Can air quality feedback be an effective tool to encourage parents and caregivers to "take smoking right outside"?

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Abstract

Second-hand tobacco smoke (SHS) is a serious cause of ill-health, particularly for children. Smoking indoors leads to high concentrations of SHS and behaviour change interventions have been developed to promote smoke-free homes for children's benefit. Air-quality feedback – giving parents and caregivers personalised information on the effect of smoking on air pollution at home – has been used in several trials with positive results.

A qualitative study was conducted comparing attitudes to SHS and outdoor air pollution. Focus group participants and internet commenters viewed outdoor pollution as a serious health risk, suggesting that comparing SHS to outdoor air pollution could be a promising avenue for increasing awareness about the risks from SHS and promoting behaviour change.

An air-quality feedback intervention using a low-cost particle counter was developed and piloted, with lessons from this feasibility study used to develop an innovative intervention using mHealth techniques and remote monitoring for use in a larger trial in four centres around Europe. This study of 68 homes resulted in a statistically significant decline of 17% in measured SHS over the intervention period, but resulted in only eight participants making their homes fully smoke-free.

An algorithm was developed to detect smoking in homes using low-cost particulate matter sensors. When tested with data from 144 homes in Scotland, 135 were correctly classified (113 smoking homes, 22 non-smoking homes). Similar predictive rates were achieved in a study of 16 homes in Israel demonstrating that it could be used in different environmental conditions. The algorithm did not enable detection of the periods when smoking occurred in homes.

Air-quality feedback can play a role in changing smoking behaviour but may require careful targeting at those with the capability and opportunity to make the change. Future research could use these techniques more widely as part of an "endgame" approach to tobacco control.

Contents

List of figures

List of tables

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1 Introduction

1.1 Smoking tobacco

Humans first discovered the tobacco plant in the Americas, where its smoke was valued as an element in religious ritual and for its relaxant properties [1]. Following the European discovery and invasion of the new world, merchants imported the plant for the enjoyment of the fashionable and wealthy.

Even in the early years of tobacco use in Europe, some expressed concerns about the health effects of this exciting new pastime. James VI of Scotland famously wrote in 1604 that smoking was a *'custome lothsome to the eye, hatefull to the Nose, harmefull to the brains, daungerouse to the Lungs, and in the blacke stinking fume thereof, neerest resembling the horrible Stigian smoke of the pit that is bottomelesse'* [2].

Despite its lack of royal approval, smoking only grew in popularity over the following centuries. By the mid-18th century tobacco was a major cash crop in many parts of America, including the plantations of US presidents George Washington and Thomas Jefferson, where slaves were forced to grow and pick it [1].

Figure 1 - an advertisement for a Canadian "smokes campaign" in WW1. Image courtesy of Stanford University Research into the Impact of Tobacco Advertising (SRITA) [http://tobacco.stanford.edu]

The cruel history of the crop did not dent its popularity. Tobacco even gained the coveted approval of the monarch, when Queen Victoria awarded the Royal Warrant to the Gallaher tobacco company in 1877 [3]. The development of new forms of rot-resistant tobacco and machines to produce cigarettes in the late 1800s made it easier than ever to sell easy-to-smoke tobacco to the public [4].

During the First World War, major campaigns raised money to send tobacco to soldiers (Figure 1), and cigarettes (previously widely perceived as a feminine way to smoke) were included in military rations [5]. Cigarette smoking became more and more common until, by 1950, around 80% of men and 40% of women in the UK smoked [6] - and the vast majority of smokers smoked cigarettes.

1.2 Smoking and health

As tobacco smoking in Europe and the United States reached its height following the First World War, concerns about the health risks of smoking were becoming more pronounced. The first epidemiological evidence of a link between tobacco smoking and lung cancer was presented in Germany in 1929 [7], but the discovery made little impact internationally.

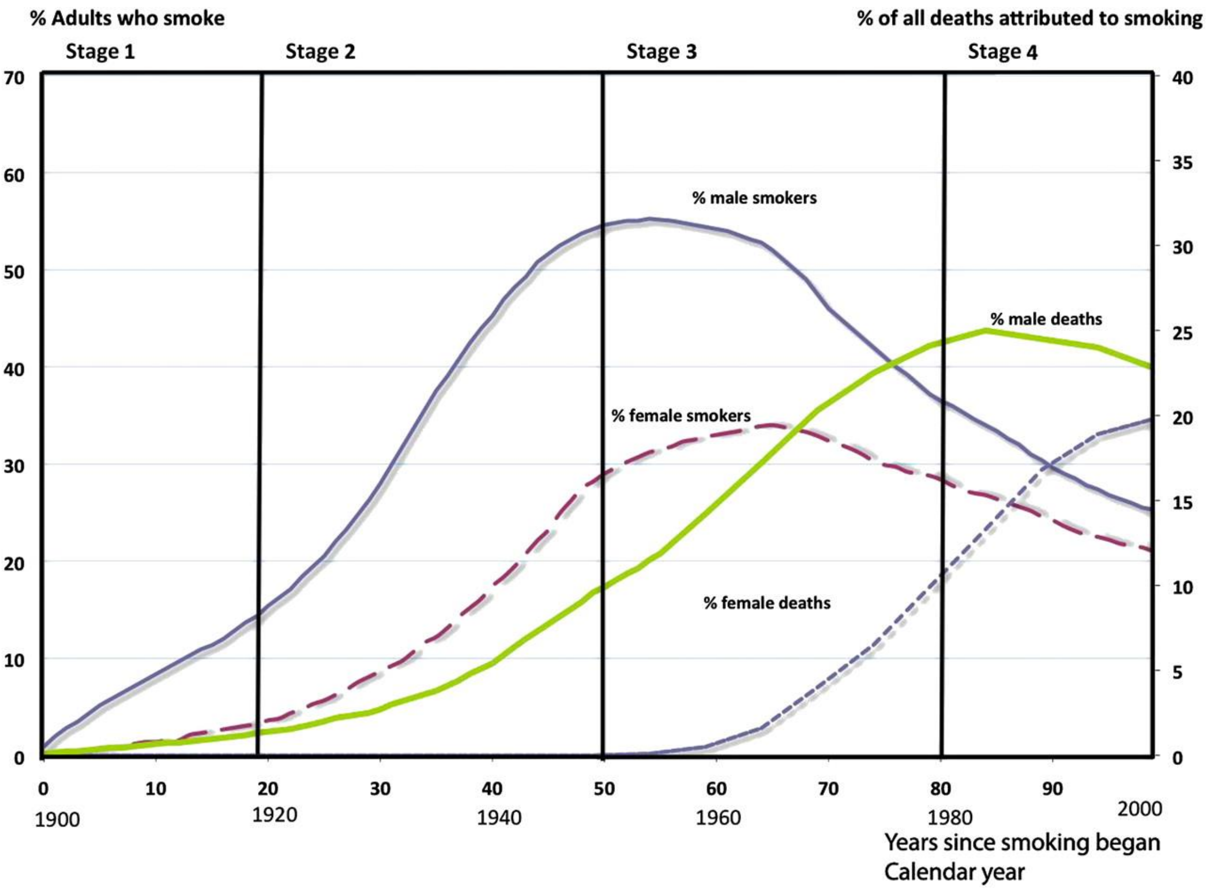
After the second world war, a wave of concern followed the publication of Doll & Hill’s 1950 study “Smoking and Carcinoma of the Lung” [8], which demonstrated the clear epidemiological link between smoking status and the odds of developing lung cancer. The publication of this paper, and press articles about it such as the US Readers’ Digest’s “Cancer By The Carton” [9], led to a popular backlash against tobacco smoking. The tobacco industry responded with a full-page advert in major US newspapers. That advert, titled “A Frank Statement to Cigarette Smokers” [10], cast doubt on the scientific evidence that smoking caused cancer with misleading and incorrect statements – a pattern the industry would continue to use as more evidence of the harm of smoking accumulated.

Over the following decades, epidemiological evidence linked smoking to diseases such as heart disease, chronic obstructive pulmonary disease (COPD) [11] and diabetes [12]. Although tobacco industry efforts continued to delay measures to restrict and reduce the sale of cigarettes [5], survey data showed that the deleterious health effects of tobacco became more widely recognised in developed countries such as the US and UK [13].

1.3 The tobacco epidemic

Smoking behaviour has been observed to follow a consistent pattern following introduction to a country, often referred to as the tobacco epidemic model [14]. This reflects changes in the socio-economic and demographic character of smoking in a population.

Figure 2 - the stages of the tobacco epidemic, as presented in Figure 1 from Thun et al, 2012 [15]



As it is described in the first publication proposing the epidemic model [14] (and shown in Figure 2), the epidemic begins with stage one, where smoking prevalence is low among both men and women (although it may be lower among the former than the latter). There are few deaths related to smoking at this point.

In stage two, smoking prevalence begins to rise rapidly, primarily due to male smokers. Prevalence among women rises as well, but this rise begins around a decade after this stage of the epidemic begins. There is little differentiation by socio-economic status, and where there is a difference it is that wealthier people are more likely to smoke. This stage peaks with a smoking prevalence rate in excess of 50% of the adult male population after 20-30 years. By the end of this period, lung cancer rates among men may be ten times what they were in stage one, although they are still relatively low.

With stage three of the epidemic, smoking prevalence among men begins to decline. There may be a small initial decline in prevalence among women, but this may level off into a plateau for a decade or more before declining further.

Countries in the fourth stage of the tobacco epidemic include the UK, Australia and France, among many other developed nations. These countries experience continuing declines in smoking prevalence over time from very high levels to low double digits – government survey data suggests that the adult daily smoking prevalence in Australia was 12.2% in 2016 [16] while the overall UK adult smoking rate was 15.1% in 2017 [17]. It is widely expected that smoking prevalence in these countries will continue to decline into the so-called "tobacco endgame" [18], when smoking will be either highly uncommon or totally eliminated in a country.

Later research on the progression of smoking in developing countries has suggested that, while the epidemic model as originally proposed is broadly accurate in developed countries, it is difficult to predict when (or whether) women will begin to take up smoking in the developing world [15]. Modelling the epidemic by gender may provide more valid results.

1.4 Second-hand smoke (SHS) – a new source of health concern

The act of smoking is so called because of the visible and obvious smoke produced by the burning tobacco leaf. Anyone who has seen a smoker has observed that smoke is not only inhaled but also exhaled (mainstream smoke), as well as emitted from the burning end of a cigarette (so-called sidestream smoke). When it became known that inhaling the smoke directly was harmful to health, it was a logical step to ask whether inhaling smoke present in the environment could also lead to disease. This became a new topic of research interest.

The 1972 US Surgeon General's report "The Health Consequences of Smoking" drew on early evidence to suggest that SHS could be harmful to those with pre-existing medical conditions [11].

By the 1980s, research began to suggest that otherwise healthy non-smokers could be harmed by exposure to SHS when epidemiological studies were conducted linking exposure to lung cancer [19] and cardiovascular disease. One seminal piece of evidence came from a study of the wives of smoking men in Japan, which demonstrated that those who lived with smokers were more likely to develop lung cancer [19]. Later research would examine the particular risks of SHS to children [20] and workers such as airline cabin crew [21] and restaurant & bar workers [22] exposed through their occupation.

A further US Surgeon General's report, "Health Consequences of Involuntary Smoking" released in 1986 [23] detailed the available evidence that SHS causes harm to health. Since then, it has become common knowledge around the world that SHS is harmful – one 2011 study suggested that 92% of people aged 13-15 in developing countries agreed that SHS causes harm to health [24].

1.4.1 Health effects of second-hand smoke

SHS is well-established as a cause of health harm. SHS's role in causing lung cancer and heart disease is well known [23], and it has also been linked to the development of stroke [25], COPD [26] and diabetes [27] among other diseases.

Children are at particular risk from SHS exposure, as in a given environment they breathe in a greater amount of SHS proportionate to their weight - respiratory rate declines from birth until adulthood, so children (and particularly young children) breathe faster than adults [28,29]. Illnesses such as middle ear disease, childhood asthma, bacterial meningitis and sudden infant death syndrome have all been linked to the pollutant. In one major global study conducted on data from 2004, 28% of deaths linked to SHS were thought to have occurred in children – more than 160,000 [30]. The majority of disability-adjusted life-years (DALYs) lost due to SHS in children are related to lower respiratory infections [30] in under-fives, according to that study (which estimated a loss of over five million DALYs for this reason worldwide in 2004).

SHS exposure provides a fraction of the health risk of active smoking. One literature review suggested that those exposed to SHS have a relative risk of developing cardiovascular disease of 1.31, compared to 1.78 for active smokers [31]. This is a higher level of risk than would be expected purely from the dose of smoke inhaled by passive smokers compared to active smokers. This may be due to the differential toxicity of mainstream and sidestream smoke. Sidestream smoke is the primary component of SHS and is more toxic than mainstream smoke, potentially because it does not pass through a cigarette filter [32] or through smokers' lungs.

