 3.36	(1, 24) 0.31	(2, 23) 1.06	(1, 24) 2.02	(2, 23) 2.64
P-value	0.087	0.018*	0.827	0.016*	0.582	0.192	0.168	0.093
95% Confidence Interval	-.828 to .060	-2.945 to .317	- -.277 to .224	-2.998 to -.334	-.339 to .591	-2.972 to .631	-.527 to .097	-2.869 to .235
Coefficient	-.383	-1.631	-.026	-1.666	.125	-1.170	-.215	-1.316
Standard Error	.213	.629	.121	.645	.225	.871	.151	.750
R^2	0.13	0.35	0.00	0.21	0.01	0.08	0.07	0.18
Adj. R^2	0.09	0.28	-0.03	0.15	-0.02	0.00	0.03	0.11
Environmental Stimuli	.007	-.465	-.251	-.472	-.261	-.447	-.199	-.427
F-ratio	(1, 25) 0.00	(2, 24) 2.97	(1, 25) 1.69	(2, 24) 4.75	(1, 21) 1.55	(2, 20) 3.41	(1, 24) 1.00	(2, 23) 3.26
P-value	0.968	0.023*	0.205	0.012*	0.228	0.037*	0.328	0.030*
95% Confidence Interval	-.451 to .469	-3.504 to -.290	-.507 to .114	-3.269 to -.446	-.823 to .207	-3.261 to -.109	-.403 to .140	-3.137 to -.174
Coefficient	.008	-1.897	-.196	-1.858	-.308	-1.685	-.131	-1.656
Standard Error	.223	.778	.151	.683	.247	.755	.131	.716
R^2	0.00	0.19	0.06	0.28	0.06	0.25	0.03	0.22
Adj. R^2	-0.03	0.13	0.02	0.22	0.02	0.17	-0.00	0.15
Emotional Functioning	.060	-.436	-.229	-.465	-.317	-.333	-.243	-.345
F-ratio	(1, 25) 0.09	(2, 24) 2.60	(1, 25) 1.39	(2, 24) 4.36	(1, 20) 2.24	(2, 19) 2.45	(1, 24) 1.51	(2, 23) 2.47

P-value	0.764	0.033*	0.250	0.014*	0.150	0.131	0.232	0.083
95% Confidence Interval	-.386 to .519	-3.356 to -.150	-.481 to .131	-3.187 to -.393	-.811 to .133	-2.755 to .385	-.400 to .101	-2.697 to .176
Coefficient	.066	-1.753	-.175	-1.790	-.338	-1.185	-.149	-1.260
Standard Error	.219	.776	.148	.677	.226	.750	.121	.694
R^2	0.00	0.17	0.05	0.26	0.10	0.20	0.05	0.17
Adj. R^2	-0.03	0.10	0.01	0.20	0.05	0.12	0.01	0.10