The dose-response effect of SHS exposure on particular health outcomes is little-studied, with sources including the US Surgeon General's office suggesting that there is simply no safe level of exposure to SHS [23]. However, it may be expected that the cardiovascular health effects of SHS may scale logarithmically, with increases at lower levels leading to greater changes in health than increases at higher concentrations [33].

1.4.2 Prevalence of SHS exposure

Exposure to SHS is common around the world. Worldwide, a 2011 study of survey data suggests that 33% of male and 35% of female non-smokers were exposed to SHS in 2004 [30]. Regional variations in this exposure exist, particularly between countries where the tobacco epidemic is in its earlier stages (such as many African nations) and those where it is advanced (such as Europe and Southeast Asia). That 2011 study suggested that 603,000 deaths – 1% of worldwide mortality – were attributable to SHS exposure in 2004 [30].

It has been estimated that around 40% of children were exposed to SHS in the home in 2004 [34], contributing to a significant burden of disease [35]. This exposure varies widely by country and ethnic group depending on the demographics of smoking, linked to stage of the tobacco epidemic. In ethnic groups where traditional gender roles are prevalent, and smoking is largely confined to men who are usually outside of the home, a different pattern of exposure may exist to those where men and women smoke at broadly equal rates and are more likely to be out of the home to work or for other reasons. This is visible among the different ethnic populations of Israel for example – Jewish children are significantly less likely to be exposed to SHS at home than children from other religious and ethnic backgrounds [36].

1.4.3 Knowledge about second-hand smoke

The essential concept that SHS is a health risk is well-understood across the globe [24]. General awareness of the harmfulness of SHS is particularly high in high income countries like the UK, Australia, Canada [37] and the USA [37,38]. But individual perceptions of risk may vary by social class [39], ethnicity [40] and other factors.

Smokers are often aware that instituting smoke-free homes policies will improve their children's health. A range of factors may influence children's SHS exposure at home, including lower economic status (in countries at an advanced stage of the tobacco epidemic), lower education and parental attitude towards SHS [41].

Some smokers may institute restrictions on smoking around their children for only the first months of the child's life, suggesting a belief that older children can tolerate smoke without serious risk [42]. Some may adopt ineffective mitigation strategies, such as smoking in only one room of the home, smoking while children are not present or opening windows.

1.4.4 The tobacco industry and second-hand smoke

Concerted efforts have been made by tobacco industry interests to undermine public confidence and understanding in the science of SHS. As early as the 1980s, industry figures were aware that SHS was harmful to health. Major tobacco companies set out to undermine this evidence by funding flawed studies of their own [43], and directing attention away from SHS through schemes such as the Centre for Indoor Air Research (which promoted the idea that SHS was just one of a number of indoor air pollutants, rather than a serious threat to health) [44].

A major public relations exercise carried out by Philip Morris International and British American Tobacco in Latin America sought to emphasise the role of outdoor pollutants in poor indoor air quality, by paying scientists to write and publish articles favourable to the industry [45]. Public perceptions of the relative harms posed by tobacco and non-tobacco sources of air pollution may thus be influenced by these methods.

1.5 Using the law to protect against SHS exposure

As the harm of SHS has been better understood scientifically, smoking can no longer be considered an activity which harms only the smoker but one which causes harm to others, particularly children.

1.5.1 Making indoor spaces smoke-free by law

As the evidence of SHS as a serious health risk has grown, it has become clear that any smoking indoors can be harmful to health, and that ventilation, either mechanical or traditional, is incapable of removing SHS entirely from an indoor environment [46].

With this in mind, many locations where patrons often smoked indoors, such as restaurants, bars and aeroplanes, came under pressure to change their policies to reduce harm to patrons and, particularly, employees. Early measures were taken in California, including a 1995 law restricting smoking in the majority of workplaces [47].

Legislative efforts to make all indoor public places smoke-free took off in the 2000s. The Framework Convention on Tobacco Control [48], a major public health treaty first adopted in 2003, included legislative restrictions on SHS exposure as a requirement in article 8. The Republic of Ireland became the first country to pass a smoke-free places law in 2002 (implemented in 2004) [49] and, confounding predictions of failure due to a culture of smoking in pubs, the law was widely complied with.

Scotland's smoke-free legislation, passed by the Scottish parliament in 2005 and introduced in 2006, was accompanied by a comprehensive programme of scientific evaluation [50] taking in eight outcome areas – knowledge, measured SHS exposure, compliance, change in culture, smoking prevalence rates, smoking-related ill-health and death, the economic impact of the law on restaurants, bars and pubs (thought to be at risk of a loss in trade after the law entered into force) and the impact on health inequalities. These measures showed that the smoke-free law was well-obeyed – with measured fine particulate matter ($PM_{2.5}$) in bars falling by 86% after the introduction [51] – and that it may have had a substantial impact on health, with and a 17% reduction in admissions to hospitals due to acute coronary syndrome [52] and an 18% fall in children's hospital admissions due to asthma [53] attributable to the law. Further changes in health in Scotland may also have been related to smoke-free public places, including a decline in prevalence of asthma among schoolchildren in Aberdeen of around 30% [54].

Smoke-free public places laws have since become common, particularly in the developed world [55]. Where they have been successfully applied they have led to significant population-level effects – since the law was introduced in Scotland, the percentage of adults with no measurable exposure to SHS has increased from 16% to 80% [56], suggesting that the vast majority of the Scottish population now enjoys protection from exposure at the workplace.

1.5.2 Other smoke-free laws

A range of further measures to reduce SHS exposure have been taken by governments in the wake of successful smoke-free laws.

Smoking in severely confined spaces can cause extremely high and persistent concentrations of SHS-related $PM_{2.5}$ in the air [57]. Several jurisdictions, including Scotland [58], have responded to this evidence by restricting smoking in vehicles. These laws may apply only when children are carried in the car, or may be in force at all times (as in the case of work vehicles used by more than one person in Scotland [59]).

Some smoke-free places laws have involved outdoor locations such as beaches and parks [60]. Due to the open spaces involved, SHS quickly dissipates outdoors and so such laws are unlikely to substantially reduce SHS exposure at a population level. The call for these laws and restrictions may be motivated by a desire to denormalise smoking by preventing children from seeing it or to reduce the number of cigarette butts left in the environment rather than concern about the health harm of SHS in these locations [60].

1.6 Promoting smoke-free homes

In countries with comprehensive and well-enforced smoke-free public places legislation, the only remaining indoor environment in which people are exposed to SHS is the home. This is the case in Scotland and particularly affects children. In 2016 data from the Scottish Health Survey suggested that 7% of children were exposed to SHS in their homes [61].

Protecting children from SHS has been a public health priority in recent years, with the Scottish Government now implementing a target to reduce children's SHS exposure by half from 2012 to 2020 [62]. The majority of SHS exposure occurs in the home [63] and so promoting smoke-free homes has been an area of focus for this work. This can have a knock-on effect on smoking prevalence, as having a smoke-free home is associated with attempting to quit smoking [64].

1.6.1 Interventions to promote smoke-free homes

A recent review [65] identified seven studies of interventions to encourage parents to reduce SHS in homes which used air quality as an outcome measure rather than relying on parental reporting. Of these, two studies used air cleaners to reduce SHS concentrations in household air [66,67]. This was seen to lead to fewer hospital visits in a population of children with asthma [66] and more symptom-free days in a similar population [67]. However, these children's cotinine levels did not fall as would be expected if they were no longer exposed to tobacco smoke, suggesting that they were still vulnerable to many of the health risks of SHS. Three studies used counselling [68] or motivational interviewing [69,70] to promote smoke-free homes, showing particular success in the case of motivational interviewing.

One [71] used culturally sensitive publications for both children and adults, achieving some success and suggesting that a low-cost and light-touch intervention, when delivered appropriately, can succeed. One involved the feedback of air quality information to encourage smokers to keep their homes smoke-free [72].

1.6.2 Feedback for behaviour change

Personalised feedback has been used in many interventions to promote a range of behaviour changes. Many unhealthy activities result in measurable changes to body chemistry or to other aspects of health. Providing information on those measurements to the person in question has been used as a strategy to promote behaviour change. The use of measurements of carbon monoxide in exhaled breath, for instance, is common practice in smoking cessation [73]. By analogy, air quality feedback has been investigated as a tool to promote smoke-free homes.

Outside of the scientific arena, personalised feedback has been used to promote positive behaviour change. "Smart" electricity meters which provide information on daily electricity usage are now widely available in the UK, with one study in Northern Ireland [74] finding that electricity usage fell by 11-17% in households equipped with a meter, compared to those using conventional metering.

1.7 Detection of second-hand smoke in air

Tobacco smoke is a complex mix of aerosols and vapours. Many of these components are detectable in the air, and can be used as markers for the presence of SHS. A range of techniques have been used to measure SHS in air with varying success. In general, particulate matter (PM) and air nicotine have been the most commonly used markers [75,76].

1.7.1 Particulate matter

Particulate matter (PM) and especially fine particulate matter (or $PM_{2.5}$) has been used widely as a marker for the presence of SHS indoors [76]. $PM_{2.5}$ represents fine particles smaller than 2.5μm in diameter, which are understood to have a serious impact on cardiovascular [77] and pulmonary [78] mortality and morbidity. The term itself does not refer directly to the composition of the particles, but to their size – $PM_{2.5}$ can comprise particles of metal, carbon following combustion, mould spores and many other types of particle. Particles may be solid or liquid.

$PM_{2.5}$ is generally measured in terms of its mass concentration, usually expressed as micrograms per cubic metre (μg/m^3), referring to the total mass of particles present in a volume (1m^3 or 1000 litres) of air. Mass concentrations are widely used in research on the health effects of $PM_{2.5}$, and are used by some health agencies to suggest limits on exposure to protect health – the World Health Organisation, for instance, recommends reducing exposure to $PM_{2.5}$ to a mean level below 25μg/m^3 over 24 hours, and below a mean of 10μg/m^3 in a year [79]. Since 2010 these guidelines apply to exposure in both indoor and outdoor environments. It should be noted that while $PM_{2.5}$ is harmful in itself, it is just one of the harmful components of tobacco smoke, and so while these guideline limits are useful they do not represent effective safe levels of SHS in an environment. The scientific consensus is that there is no safe level of SHS exposure [23].

1.7.2 Measuring $PM_{2.5}$

The most robust method of measuring PM concentrations uses the weight of particles extracted from a given volume of air using a pump and filter. The air can be drawn through a size-selective sampling head on to a filter, and the increase in filter weight determined using an extremely sensitive scale. This mass increase is then divided by the volume of sampled air to give a concentration of the PM in micro or milligrams per cubic metre (mg/m^3 or μg/m^3). This methodology is well developed in occupational exposure assessment of PM in work settings and is well described by the HSE Methods for Determining Hazardous Substances (MDHS) 14/4: "General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols" [80].

This method of PM monitoring, while highly accurate, is complicated, requiring fine scales, air pumps, filters and care and knowledge of the monitoring process. Due to the need to weigh samples in a controlled environment, concentration data may not be available quickly after monitoring has taken place. Concentrations measured will reflect an average over the total period monitoring takes place, so this form of detection will not pick up periods of high and low PM during monitoring. Long sampling times may also be required to ensure that filters collect a sample greater than the limit of detection.

For many applications it is advantageous to have information on the concentration of PM in the air immediately in "real-time", which can allow for speedy reaction to new information (such as taking action to reduce workplace PM concentrations in the event that they breach legal safe limits).

Real-time $PM_{2.5}$ monitoring can be achieved through the use of optical particle counters (OPCs). These devices use a laser or bright LED in combination with a sensor and (in some cases) a reflector to detect either the scattering of light or the obscuration caused by particles in the air. In light scattering, particles passing through the laser beam will refract light onto the detector at the side. The amount of light refracted can be used to determine the size of the particle [81].

As technology has improved OPCs have become cheaper. New low-cost OPCs allow for immediate monitoring with relative ease, often minute-by-minute or (in some cases) even more frequently. However, the mass concentrations reported by these monitors are dependent on the type of aerosol present in the sampled air and the aerosol used to calibrate the monitor. Aerosols with different size distributions, for instance, can lead to highly variable mass concentrations despite similar particle numbers. Other factors, such as relative humidity, can also impact the accuracy of the results [82]. Work by Kurmi & Semple [83] suggests that OPCs should be calibrated in the specific environment in which they are to be used.

Examples of OPCs include the TSI Sidepak AM510, the Dylos DC1700 and the Plantower PMS5003 (a low-cost sensor used in a range of monitors).

Other techniques for particle monitoring include beta attenuation monitoring, which uses the absorption of beta radiation (electrons or positrons) to determine the mass of particles drawn onto a cycling filter. As the amount of beta radiation which is absorbed depends only on mass, it is possible to determine the total mass gained by the ribbon from the air with a great degree of accuracy [84]. The BAM-1020 monitor (Met One Instruments, Inc., Grants Pass, Oregon) can provide highly reliable hour-by-hour concentration data on $PM_{2.5}$, but the monitors are expensive and difficult to move, so rarely suitable for widespread monitoring in homes.

1.7.3 $PM_{2.5}$ as a marker for SHS

SHS is one of the most significant sources of $PM_{2.5}$ indoors, with high concentrations measured in indoor environments closely related to the number of cigarettes smoked [85,86]. Few other indoor activities can produce the same high levels of $PM_{2.5}$ as smoking, particularly in developed countries where open flames are rarely used for cooking indoors [87]. However, activities such as frying food or using a fire can still lead to elevated levels of $PM_{2.5}$ which can be confused for SHS. Thus $PM_{2.5}$ monitoring does not definitively identify the presence of SHS in a home. However, smoking is generally the predominant source of $PM_{2.5}$ in homes where smoking takes place [88].

SHS-related $PM_{2.5}$ has been observed to persist in a home environment for several hours after a cigarette is smoked [89]. This may allow greater confidence in the use of $PM_{2.5}$ as a marker for SHS, as $PM_{2.5}$ derived from other sources may not persist for this length of time.

1.7.4 Air nicotine detection

Nicotine, the primary addictive component in tobacco, is present in SHS. As nicotine is only found in tobacco smoke and e-cigarette aerosol, detecting it is useful in detecting SHS with a low risk of false positives (a concern when using $PM_{2.5}$ as a proxy).

The most common technique for nicotine measurement is passive sampling using a sodium bisulfate filter. This sampler is placed in the sampling location for days to weeks to allow air to diffuse through a porous membrane, and the filter to pick up vapour-phase nicotine. The filter is then removed and analysed by gas chromatography or mass spectroscopy to determine the mean concentration of nicotine present in the air over the sampling period [75].

Novel techniques have included the use of conductive polymer films to detect ambient nicotine, allowing detection in real-time [90]. However, this technology is new and relatively little-used. In the future it may be suitable for use in SHS exposure assessment research, and potentially in air quality feedback interventions.

1.7.5 Other markers of SHS

Carbon monoxide (CO) detectors have been used to detect SHS [91]. As a product of combustion, it has similar drawbacks to using PM – as a non-specific marker it can be detected from other sources such as vehicular pollution. CO is easily detected using low-cost monitoring equipment, but this equipment may be unable to detect the relatively low concentrations of CO generated from smoking.

Tobacco-specific nitrosamines (TSNAs) are carcinogenic compounds found in tobacco smoke, sometimes used as biomarkers for smoking [92]. Some research has been conducted on measuring TSNAs in indoor air as a marker for SHS, but this method has been little used [75].

3- ethenylpyridine (3-EP) is a product of the decomposition of nicotine at high temperatures (as present in a lit cigarette). 3-EP is more stable than nicotine in the air, but is generally present at lower concentrations which can make it harder to detect [75,93]. It has been used in exposure assessment studies in Finland [94] where the method was developed, and occasionally by tobacco industry sources [75].

Polycyclic aromatic hydrocarbons (PAHs), chemicals produced through incomplete combustion of organic matter, have been studied occasionally as markers of SHS in air. However, as these chemicals are produced by many other sources than tobacco smoking they are not necessarily a reliable marker, with some studies showing no clear association between SHS in air and PAH levels [75,95].

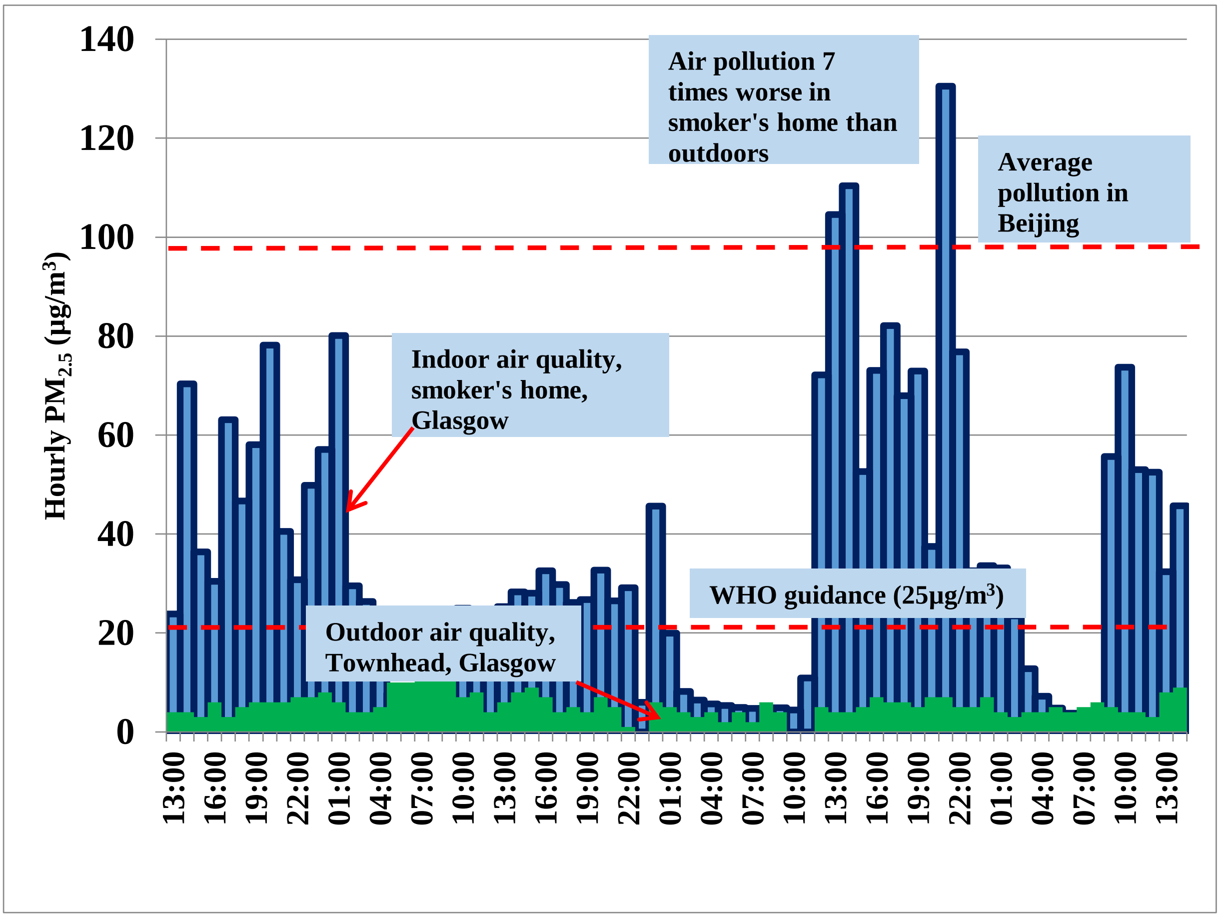
Solanesol is an alcohol present in tobacco leaves which forms particles in tobacco smoke [96]. As it is not otherwise present in the environment, it can be used as a specific marker for SHS. However, chromatographic techniques are required to analyse samples, a complex and time-consuming requirement.

Other markers which have been used include volatile organic compounds (VOCs), nitrogen oxides, aldehydes and metals. These are not specific to SHS but are present as a component [75].

1.8 Demonstrating the comparative impact of SHS on air quality

Research at the University of Aberdeen [72] and elsewhere [97] has used low-cost air quality monitors to study the levels of $PM_{2.5}$ in smokers' homes. As expected, these levels were often extremely high, exceeding the levels found in outdoor air in major industrialising cities such as Delhi and Shanghai [89]. Research in Scotland has shown that concentrations of $PM_{2.5}$ in smokers' homes are frequently many times greater than outdoor concentrations at the same time (as shown in Figure 3).

Figure 3 – Hourly indoor $PM_{2.5}$ concentrations from a low-cost air quality monitor (blue) compared to outdoor $PM_{2.5}$ concentrations from a reference gravimetric monitor (green) over several days in Glasgow, Scotland, demonstrating the much greater impact of SHS than outdoor sources on indoor air quality.



To challenge perceptions by demonstrating the greater concentrations of fine particulate pollution from SHS compared to transport-related pollution, educational tools have been developed. One used vehicles running in a garage to demonstrate higher $PM_{2.5}$ levels produced by smoking than combustion engines [98], while another piped diesel lorry exhaust fumes into a small room and compared $PM_{2.5}$ levels to those produced by smoking two cigarettes [99]. These demonstrations have not been trialled on a large scale, but perceptions were seen to change among observers, suggesting that direct objective air quality measurement data can influence thinking and decision-making about SHS.

This approach of quantifying SHS concentrations in homes has informed the Scottish Government's recent mass media campaign "Take it Right Outside" [100]. This campaign aims to encourage smokers to reduce the level of SHS in their homes through information about the time SHS lingers in the home and the continued impact of invisible smoke, such as the message "*You can't see or smell it, but it's there*" [100].

1.9 The original research contributions of this thesis

This thesis will explore whether air quality information can be successfully used to change smokers' views of smoking and smoking behaviour within the home. Key to this will be development of the best method to present air quality information to maximise the potential behaviour change.

Several approaches have been taken in this thesis to answer this question. Qualitative research has been used to explore the way people understand and relate to air pollution more generally and SHS in particular (chapter 4). A pilot intervention using new principles and designs to provide air quality feedback has been developed and tested (chapter 5). A new system for measuring and relaying information about SHS in real-time has been developed and evaluated (chapter 6). An intervention incorporating learning from a pilot intervention has been tested, using the SHS real-time measuring system to deliver information on air pollution in the home to those living in a home where smoking was permitted (chapters 6 & 7). And finally, a new test method to use $PM_{2.5}$ data to determine whether SHS is present in a home using a low-cost PM monitor was developed and tested, with the prospect of using it in future air quality feedback interventions (chapter 8). The full aims and research questions of this thesis are given in chapter 3.

2 Literature review

2.1 Chapter synopsis

This chapter describes a narrative review of relevant literature of interventions to promote smoke-free homes for children's health . Only personal health interventions were considered – higher level policy and population approaches, such mass media campaigns [100], were not included. Particular focus was given to identifying interventions with a focus on reducing smoking indoors without requiring smoking cessation, those which involved parents after the birth of a child (and not primarily within the prenatal period) and those using elements of air quality feedback or objective measures of exposure to SHS.

2.2 Introduction

Four recent systematic reviews have been published analysing interventions intended to promote smoke-free homes [65,101–103]. One was published in 2014, two in 2015 and one in 2018 (an updated Cochrane review). Table 1 summarises information about the subjects and conclusions of these reviews. They have found that a range of measures are used to protect children from SHS exposure in their home, but that there is no single best strategy to promote smoke-free homes.

2.3 Methods

Studies identified in the four systematic reviews listed in Table 1 were assessed for use in this narrative review. In addition, keyword searches were conducted in the Embase and Medline databases, as well as Google Scholar (Alphabet Inc., Mountain View, CA) for literature concerning interventions to promote smoke-free homes published after the inclusion cut-off dates of these reviews. Papers, theses and books listed in these databases were considered. Studies in any population which involved a trial of a personal health intervention were included, regardless of size, control or outcome measure.

Intervention trials referred to in this review are given in Table 2, along with key information about the interventions in question.

Table 1 - Recent reviews of evidence on interventions to protect children from SHS exposure

Review	**Subject**	**Papers reviewed**	**Search cut-off date**	**Conclusions**
Rosen et al, 2014 [101]	Randomised trials of interventions to reduce SHS in homes to protect children	30	October 2013	Interventions can have small but significant benefits which could be large if implemented on a population scale; both less and more intensive interventions can work; SHS exposure monitoring is a promising strategy
Rosen et al, 2015 [65]	Randomised trials of interventions to reduce SHS in homes to protect children where measures of household air pollution (either PM or air nicotine) were used as an outcome measure	7	July 2014	Few studies have used these techniques as outcome measures, but those which have suggest that smoke-free homes interventions can reduce but not eliminate SHS in homes
Brown et al, 2015 [102]	Parent-focused interventions (including smoking cessation interventions)	28 (including 12 on SHS reduction specifically)	December 2014	Further research required on family dynamics of SHS exposure. Quality of study reporting makes it challenging to identify effective elements of interventions.
Behbod et al, 2018 [103]	Controlled trials of interventions designed to reduce exposure of children to SHS	78 (all studies reviewed, several studies led to multiple papers)	February 2017	24 studies showed a significant effect. Most of these took place in clinical settings. Counselling was frequently used in both successful and unsuccessful interventions.

*Table 2 – Details of intervention studies referenced in this review, including intervention design and outcomes. Significant effects are marked with * (using the definition of significance given in each study). Randomised controlled trials are marked "RCT", feasibility trials are marked "FT".*

Study	**Design**	**Location**	**Size**	**Population demographic**	**Intervention type**	**Outcome measures**	**Results**
Abdullah et al, 2015 [104]	RCT	Shanghai, China	318 families (164 in intervention group, 154 in control group)	Smoking caregivers with children aged 5 or younger	Repeated counselling sessions in person and by phone over three months	Self-reported smoking behaviour change, children's mean urinary cotinine at six months	62% of intervention group adopted smoke-free restrictions in the home vs 45% of control*, mean urinary cotinine was significantly lower in the intervention group than the control at follow-up*.
Butz et al, 2011 [67]	RCT	Baltimore, MD, USA	126 households (41 in intervention group, 41 in enhanced intervention group, 44 in control group)	Families with children aged 6-12 diagnosed with asthma	Intervention group given air cleaners, enhanced group given air cleaners plus coaching	Self-reported SHS, urine cotinine, household PM sampling, passive air nicotine	19µg/m³ fall in PM2.5 in intervention group*, 16.6µg/m³ fall in enhanced group.* No change in air nicotine or urine cotinine.

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Chellini et al, 2013 [105]	RCT	Tuscany, Italy	218 women (110 in intervention group, 108 in control group)	Women (smokers or non-smokers) aged 18-49 with children	Brief counselling on SHS, gifts. All participants (including control group) received a self-help booklet	Self-reported change in smoking rules in homes	No significant change compared to control group.
Chilmonczyk et al, 1992 [106]	RCT	Portland, ME, USA	103 mother/child pairs (52 in intervention group, 51 in control group)	Mother/child pairs where the mother smoked ten or more cigarettes per day	Feedback of child's urinary cotinine results to parent	Change in child's urinary cotinine	No significant change compared to control group.
Collins et al, 2017 [107]	RCT	Philadelphia, PA, USA	Trial ongoing	Mothers with children under 6 exposed to tobacco smoke	Complex mHealth intervention featuring smartphone app and SMS messaging	Child urinary cotinine, self-reported cigarettes per day, adult abstinence (verified by salivary cotinine and carbon monoxide)	Trial is ongoing

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Conway et al, 2004 [108]	RCT	San Diego, CA, USA	143 (71 in intervention group, 72 in control group)	Spanish speaking adults of Hispanic descent with children between 1 & 9 years old	In-person and telephone counselling delivered by culturally appropriate community workers	Self-reported child exposure to SHS, child's hair nicotine, child's hair cotinine	No significant change in any outcome measure.
Davis et al, 1992 [109]	RCT	Northeastern United States	630 (198, 203 and 229 in each group)	Smoking mothers of children under 6	Test of three types of self-help guide of different styles and reading levels, one targeted specifically towards young mothers	Self-reported quit attempt in the last 6 months at follow-up (6 months after intervention), self-reported quit (one week or longer) at follow-up.	No difference in change by type of guide.
Emmons et al, 2001 [110]	RCT	USA	291 (141 control vs 150 intervention)	Current smokers/recent quitters with a child under 3 living in the home	Air quality feedback - air nicotine information given by post	Change in air nicotine measurements in two indoor locations between baseline and follow-up	Significant decline in air nicotine measured in both locations in intervention group (4.3µg/m³ decline in kitchen measurements)*

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Groner et al, 2000 [111]	RCT	Columbus, OH, USA	479 (153 in child health group, 164 in maternal health group and 162 in control group)	Female caregivers accompanying a child (under 12) to hospital	Participants given self-help materials and brief counselling on quitting smoking (maternal health group), reducing children's SHS exposure (child health group) or no counselling (control).	Change in self-reported smoking location in home, change in knowledge about SHS at 1 and 6 months	Significant change in both outcome measures at six months in child health group at six months.*

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Halterman et al, 2011 [112]	RCT	Rochester, NY, USA	530 (split by exposure to SHS and intervention/control)	Asthmatic children between 3 and 10 years old	Asthma medication given to school nurses for directly observed therapy, family of SHS-exposed intervention group also received motivational interviewing	Symptom-free days over winter season	Intervention overall effective, no additional effect from motivational interviewing
Hannöver et al, 2009 [113]	RCT	Mecklenburg-West Pomerania, Germany	644 (299 in intervention, 345 in control)	Women who smoked prior to or during pregnancy	In person counselling at home, then two phone sessions 4 and 12 weeks later.	Sustained abstinence from smoking and repeated 4 week point prevalence, follow-ups at 6, 12, 18 and 24 months.	No statistically significant change in smoking at any follow-up point.

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Harutyunyan et al, 2013 [114]	RCT	Yerevan, Armenia	250 (114 control vs 110 intervention completed)	Households with a non-smoking mother and a child 2-6 years of age living with at least one daily smoker	Immediate air quality feedback - comparison between indoor air during smoking and outdoor air	Hair nicotine of children	17% reduction (compared to control group)*
Hovell et al, 2009 [68]	RCT	San Diego, CA, USA	150 (74 in control group, 76 in intervention group)	Smoking mothers with children under 4 who were exposed to 3 or more cigarettes per day	14 biweekly counselling sessions over six months covering SHS reduction and smoking cessation, provision of nicotine replacement therapy	Self reports of smoking and SHS exposure, children's urinary cotinine to 18 months, air nicotine at six months	Self-reported indoor smoking declined by significantly more in intervention group (79.8%) than in control (54.9%)*. 25% declines in both groups in urinary cotinine.

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Hovell et al, 2019 [115]	RCT	San Diego, USA	298 (149 in intervention group, 149 in control)	Households with a smoker and a child under the age of 14	Immediate air quality feedback using light and sound signals over three months, additional counselling (see also Hughes et al 2018)	Reduction in daily particle events (when particle number concentrations spiked)	Decline of 0.13 particle events per day in intervention group.*
Huang et al, 2013 [116]	RCT	Taipei, Taiwan	292 (136 in intervention group, 156 in control)	Pregnant women and women with children under 3 years old	Telephone counselling and self-help materials	Determinants of change according to the transtheoretical model and knowledge about SHS following the intervention	Significantly greater knowledge and determinants of change among both pregnant women and mothers following the intervention.*

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Hughes et al, 2018 [117]	RCT	San Diego, USA	298 (149 in intervention group, 149 in control)	Households with a smoker and a child under the age of 14	Immediate air quality feedback using light and sound signals over three months, additional counselling (see also Hovell et al 2019)	Change in daily geometric mean particle concentrations	18.8% reduction in intervention group* compared to 6.5% reduction in control group
Jiménez-Muro et al, 2013 [118]	RCT	Zaragoza, Spain	412 (205 in the intervention group, 207 in control)	Women at one hospital who gave birth between January 2009 and March 2010	Motivational interviewing to prevent smoking relapse in post-partum women, four sessions by telephone over three months following birth of a child	Smoking at three months post-partum	Self-reported smoking abstinence among recent quitters was 74% in the intervention group, significantly greater than the 37% in the control group.*

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Kegler et al, 2015 [119]	RCT	Atlanta, GA, USA	498 (246 in intervention group, 252 in control)	Callers to the 2-1-1 advice line living with a child or other non-smoker, who smoked in the home or lived with someone who smoked in the home	Three self-help booklets and one coaching call over six weeks	Self-reported smoking ban in the home, verification with air nicotine monitoring	30.4% of intervention group participants reported a smoking ban at 3-month follow-up, and 40% at 6-month follow-up, compared to 14.9% and 25.4% in the control group respectively.* At three month follow-up, there were significantly more verified SHS-free homes in the intervention group than the control (14.2% vs 8.3%).*
Klepeis et al, 2013 [120]	FT	San Diego, CA, USA	3	Families with one or more smokers and a child or pregnant woman	Test of a light and sound -enabled monitor designed to provide air quality feedback	No objective outcome measure	n/a

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Lanphear et al, 2011 [66]	RCT	Cincinnati, OH, USA	225 (110 in intervention group, 115 in control)	Children 6-12 who had received treatment for asthma and who were exposed to SHS daily from five or more cigarettes	Two air cleaners installed in intervention home for three months	Number of unscheduled asthma-related visits to healthcare practitioners, PM number concentrations in home	18.5% fewer asthma exacerbations among the intervention group than the control, 25% reduction in particle levels in intervention group (compared to 5% in control)*
Marsh et al, 2016 [121]	FT	Nottingham, England	12	Caregivers who smoked inside their homes and lived with a child under 5 years old	12 week programme including counselling, feedback on child's salivary cotinine or air quality, nicotine replacement therapy	Child's salivary cotinine, PM2.5	Salivary cotinine increased (by 1.3ng/ml), mean PM2.5 reduced by 49%

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
McIntosh et al, 1994 [122]	RCT	Ann Arbor, MI, USA	72 (37 in intervention group, 35 in control)	Parents or caregivers of a child with diagnosed asthma	Postal feedback on child's urinary cotinine	Self-reported outdoor smoking	Self-reported outdoor smoking was greater among intervention group (35%) than control (17%) post-intervention, but there was no statistically significant difference.
Mdege et al, 2019 [123]	RCT	Dhaka, Banglades h	1,800 (divided between two intervention groups and one control group)	Households with a mosque-goer containing at least one smoker and a non-smoker	Ongoing three arm trial - a delayed air quality feedback intervention (24hr PM2.5 measurement in homes) plus community counselling, community counselling alone, and a control group.	Change in mean PM2.5 at follow-up	n/a (study ongoing)

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Phillips et al, 2012 [124]	RCT	Loma Linda, CA, USA	54 (24 in intervention group, 30 in control)	Mothers of infants admitted to neonatal intensive care, who had smoked within a year of pregnancy but were currently non-smokers	Intervention group received self-help materials (books, DVDs, handouts) and watched a video in NICU encouraging bonding and skin-to-skin contact with their baby. Both groups received motivational interviewing on continuing smoking abstinence,	Mother's smoking status eight weeks post-partum, verified with carbon monoxide testing and salivary cotinine	81% of mothers in the intervention group were non-smokers at eight weeks, compared to 46% in the control group.*

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Prokhorov et al, 2013 [71]	RCT		91 (47 in intervention group, 44 in control)	Mexican-American households with two adults, one of whom was a smoker, and a child under 18 years old	Culturally appropriate self-help materials dealing with effects of SHS exposure among children	Air nicotine monitor data at 6 and 12 months compared to baseline, change in self-reported smoking rules	Significant decline in mean air nicotine in the intervention group from baseline to 12 months (1.14μg/m³ to 0.20μg/m³).* Significant increase in homes in intervention group banning smoking indoors.*
Ratschen et al, 2017 [125]	RCT	Nottingham, England	224 (102 control vs 103 intervention completed)	Caregivers who smoked inside their homes and lived with a child under 5 years old	Air quality feedback, counselling and nicotine replacement therapy	Change in modelled mean PM2.5, child's salivary cotinine	36.3% reduction in PM2.5 concentration in intervention group*, reduction in children's salivary cotinine*
Rosen et al, 2018 [126]	FT	Israel	29	Parents from families where one or more member smoked	Motivational interviews, child hair nicotine feedback, indoor air quality feedback	Child's hair nicotine, measured air nicotine concentration, measured PM2.5 concentration	Reduction in hair nicotine, no change in air nicotine, statistical noise made measurement of PM2.5 concentration impossible

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Semple et al, 2018 [127]	RCT	Lanarkshire, Scotland	117 (58 in intervention group, 59 in control)	Mothers with children under 6 years old	Air quality feedback (6 day measurement of PM2.5 at baseline, one month and six months)	Change in geometric mean PM2.5	No change, no difference between trial arms.
Severson et al, 1997 [128]	RCT	Portland, OR, USA	2,901 (1,682 in intervention group, 1,219 in control group)	Mothers of newborn children attending paediatric practices	Four brief advice sessions and self-help materials to new mothers over the first six months of their babies' lives, provided by paediatric practitioners	Self-reported smoking behaviour at six and twelve months	No significant effect on smoking behaviour at twelve month follow-up.
Streja et al, 2014 [129]	RCT	Los Angeles, CA, USA	242 (118 in intervention group, 124 in control)	Pairs of one parent and one child with asthma, where the parent or another adult in the home smoked	Counselling and enhanced self-help materials	Child's urinary cotinine, air nicotine, parental self-report of child's exposure to SHS	No difference in outcome at baseline and 6-month follow-up.

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Wiggins et al, 2005 [130]	RCT	London, England	731 (184 in community intervention arm, 183 in health visitor intervention arm, 364 in control group)	Women who gave birth in the first nine months of 1999 in the boroughs of Camden and Islington	Community arm offered support from a local group (drop-in sessions, home visits, telephone calls) over one year, health visitor arm offered monthly supportive listening visits from a trained health visitor for one year.	Maternal smoking at twelve month follow-up	Few community arm participants accessed support (19%) compared to health visitor arm (94%). No change in maternal smoking compared to control for either intervention arm.

Study	Design	Location	Size	Population demographic	Intervention type	Outcome measures	Results
Wilson et al, 2013 [72]	FT	Aberdeen shire, Scotland	59 (27 control vs 21 intervention completed)	Mothers with children under 6 years old	Air quality feedback (24 hour PM2.5 measurements) delivered by post	Change in geometric mean and maximum PM2.5 concentration between baseline and follow-up measurements, change in time over 35µg/m3, child's salivary cotinine	42% reduction in geometric mean PM2.5 concentration, 50% decline in maximum PM2.5 concentration measured*, 86% reduction in time over 35µg/m3*, no significant difference in salivary cotinine.
Yu et al, 2017 [131]	RCT	Changchu n, China	297 (104 in counselling intervention group, 97 in mHealth group, 96 in control)	Families with non-smoking mothers, a newborn child and a smoking father who smoked within the home	Three arm trial - counselling arm received in-person counselling and education, mHealth arm additionally received text messages on the health effects of SHS and smoking	Fathers' smoking abstinence rates at six and 12 months follow-up, mothers' reported SHS exposure	Significant increase in fathers' abstinence at six and 12 months (odds ratio 2.93 at 12-month follow-up),* significant reduction in mothers' SHS exposure (odds ratio 0.53 at 12 months) in mHealth group, greater than in counselling group.*

The keyword search strategy in Embase and Medline used the following search terms:

"smok*" OR "tobacco" OR "cigar*"

AND

"second-hand smoke" OR "secondhand smoke" OR "environmental tobacco smoke" OR "passive smok*" OR "involuntary smok*"

AND

"child*" OR "infant" OR "adolescent" OR "youth"

AND "intervention" OR "programme" OR "health promotion" OR "health education" OR "trial"

Searches in Medline and Embase were conducted on 26 June 2018. Searches in Google Scholar used less formal schema, due to the search engine's ability to expand terminology and its "relevance" display order.

Results were assessed for relevance to the aim of this review by title and abstract screening, then by full-text screening where required. Additional studies identified from bibliographies of other articles or from other sources were included where relevant. Only articles in English were considered.

2.4 Results

2.4.1 Outcome measures for SHS-reduction intervention studies

A range of strategies have been used to measure the success of smoke-free homes interventions. The simplest method may be to ask participants or others living in their households about rules and practices before and after the intervention has taken place. This is quick and requires few resources, making it ideal for lower intensity interventions such as telephone-based counselling. However, it is obviously vulnerable to misreporting – a participant who has spent weeks undergoing an intervention designed to change their behaviour, and which may involve receiving detailed information on the harm SHS can do to them and their children, may be understandably reluctant to report that they still smoke in their home. Studies combining objective assessment of children's SHS exposure with questions have shown highly variable correlation, possibly depending in part on how specific the questions are, and how well they assess intensity of smoking behaviour [132].

Objective outcome measures can be used to determine the presence of SHS in the home over time. These have included air nicotine monitoring and PM monitoring [75], and could potentially include other markers of SHS in the indoor air. These strategies allow measurements of proxies for the presence of SHS, and (in the case of PM monitoring) can give detailed information over time about the impact of an intervention on home smoking behaviour. However, they require specialised equipment (such as optical particle monitors or similar sensors in the case of PM) and, in the case of air nicotine, require laboratory analysis. Location of sensing equipment can also impact results – although SHS permeates throughout indoor environments quickly, proximity to a source can still have an effect on readings (as demonstrated in research on outdoor exposure to SHS – in one study, the presence of each smoker increased personal exposure to $PM_{2.5}$ by 30% [133]).

Air quality monitoring does not directly measure the actual exposure of an individual to SHS. Techniques are available to do so using biomarkers of nicotine exposure. These involve tests for cotinine (a metabolite of nicotine) in the saliva or urine of an individual exposed to SHS in the home, or testing hair for the presence of nicotine. Cotinine persists in the body for many days and has an elimination half-life of approximately 16 hours [134]. Hair nicotine testing can be used to detect SHS exposure over much longer periods, and offers a "historical record" of exposure over several months depending on the length of hair available [134]. However, these forms of testing require laboratory expertise and correctly attained samples – samples which are too small or stored incorrectly could lead to tests failing to function correctly. Researchers may therefore need to take samples themselves rather than allowing participants to do so, requiring additional contact time and resources for visits.

Among children with illnesses exacerbated by SHS exposure (such as asthma), severity and frequency of symptoms, or events requiring medical care, can be used as an outcome measure [112], as can caregivers' perceptions of a child's illness [122]. This method can only be used in a population which is more highly vulnerable to SHS exposure.

As each strategy for assessing outcome or intervention performance has its positives and negatives, many intervention studies have used multiple outcome measures to ensure validity of results through cross-comparison.

2.4.1.1 Exposure to SHS outside the home – a potential confounder

Cotinine testing results may not reflect behaviour change at home if the individuals tested are frequently exposed to SHS in other environments (such as indoor public places, including bars where comprehensive smoke-free laws do not exist [51]). In Scotland, as in many developed countries with well-enforced indoor smoking restrictions, the home is the primary source of exposure to SHS [135].

Young infants may additionally be exposed to nicotine through ingestion. Third-hand smoke, chemicals derived from SHS which settle on surfaces in the environment, may be collected on the hands and ingested following hand-to-mouth contact [136].

2.4.1.2 Other confounding sources of exposure

As cotinine is a metabolic product of nicotine, its presence in the body can be associated with the use of non-smoking sources of nicotine such as nicotine replacement therapy (NRT), e-cigarettes or minor dietary sources of nicotine such as potatoes and tomatoes [137]. This nicotine exposure could also come about through hand-mouth contamination, particularly in the case of younger children – ingesting SHS residue could lead to elevated levels of cotinine which could be misinterpreted as exposure to airborne SHS [138].

While conventional NRT products do not provide a route for second-hand exposure, many e-cigarettes produce measurable and often visible mainstream aerosol exhaled by users. The effects of second-hand exposure to e-cigarette aerosol are not fully understood, but it has been demonstrated to raise cotinine levels in exposed non-users in a manner similar to SHS [139].

2.4.2 Interventions and strategies to promote smoke-free homes and reduce children's SHS exposure

A wide range of approaches have been used to promote smoke-free homes and reduce children's SHS exposure. Further information about these strategies and interventions which have employed them is given below.

A distinction can be made between reducing SHS exposure and attaining a smoke-free home. The former can be achieved through the reduction of smoking indoors or through mitigation strategies (such as improving ventilation), while the latter requires the restriction of all smoking in the home. Due to the long time SHS-related PM can persist in the air at harmful levels [89], as well as the potential of third-hand smoke to cause harm days or weeks after smoking has taken place, strategies which rely on changing the time at which smoking takes place (moving smoking to times when children are out of the home, for instance) may not be effective in avoiding the health effects of exposure to SHS. For ease, all such interventions (including those aiming to reduce smoking indoors rather than eliminate it entirely) are referred throughout as “smoke-free home interventions”.

It is difficult to disaggregate the health effects of the many harmful components of SHS aerosol. Air nicotine and PM measurements over time do not necessarily represent the time these components spend in the air – gases may diffuse more quickly than PM, and chemical reactions may change the nature of some chemicals making them more or less harmful (such as nicotine in the air reacting with nitrous acid to form tobacco-specific nitrosamines, notable carcinogens) [140]. Some elements of SHS may persist for longer or shorter periods than particular outcome measures demonstrate, and so smoking-related harm, such as cardiovascular illness, may not have a simple linear relationship between smoke inhaled and harm suffered [141]. Different sources of PM may have different health effects and different dose-response relationships – for instance, cytological testing has demonstrated that exposing cells to “model” PM (such as diesel exhaust particulate) does not result in identical immune responses to exposure to real ambient urban PM [142].

The US Surgeon General has reported that no level of SHS can be considered “safe” [23]. For this reason, a completely smoke-free home is necessary to achieve the full health benefits of SHS exposure reduction.

Behaviour change interventions have frequently used multiple overlapping strategies, and so not all interventions can be categorised under one heading. This may also make it difficult to determine the effective element of an intervention – a programme which employs both air quality feedback and motivational interviewing, for instance, could result in change because of either method or both.

2.4.2.1 Self-help materials

Self-help interventions involve giving participants information about SHS in the home and leaving them to resolve the issue themselves. This can be inexpensive and can reach a large number of people, but may not be an effective way of promoting behaviour change, as there is no guarantee that the materials will be used or used appropriately without additional support. Many interventions may use self-help materials and strategies, either as a main component of the intervention or as a control for comparison with a more intensive intervention arm.

Self-help materials may be more likely to be effective when the materials given to participants are tailored to their needs and cultural context. One study [71] carried out among Hispanic people in Texas gave a control group of smoking parents a standard leaflet on SHS, while the intervention group received customised comic books and photobooks featuring Hispanic people dealing with issues around SHS. Mean ambient air nicotine concentrations showed a significant fall (from 1.14μg/m^3 at baseline to 0.20μg/m^3 at 12-month follow-up) suggesting that SHS exposure reduced in the intervention group vs no significant change in the control (an insignificant decline of 0.55μg/m^3 at baseline to 0.17μg/m^3 at 12-month follow-up).

However, cultural relevance alone may not decide the efficacy of an intervention. Another similar self-help intervention study, using culturally relevant materials to promote smoke-free homes for Hispanic children with asthma in California, failed to show any effect on smoking behaviour as assessed by air nicotine monitoring and child's urinary cotinine [129].

Materials which are highly relevant to parents' personal circumstances could also be more effective. One study in Loma Linda, California gave tailored self-help materials to parents of babies in a neonatal intensive care unit, resulting in a significant drop in mothers' smoking relapse rate in the intervention group (81% smoked at follow-up 8 weeks after giving birth in the intervention group compared to 46% in the control group, $p<0.001$) [124].

Tailoring in this fashion may not be sufficient to guarantee success – a comparative study in the North East of the United States of three sets of self-help materials given to mothers of young children (to encourage them to quit smoking) found no difference in quit attempts or successful quits between them, despite substantial tailoring of one set of materials to their specific circumstances [109]. Similarly, there was no difference between materials with different reading ages.

In general, self-help materials are likely to have limited effectiveness for promoting behaviour change, though their frequent inclusion in interventions along with other strategies means that it is difficult to determine whether they have a complementary effect. Those which are effective may be tailored to the circumstances and background of the study population.

Figure 4 - A range of self-help materials and gifts given by NHS Greater Glasgow & Clyde for use promoting smoke-free homes.

2.4.2.2 Gifts and mementos

Participants who make a commitment to a smoke-free home as part of an intervention may be given items to remind them of their commitment. These could include signs with relevant messages [128] or small items, such as stationery holders or fridge magnets (Figure 4) with a study logo or message [105], designed to reinforce key intervention messages.

No studies have directly measured the impact of these items on smoking in the home except as part of larger intervention programmes, so it is not possible to determine with certainty what effect they might have in promoting smoke-free homes.

2.4.2.3 Counselling and motivational interviewing

Counselling support has been investigated as a strategy for SHS exposure reduction in a number of studies.

Motivational interviewing (MI) is a common technique for promoting behaviour change, which has been defined as “a directive, client-centred counselling style for eliciting behaviour change by helping clients to explore and resolve ambivalence” [143]. In MI, a counsellor provides direction to overcome ambivalent attitudes to behaviour change by eliciting motivation from the client themselves. Counsellors do not confront or persuade clients to make change, but instead allow clients to express their views and help guide them to a resolution in line with what they want and believe. Counselling can take place in person or by phone.

The form counselling takes may affect its results, as different counselling techniques place emphasis on different qualities. Inexperienced counsellors may not be able to promote behaviour change as effectively as those with better knowledge. One study [108] of a smoke-free homes intervention recruited lay community health advisors (many of them volunteers) to deliver behaviour change counselling, partially directed by participants. This intervention was ineffective, with the study authors suggesting that the advisors’ lack of training in behaviour change techniques may have made it difficult for them to deliver elements of the intervention correctly. Another study gave mothers of new-borns smoking cessation and relapse-avoidance support from either professional health visitors or community charity groups [130]. Uptake was much higher in the group receiving professional support (although smoking outcomes were not significantly different) suggesting that a professional model may be more likely to succeed in delivering an intervention.

Non-MI forms of counselling have been used in some interventions to positive effect. A trial in China reported an intensive telephone-based counselling trial which led to an increase in self-reported smoke-free home rules (62% vs 45% in the comparison group) [104]. This study used non-confrontational counselling methods which may be closely related to MI techniques (although this information was not given in the paper describing the study).

Counselling interventions do not necessarily involve in-person contact, and do not need to be intensive. One intervention study used a brief intervention model with callers to a charity-run health and social service helpline in a large city in the United States [119]. Callers were randomised into two trial arms, with the intervention arm receiving a set of three mailings and one counselling phone call (using MI techniques) over the course of six weeks. Participants were asked at baseline, three months and six months about their home smoking rules. The intervention group was significantly more likely to report having well-enforced smoke-free homes rules at the final contact (18.3% vs 8.7% in the control group).

Other non-intensive interventions have not been effective. One study in Italy did not demonstrate a significant change in a counselling intervention intended to be low-intensity [105]. It should be noted that no objective outcome measure was used in this study, only self-reported smoking rules in the home.

In general, more intensive interventions (with more contacts from researchers or health professionals) may be more likely to succeed than less intensive interventions. Delivery of these programmes by trained counsellors or medical professionals may improve uptake over a community setting.

2.4.2.4 Text message support

As mobile phones have become more common, many behaviour change interventions (including smoking cessation interventions [144]) have been developed to use them in mobile health or "mHealth" strategies. One common strategy is to send regular text messages with short pieces of information reminding the participant of their decision to make their home smoke-free, as well as pieces of advice on doing so and the reasons why a smoke-free home is important for health. An ongoing study in Pennsylvania has adopted this strategy, providing individualised reminders of goals from telephone counselling sessions as well as regular informational texts [107].

One recent intervention study in China [131] randomised participating parents to three groups: a group receiving motivational interviewing, a group receiving motivational interviewing and regular text messages about the importance of keeping a smoke-free home and the health effects of quitting smoking, and a control group. Self-reported father's smoking cessation (the primary outcome measure) was significantly higher in the interviewing plus text messaging group than the control group at six month follow-up.

2.4.2.5 *Pharmaceutical support*

Nicotine replacement therapy (NRT) and other medications (such as varenicline) are commonly used smoking cessation aids, designed to reduce desire to smoke by providing nicotine from another source or reducing cravings. Some interventions have provided these medications to promote smoke-free homes. Ratschen et al, 2017 [125] provided participants with NRT in addition to air quality feedback and counselling support, an approach which resulted in significant behaviour change. However, it is not possible to determine which elements of the intervention led to changes in behaviour.

Providing smokers with NRT for temporary smoking abstinence at home may be a fruitful topic for future research, but has been relatively little studied.

2.4.2.6 *Smoking cessation interventions for smoke-free homes*

Smoke-free homes can be achieved by removing cigarette smoking from the indoor environment, through a smoker choosing to smoke elsewhere or by them quitting smoking. Accordingly, a number of interventions have been developed which promote quitting as a tool for reducing the harm of exposure to SHS.

One three-armed trial studied a low intensity intervention promoting smoking cessation to mothers of young children (recruited in a healthcare setting) [111]. Participants received either usual care, brief (10-15 minutes) of counselling on smoking cessation focused on the consequences of smoking on their own health, or similar counselling focused on the consequences of SHS exposure on their children's health. While the child health-focused counselling affected self-reported smoking location, it did not prompt quitting at a higher rate either than the mother's health-focused group or the control.

One study combined these two aims, hypothesising that smokers receiving counselling sessions on keeping a smoke-free home would be more likely to want to quit [68]. Those smokers who expressed an interest in quitting were given NRT, but those who were interested only in a smoke-free home did not. Over an eighteen month follow-up period, intervention participants were significantly more likely to quit than the control group.

Mothers often quit smoking during pregnancy due to well-known concerns about the impact of maternal smoking on fetal development. However, relapse following birth is common [145]. Interventions have been developed to encourage new mothers to maintain successful quits made during pregnancy, by giving them information and counselling about the effects of SHS on newborn children. One study provided motivational interviewing in person and by phone on three occasions to new mothers, showing a small but significant change in smoking behaviour in the intervention group at six month follow-up [113]. However, this was not maintained one year on, with the authors speculating that this was due to the relatively low intensity of the intervention compared to conventional smoking cessation interventions. In another study, using similar motivational interviewing techniques by phone, the intervention group was twice as likely to report cessation at 12 weeks than the control group [118]. This may indicate that low-intensity counselling interventions can prompt behaviour change, but that they do not guarantee maintenance of that change.

2.4.2.7 Air cleaners

Two recent studies have used air cleaners in homes where individuals smoke as an attempt to reduce exposure to SHS [66,67]. One randomised control trial in the United States showed a reduction in measured PM of 25% in the intervention arm [66], while another showed a reduction of 16 – 20μg/m^3 from baseline to six-month follow-up in the trial arms using air cleaners [67]. Air cleaners are designed to reduce the concentration of PM in indoor air. However, PM is only one of the harmful components of SHS. Constituents which are not in particle phase (e.g. carbon monoxide) would not necessarily be removed from the air through the use of such a device, and so harm from other components of SHS could continue.

2.4.2.8 Interventions using personalised feedback

Personalised feedback has been used for a range of health conditions in an attempt to promote behaviour change. For instance, information on an individual's risk of developing a disease (such as type-2 diabetes) with the hope of encouraging patients to engage in healthier behaviours (for instance increased physical activity) [146].

In general terms, there is not strong evidence for the use of personalised feedback to promote changes in health behaviours. A 2017 review of systematic reviews on the communication of personalised disease risk as a behaviour change tool [147] concluded that, of nine systematic reviews analysed, none provided evidence of "strong or consistent" effects on behaviour. However, these relied on a range of studies using different markers for a range of health behaviours, including smoking, diet and physical activity. There was some evidence for short-term reductions in smoking, but little for longer term cessation. There was evidence that visual feedback of risk (such as medical imaging) could affect behaviour. One hypothesis offered for the lack of success of this approach was that the communications used did not effectively encourage self-efficacy – they did not increase the ability of an intervention participant to enact significant behaviour change (such as smoking cessation).

Several interventions have been developed using biomarkers of children's exposure to SHS to encourage parents to protect them. Several interventions have provided parents with children's salivary or urinary cotinine, a measure of exposure to tobacco smoke which can be used to detect exposure to SHS. One study gave parents information on their baby's urinary cotinine in a primary care setting, with healthcare practitioners taking a urine sample during a regular check-up and phoning the parent with the results later. No significant difference in cotinine level was observed in follow-up measurements [106]. A similar intervention, using urinary cotinine feedback to promote smoke-free homes for children with asthma, found that feedback had a strong effect on parents' odds of reporting trying to smoke only outside of the home but no significant effect on their (self-reported) odds of succeeding [122].

2.4.2.9 Interventions using air quality feedback

Several personal health interventions have been developed to share personalised air quality information with participants in an attempt to encourage them to keep smoke-free homes.

Detecting and quantifying SHS in the air is a difficult problem with a number of potential solutions. A wide range of markers in air can be detected and quantified to provide an assessment of the presence and concentration of SHS in the environment [91]. All air quality feedback interventions published so far in the literature use either air nicotine or fine particulate matter as their marker.

One early study to use air quality feedback was the Keeping Infants Safe from Smoke (KISS) study [110]. Researchers recruited parents or grandparents (either smokers or those who had recently quit) and randomised them into either a self-help (control) group or an MI (intervention) group. Passive nicotine samplers were placed in the homes of participants, and this information was shared with those in the intervention group. Those participants also received a 30-45 minute long motivational interviewing session. Control group participants received only a booklet by post with no further information on SHS reduction in the home. Air nicotine levels in the intervention group declined significantly over the study period (as measured three months and six months after the initial visit), while there was no significant change in detected nicotine in the control population.

While this study indicated a substantial reduction in measured SHS concentrations in intervention homes (and therefore likely a reduction in exposure for children living in those homes) it cannot be stated definitively that the air quality feedback element of the study resulted in that decline rather than the MI or goal-setting elements of the intervention. A multi-arm design, in which one group received minimal support, one group MI but no air nicotine feedback and another the full intervention as described could feasibly test this element of the intervention programme separately from other elements.

The REFRESH trial [72] used TSI Sidepak AM510 Personal Aerosol Monitor (TSI, MN, USA) particle counters to monitor indoor air quality in smoking homes. This information was then given to participants in the form of graphs and written information and combined with MI. This small trial demonstrated reductions in maximum $PM_{2.5}$ concentrations (mean 50% reduction) and in time spent over the then-World Health Organisation 24 hour guideline limit of 35µg/m^3 in homes in the intervention group (mean 86% reduction), significantly more than in the control group who solely received MI. This suggested that air quality feedback could potentially convince parents to keep their homes smoke-free. The REFRESH study identified certain barriers to the use of this approach, including equipment cost, noise of the Sidepak instrument and the need for trained researchers to prepare and deliver feedback. Follow-up work identified a lower cost monitor, the Dylos DC1700 (Dylos Inc, CA, USA), as a viable replacement for the Sidepak device in this type of intervention [148].

A randomised control trial of an intervention with an air quality feedback component was conducted in Armenia and published in 2013 [114]. The intervention arm included air quality feedback and counselling for smokers in the household. $PM_{2.5}$ from smoking was demonstrated using a TSI Sidepak AM510 monitor, which was used by a researcher in the home for a short period of time to demonstrate the impact of smoking a cigarette on the indoor air. Data from the monitor was downloaded immediately during a home visit by a counsellor, and graphical feedback (using a chart) was shown to them, including several minutes of monitoring indoors before smoking occurred, measurements during smoking and measurements of outdoor air, allowing comparison between these three conditions. This is distinct from other recent air quality interventions as the monitor was only used for a short period of time as an educational tool – there was no attempt to track air pollution over time and relate it to a participant's smoking. Nevertheless, the intervention was effective according to its main outcome measure (Table 2) – an overall 17% reduction in children's hair nicotine was seen at follow-up in the intervention group.

A 2013 feasibility study in the United States described a similar intervention using a customised Dylos DC1100 monitor, with information provided instantaneously in the form of visual and audio cues when high levels of $PM_{2.5}$ were detected [120]. This programme was designed to provide immediate information on SHS levels in homes in order to shape behaviour and mitigation strategies (such as smoking outdoors and increasing ventilation).

This pilot study was followed by a randomised controlled trial conducted using a similar protocol, published in 2018 [117] (with a follow-up report published in 2019 [115]). Customised Dylos DC1700 monitors were placed in homes for around three months, providing auditory and visual feedback (in the case of the intervention group).

Coaching sessions on SHS reduction were also provided to the intervention group, giving details of previous "particle events" which led to elevated $PM_{2.5}$ concentrations in the home. This study demonstrated a fall in geometric mean $PM_{2.5}$ concentrations of 18.8%, significantly higher than the 6.5% reduction in control homes. However, as the coaching sessions were not provided to the control group, it is possible that they were the effective component of the intervention rather than the air quality feedback per se.

A 2015 pilot study in Israel [149] used both Sidepak and Dylos instruments to feed air quality information back to smoking parents, along with information from samples of children's hair analysed for nicotine. Challenges were identified in using air quality feedback, due to the non-specificity of $PM_{2.5}$ and the presence of non-tobacco sources of $PM_{2.5}$. A further feasibility study of an intervention incorporating air quality feedback ("Project Zero Exposure") was published in 2018 [126] and again found challenges with the use of $PM_{2.5}$ monitoring. This could have been related to the short period of time over which monitoring took place (24 hours). Later phases of this trial used a short demonstration of change in air quality after lighting a cigarette, in a similar fashion to Harutyunyan (2013) [114]. Changes in outcome measures were seen, but the sample size of the study was too small to determine if this was significant.

A further randomised controlled trial conducted in Nottingham, England provided feedback to smoking parents in the form of annotated graphs produced using TSI Sidepak monitors. This study suggested that an air quality-based intervention could lead to reductions in $PM_{2.5}$ measured in homes of 35% following a twelve week intervention period [125].

Air quality feedback in this case was derived from three monitoring periods of 16 – 24 hours at baseline, seven weeks and twelve weeks into the intervention. These short monitoring periods could potentially have confounded results, as non-SHS sources of PM (such as frying or baking fumes [88]) or other factors could cause results in a short period to be unusually high.

Specialist “smoke-free advisors” were also recruited to take part in the intervention. These advisors contextualised the results of the air quality feedback, but also provided nicotine replacement therapy to the intervention group – potentially a powerful smoke-free home intervention itself. It is therefore not possible to say definitively that the air quality feedback component of the intervention led to behaviour change.

Another recent randomised controlled trial in South Lanarkshire in Scotland, “First Steps to Smoke-free” [127], incorporated measurements of $PM_{2.5}$ concentrations in homes measured over three periods of three – seven days, at intervention baseline, one month after the start of the intervention and six months on, as both its air quality feedback component and primary outcome measure.

Participants were mothers of young children who were existing service users of the “First Steps” project in Lanarkshire. This project is designed to engage with women having their first child who may have additional support needs, often related to low socioeconomic status. Control group participants received standard National Health Service advice on SHS reduction in homes at each visit – baseline, one month and six months. Intervention group participants also received air quality feedback from a known adviser at First Steps following the baseline measurement period and then once again at one-month follow-up. All participants received information about their air quality at six-month follow-up.

This study showed no evidence of change in either the intervention group or the control group over the three visits, making this study an outlier compared to other trials of air quality interventions. The authors hypothesise that while participants were motivated to reduce their smoking in the homes, they were unable to do so due to a lack of opportunity (through barriers such as a lack of garden space or the presence of other smoking adults in the home).

These studies have indicated that air quality information can have an impact on how individuals view the harm and risk of second-hand smoke, and the measures they take to avoid that risk.

One clear distinction among the studies is the length of time over which measurements took place. This ranged from a few minutes (as in Harutyunyan et al, 2013 [114]) through multiple twenty four-hour periods (Wilson et al, 2013 [72], Ratschen et al, 2017 [125]) to three six-day monitoring periods with two episodes of feedback (Semple et al, 2018 [127]) and continuous monitoring and feedback over a three month period (Hughes et al, 2018 [117]).

Measurement time is an important factor as a wide range of sources can affect air quality in a home in the short term, particularly when the measured element is PM (which can be elevated by cooking, vacuuming and outdoor events as well as smoking). A short, 24 hour measurement period may not accurately represent average PM concentrations in a home, which could result in participant confusion and disengagement (and make air quality measurements less accurate as an outcome measure for a study). Short measurement times could also lead to erroneous results as participants may change their behaviour due to the presence of the monitor in an example of the Hawthorne effect, in which awareness of observation affects participant behaviour [150]. Longer measurement periods may lead them to return to normal behaviour.

At least one trial on air quality feedback is ongoing at present. The Muslim Communities Learning About Second-hand Smoke (MCLASS) II study in Dhaka, Bangladesh [123] is a three-armed cluster randomised control trial on air quality feedback in a developing country setting. Air quality information is provided using a form of delayed feedback – a printed report describing an individual day's measurement using a Dylos DC1700 air quality monitor – along with culturally-appropriate messages about smoking tied to Islamic religious teachings. Of particular note in this trial is the large sample size to be recruited: the intervention is to be conducted in 1,800 homes containing both a smoker and a non-smoker. This will also be the first air quality feedback intervention trialled in a low-income country.

Of the randomised trials of air quality feedback interventions listed in Table 2, four used delayed feedback [72,110,125,126], reporting data on air quality after the events which had caused pollution had occurred, while two used immediate feedback of some kind [114,117] (Rosen et al, 2018 [126] changed from delayed to immediate feedback during the study period due to high variance in $PM_{2.5}$ data measured over time in homes). Hughes et al, 2018 additionally used coaching on the causes of high PM concentrations in the home, providing a form of delayed feedback [115,117]. This difference could cause participants to behave differently – those receiving delayed feedback cannot take immediate action on it, and must instead plan to take action in the future in order to achieve behaviour change, while those receiving immediate feedback on SHS in the home can take action, such as increasing ventilation by opening doors or windows and extinguishing or removing a cigarette. This is particularly evident in the case of Hughes et al, 2018 [117], where auditory feedback provided an immediate warning of high PM concentration.

Bellettiere et al (2014) [151] suggested that immediate feedback following a smoking event is more effective than delayed feedback. However, immediate feedback could potentially result in inaccuracies, as a sudden elevation in PM in a home may be the result of cooking events or other sources, not necessarily SHS. This was a specific goal of the immediate feedback intervention conducted at San Diego State University, where an outcome measure was to reduce the number of "particle events" which led to increased $PM_{2.5}$ concentrations indoors, including cigarette smoking, e-cigarette use, burning candles or incense and frying with oil among other behaviours [115]. This could reduce participant confidence in an intervention designed principally to reduce SHS rather than all causes of $PM_{2.5}$ indoors.

Of the five full randomised control trials of air quality interventions listed in Table 2, four showed significant effects on empirically measured household SHS concentrations or biologically determined SHS exposure compared to control groups. Geometric mean reduction in measured SHS concentration in homes was as high as 36.3% in one trial [125], suggesting that air quality feedback can be a useful strategy for reducing children's exposure to SHS in the home.

2.4.3 Developing smoke-free homes interventions

2.4.3.1 Changing behaviour

As smoking is addictive, changing smoking behaviour can be very difficult, whether the intention is to stop or to smoke outside of the home. Effective interventions should take account of the theory and prior practice of public health and health behaviour change.

Many smoke-free homes interventions have used behaviour change theory to analyse the capacity of participants to make significant change. This capacity has been modelled theoretically by a number of different approaches, notably including the transtheoretical model [152] which conceptualises various stages of change ranging from "precontemplation" (when an individual has not yet seriously considered changing their behaviour) through “contemplation”, “preparation”, “action” and “maintenance” (when a behaviour has successfully been changed and the participant wishes to continue on their new path). These stages have been measured using questionnaires. At least one smoke-free homes intervention has used progress through stages of change as an outcome measure [116].

2.4.3.2 Barriers and facilitators to smoke-free homes

It is important to take into account barriers and facilitators for creating smoke-free homes – those factors promoting the idea to a parent or caregiver, and those which may hold them back. Many parents may wish to make their homes smoke-free, but find themselves unable to do so due to factors which they believe are effectively out of their control.

A recent review by Passey et al [153] identified seven themes in issues affecting barriers, motivators and enablers for smoke-free homes: knowledge, awareness and risk perception; agency and personal skills/attributes; community norms and moral responsibilities; social relationships and influence of others; perceived benefits, preferences and priorities; addiction; and practicalities.

Barriers which have been cited include lack of support from partners, particularly smoking partners, while support itself can be a facilitator [154]. Ease of access to outdoor spaces can be a determinant of making a home smoke-free – where outdoor space is difficult to get to (such as in the case of a participant who lives in a multi-storey apartment building) making the home smoke-free may require quitting smoking [155].

Knowledge about SHS and effective strategies to reduce exposure can be a facilitator of change. By contrast, the perception of SHS as an acceptable risk for children (or a factor which does not create risk) can be a barrier. This can be linked to personal experience, such as in the case of parents who were exposed to SHS as children themselves without obvious negative effects, or social norms among a family or social group.

Changing and complex living circumstances, such as changes in the number of people living in the home (due, for instance, to volatile family relationships) can also create barriers. Parents may be unwilling or unable to leave the home if no other adult is available to mind their child. This can result in a conflict between the desire to keep children safe from SHS exposure, and the desire to keep them safe from potential harm within the home. Parents may feel guilty for

Level of addiction to nicotine can also create a barrier. Highly addicted individuals may feel the need to smoke while watching their children, and may be unable to overcome this barrier.

For these reasons, it is important to assess the capability of participants to take action before intervening, and to customise an intervention to their circumstances, if it is to have an effect.

2.4.3.3 Communicating information about SHS effectively

A range of educational and communication materials have been developed and tested to promote smoke-free homes (as detailed in "Self-help materials", above).

Cultural awareness is an important component in the design of intervention materials, though it does not guarantee effectiveness. Circumstances (such as child ill-health) may also be relevant. Reading level may be an important factor in material development, particularly in countries where the smoking population is likely to be more poorly educated than the general population.

2.4.3.4 Communicating objective SHS feedback

Objective SHS exposure feedback given to participants should be relevant and comprehensible in order to be effective.

Most studied interventions have given participants delayed feedback – where a monitor has been installed over time and results given afterwards in the case of air quality feedback, or (by necessity) using a biomonitoring test and receiving results later in the case of cotinine or hair nicotine feedback. This may take the form of printed materials or information displayed on a computer. Results have been given to participants in person or sent by post, sometimes with a follow-up phone call to discuss them [106].

Some interventions, however, have given feedback to participants immediately, either by demonstrating the effect of smoking cigarette using a monitor and computer [114,126] or by installing a monitor along with visual and auditory communications hardware to alert participants when air quality was poor [117,120]. Trials using both strategies have been effective.

In order to develop auditory warnings for use as part of an intervention Bellettiere et al (2014) [151] carried out a series of focus groups and consultations with experts in the field, and a small opportunistic survey with members of the population to be targeted in an intervention. This model of expert and participant engagement has been used in intervention development processes such as intervention mapping [156].

Comparisons with other perceived health risks could be used as a strategy to promote smoke-free homes. One educational tool has directly connected SHS and diesel exhaust, a serious and common form of air pollution outdoors. De Marco et al (2015) [99] compared the impact of diesel fumes to SHS from one cigarette on PM_1 and $PM_{2.5}$ concentrations in an enclosed space, demonstrating to affected workers at a steelworks in northern Italy that SHS-related PM was much higher than diesel exhaust PM. This strategy could be an effective educational tool.

2.4.4 Future intervention design

Any personal health intervention must balance the cost of intervention elements with those required to be effective. Interventions targeting specific at-risk populations may be more intensive than interventions designed to be delivered to larger groups. Some interventions may be effective only with particular groups, or could be tailored for that specific effectiveness.

Self-help materials (including leaflets) could be included in an intervention, but as they are unlikely to be highly effective their cost should be reduced to a minimum. Cultural and circumstantial tailoring should be considered, but not at great cost. Similarly, mementos could be used but are unlikely to promote behaviour change effectively. Low-cost, high-reach interventions could use these elements if their cost is low enough.

Counselling has been used successfully in a range of interventions. Future intervention design should include counselling elements, and motivational interviewing techniques could be used. This counselling need not necessarily be intensive, and could be delivered by telephone or in person. Behaviour change theory, including the transtheoretical model, could be used to provide guidance in this counselling. This support should consider barriers and facilitators for smoke-free homes and progressive goal-setting techniques.

Air quality feedback has been successful in several trials, and could be included in future interventions. These techniques can be intensive, particularly where delayed feedback is provided in person to participants. Care should be taken to ensure that individuals receive understandable and useful feedback.

Innovative elements, such as text message support, could be used to provide this feedback and other information on keeping smoke-free homes.

Delivery of counselling interventions should be conducted by researchers or medical professionals rather than in a community or charity setting.

2.5 Summary

A wide range of techniques have been proposed to reduce children's exposure to SHS at home. Relatively few are consistently successful.

Outcome measures used to determine the success of smoke-free homes interventions have included participant self-reporting, biomarkers such as salivary cotinine and air quality monitoring, including PM and air nicotine measures. These strategies are not exclusive and multiple approaches in one study may be used to corroborate results.

Self-help materials are widely used and simple to prepare and distribute, but are unlikely to be effective unless they are highly relevant to intervention participants. Awareness of cultural context may be helpful but does not guarantee success.

Counselling, including motivational interviewing, can be an effective means of promoting smoke-free homes. This can be true whether counselling is provided in person or by phone - even brief telephone support can result in parents changing their smoking behaviour. However, efficacy depends on the specifics of the programme, including the training given to the individuals delivering it, and the intensity of the intervention could affect results.

Smoking cessation medications (including NRT) have been used to promote smoke-free homes, but few interventions have used this strategy, which may usefully be explored in the future.

Air cleaners can reduce the concentration of SHS-related PM in the home, but not eliminate it, and cannot remove other harmful components of SHS from the air.

Personalised feedback interventions have been developed using a wide range of measures of SHS exposure. Direct measures of children's exposure, such as cotinine measures, show whether exposure has occurred accurately and can do so days or weeks after that exposure has occurred. However, this information is not available immediately and requires lab treatment. Self-reporting is easily achieved but could be unreliable. Air quality feedback is increasingly common.

Air quality feedback interventions have used two main methodologies to measure SHS in the home for feedback. Earlier studies have used passive nicotine detection. This method is silent, simple and specific for tobacco smoke, but does not provide data on SHS over time. Real-time particle monitors, by contrast, provide data on $PM_{2.5}$ over time but can detect pollution from other sources (such as cooking), and can be noisy due to the need to incorporate a fan into their design.

Nonetheless, most recent studies in this area have preferred particle monitors to air nicotine detection (although the latter has been used as an outcome measure).

Air quality feedback can be immediate, where a change in SHS is instantly reflected in feedback given to a participant by visual or auditory means, or delayed, where information on SHS concentration over a period of time is given to the participant later on.

Four of five randomised control trials of air quality feedback interventions have shown significant promise in reducing parental smoking in the home, and this strategy merits further exploration.

3 Aims and research questions

3.1 Research aims

This research aims to determine whether air quality feedback can assist smokers to protect children under their care from exposure to SHS, by eliminating or reducing smoking in the home.

3.2 Research questions

- How do smokers, ex-smokers and those living with smokers understand the relative impact on health of SHS and indoor air pollution compared to outdoor air pollution, as it applies to national policy and their own behaviour? (RQ1)
- Can giving people in socioeconomic groups associated with high exposure to SHS accurate, personalised information about the effects of SHS on air quality influence their decisions to keep their homes smoke-free? (RQ2)
- Does giving that information in different forms influence views of SHS and air quality? (RQ3)
- Can low-cost $PM_{2.5}$ monitors be used to differentiate SHS from other sources of PM, and thus provide more accurate information on the source or behaviour leading to poor air quality? (RQ4)

3.3 Objectives

1. Analyse internet forum comments about recent smoke-free places laws to learn more about attitudes on the relative impact of second-hand smoke and outdoor air pollution on indoor air quality.
2. Explore those attitudes in more depth in focus groups of smokers and non-smokers living with smokers.
3. Develop an air quality-based smoke-free homes intervention featuring new behaviour change techniques, visualisations and software.
4. Test the impact of those novel elements of the intervention first in a pilot study and then in a larger trial across a number of European cities (part of the TackSHS study).
5. Develop a candidate algorithm to differentiate SHS-related $PM_{2.5}$ from other sources, and recruit participants in a small study of smoke-free homes to provide data to test that algorithm with smoking home data.

3.4 Structure of this thesis

Multiple studies are included in this thesis. These studies, the chapters in which they are described and the author's contribution to them, are summarised in Table 3.

Table 3 - Studies included in this thesis

Chapter	Study	Author's contribution
4	Qualitative study on attitudes to SHS and outdoor air pollution	All aspects of study design, ethics application, facilitating focus groups, coding and thematic analysis.
5	AFRESH – developing and testing an air quality feedback intervention	Equal contribution to study design with colleagues. Facilitated expert panel discussions, facilitated one of three focus groups. Designed candidate SHS visualisations and final SHS visualisations. Developed AFRESH software to download and interpret air quality data from Dylos DC1700 monitor. Coordinated delivery of the intervention with the local centre in South Lanarkshire. Conducted quantitative analysis of results.
6	Development of remote air quality monitoring technology (the RAPID)	All aspects of system design and testing, including ethics application and fieldwork in Israel.
6 & 7	Measuring for Change: an air quality feedback intervention trial in four European countries	Equal contribution to study design with colleagues. Development of Tackle software to deliver feedback. Design of feedback elements including SMS and email messages. Coordination with European centres. Equal contribution to recruitment and fieldwork in Scotland with one colleague. Quantitative and statistical analysis of results.
8	Detecting smoking in homes using low-cost PM monitors	All aspects of study design, data collection and analysis.

4 Attitudes to second-hand smoke and air pollution

This chapter addresses research question 1:

- *How do smokers, ex-smokers and those living with smokers understand the relative impact on health of SHS and indoor air pollution compared to outdoor air pollution, as it applies to national policy and their own behaviour? (RQ1)*

and objectives 1 & 2:

1. *Analyse internet forum comments about recent smoke-free places laws to learn more about attitudes on the relative impact of second-hand smoke and outdoor air pollution on indoor air quality*
2. *Explore those attitudes in more depth in focus groups of smokers and non-smokers living with smokers*

4.1 Introduction

In response to the public health problem of childhood SHS exposure, the Scottish Government announced its intention to reduce children's SHS exposure at home by half from 2012 to 2020 [62]. Similar policy goals exist in England [157] and elsewhere in the world [158].

To achieve these objectives, it is important to understand the ways that smokers and those living with smokers perceive SHS as a health risk in comparison to other related risks, such as outdoor air pollution. In particular, interventions designed to promote smoke-free homes using air quality feedback should take into account participant understanding of air pollution – this feedback may be ineffective if participants do not view SHS as a significant source of air pollution, or view outdoor air pollution as more harmful than indoor air pollution. In contrast to this conception of relative harm, objective exposure assessment data has indicated that a non-smoker living with a smoker may inhale a similar mass of $PM_{2.5}$ as a non-smoker living in a heavily polluted city in the developing world [63].

It is not clear how smokers and those close to them view the relationship between SHS and air pollution issues. In particular, these individuals may view outdoor air pollution related to car use as having similar effects on air quality and health as SHS in the home, despite the significantly higher levels of particulate pollution created by smoking indoors [98]. This may affect the way they prioritise creating a smoke-free home, potentially leading to health harm to themselves and their children.

The most recent major smoke-free laws passed in the UK have been restrictions on smoking in cars carrying children. Research into the poor air quality in cars where an individual is smoking [57] was central to the case to pass this legislation, which came into effect in England & Wales in late 2015 and in Scotland at the end of 2016. This has attracted intense debate online.

Smoke-free laws, while popular in the general population [159–161], are regularly controversial, attracting debate among smokers and non-smokers alike. News website articles on the subject posted online regularly attract a large number of comments, both positive and negative. Some of these comments support the principles of smoke-free places, while others may oppose the laws, citing concerns about individual liberty, personal choice and government intrusion into private life. In particular, some commenters have been observed to cite misconceptions about the relative health effects of outdoor air pollution compared to second-hand smoke.

The aim of this phase of the research was to identify views on SHS and outdoor air pollution which may be relevant to smokers and those close to them who are likely to experience smoke-free homes interventions. To do this, an internet comment thread on an article describing the debate around smoke-free car laws was selected. Comments dealing with outdoor air pollution in this thread were analysed thematically [162] to determine the themes of the discussion used by both proponents and opponents of the law. After this analysis, focus groups with smoking parents were undertaken to discuss the themes identified in the analysis of comments.

4.2 Methods

4.2.1 Analysis of comments

A comment thread from the BBC's news website was selected for analysis. This site was selected for a number of reasons:

- it is heavily trafficked, having been reported to be the most heavily used news website in the UK [163], potentially providing access to a wide range of opinions in comments;

- there are typically high numbers of comments on articles which allow commenting, potentially encouraging a larger number of responses;
- it is statutorily politically neutral.

The article selected, titled “Car smoking ban comes into force” [164], dates from the introduction of the law banning smoking in cars carrying children in England and was published on 1 October 2015. This recent smoke-free legislation engendered public debate about the roles of government and family in protecting children from second-hand smoke, and the need to make environments smoke-free.

The comments were downloaded from the website using a custom-written script and loaded into the NVivo qualitative data analysis software [165] for analysis. Comments were coded for content relevant to air pollution and SHS issues and the codes informally grouped into themes. A sample of comments with codes were checked by Dr Zoë Skea (University of Aberdeen), who also grouped codes into themes. Both researchers met to discuss and agree on emergent themes.

4.2.2 Focus groups

Following the thematic analysis of online comments, a topic guide for the planned focus groups was developed using relevant themes. This allowed for the exploration of these themes in greater depth, providing understanding of how attitudes develop based on different factors.

It was the intention to recruit three focus groups of around six to ten subjects with the participation of third sector organisations working in deprived communities in Scotland. This sample size and number of groups was selected to allow a range of opinion, potentially from different centres, while still being achievable in the available timeframe.

Potential partner third sector organisations were chosen on the basis of their service delivery in lower socioeconomic status areas in and around Glasgow. Organisations in this location were selected because workers at these organisations had been able to make contact with appropriate subjects for similar groups in the past.

Potential subjects were approached by members of staff at the organisation and given information informally about the purpose of the focus group. Potential participants were then invited to focus group sessions.

Recruitment used inclusion criteria set out in Table 4. Like other smoking-related risks, second-hand smoke indoors disproportionately affects lower socioeconomic status communities [61] so we believed it was appropriate to focus efforts to understand it on these groups. As the harm of second-hand smoke is particularly acute for children, and follow-up work was focused on the development of interventions to promote smoke-free homes where children live, caregivers (full- or part-time) were recruited.

Table 4 - Inclusion and exclusion criteria for the focus group elements of this study

Inclusion criteria	**Exclusion criteria**
Takes care of at least one child under 16	Unable to provide informed consent
Smoker or lives with a smoker	Under 18
Living in a deprived area (SIMD quintile 1 or 2)	
Able to understand and communicate in English	

Recruits were not asked for further demographic data.

Focus group members were asked to agree to audio recording as a precondition of taking part in this research. Interviews were transcribed by the author.

Focus groups were semi-structured and conducted using the topic guide developed following comments analysis (Appendix I). Thematic analysis was conducted by the author with Dr Zoe Skea providing additional code and theme checking. Both researchers agreed on themes.

4.2.3 Ethics and consent

Ethical approval for this study was given by the College Ethics Review Board of the School of Medicine, Medical Sciences and Nutrition at the University of Aberdeen (reference number CERB/2018/1/1525, 6 March 2018). Informed consent was given in writing by all focus group participants at the beginning of each group.

4.3 Results

4.3.1 Comment analysis

There were 1,109 comments made on the article before it was closed to comments at some time after 16:26 (BST) on 1 October 2015. 88 of those made some mention of outdoor air pollution or issues relating to it.

These comments were read and coded to identify the relevant themes emerging from this online discussion. Selected themes and example comments are shown in Table 5. Numbers in brackets following quotes represent comment index numbers in chronological order.

Commenters frequently expressed cynicism about the likely health impact of a ban on smoking in cars carrying children compared to the effects of vehicular air pollution: "So its OK to sit in traffic with a petrol diesel lorry/car in front belching out all these nasty hydrocarbons is it?" (#29). In hyperbolic comparison with cigarettes, cars were referred to as "belching disgusting clouds of black smoke" (#30).

Many commenters dismissed the idea of curbing vehicle emissions as unlikely or politically impossible: "cant see them banning cars though that [would] improve your health." (#17). This may have related to a perception that the law on smoking in cars was tokenistic rather than intended to make a significant difference: "why aren't you vigerously[*sic*] campaigning for a ban on diesel engines? Given that their pollutants currently kill more people [than SHS]" (#47)

Others suggested that restrictions on driving were necessary as a priority: "what is the point of this when the planet as a whole is being poisoned, I think anyone driving diesel cars should also be fined" (#44).

One common topic of concern and ridicule was the Volkswagen (VW) emissions scandal, in which VW was found to have cheated European Union emissions standards for diesel cars. Commenters referred to VW vehicles as particularly polluting, with one suggesting that "a fag puff is cleaner than whats coming out the car" (#42).

No commenters mentioned non-vehicular sources of outdoor air pollution. This may be due to the topic of the discussion (which neatly juxtaposes emissions from cars with emissions from cigarettes) or may be due to the high prominence of vehicular air pollution in UK political discourse.

Table 5 - Selected themes and example comments from this analysis

Theme	**Example comments**
Air pollution is just as bad as SHS	"I totally agree that children should be kept safe from smoke... and the fumes from the plethora of cars!" (#4) "Whilst if the kids open the window they can breath in deadly fumes from Diesel vehicles which the european Governments have cosied up to the European manufacturers over. But Smoking is non PC whereas European Diesels are PC so let's keep poisoning the kids..." (#63)
Tackling SHS is the correct priority for action	"In this day and age, motor vehicles are a necessary evil.I can't say the same about smoking, can you?" (#26) "Total nonsense. Smoking definitely kills more than exhaust fumes! Get your facts right instead of subscribing to gossip." (#48) "A lot of people here have no grasp of logic and (more specifically) relevance. References to diesel fumes, unleaded petrol, junk food and so forth ... yes, other things are harmful, some less, some more, what has it to do with this?It makes as much sense to say "Well, if an anvil fell on you it would do a lot more harm than passive smoking so they should do something about that first"." (#80)
Children's health is the priority	"How can anyone even argue that smoking in a car with children is acceptable?It's nothing to do with driving skills, car emissions or anything else other than slowly poisoning children.If you think it's ok to poison children then you're wrong. Simple." (#18)
Car emissions should be curbed	"Why not set a deadline by which time the exhausting of particulates is banned? I am sure such a deadline would motivate the industries concerned to find a solution." (#3) "But unfortunately the main danger is not within the car but on the outside in the vicinity of the vehicle. Large volumes of extremely toxic gases are puffed out of car exhaust pipes several times a second. Perhaps banning cars from anywhere near the school gates would be an even better call?" (#76)

4.3.2 Topic guide

A topic guide was developed using the themes analysed in the comments, relating to the relevant research questions and objectives of this research.

The topic guide is available in Appendix I.

4.3.3 Focus groups

Five third sector organisations working with the target group were contacted. Three responded to inquiries and one was able to assist in recruiting groups within the timeframe of this study.

Three focus groups were conducted in May 2018 (one group) and July 2018 (two groups) with participants identified and contacted through Healthy Valleys, a community third sector organisation in South Lanarkshire. Due to limits on the available resources and staff time at Health Valleys, participants were recruited opportunistically at regular events run by the charity rather than generally among the population, and therefore focus groups were limited to attendees of those events. For this reason, it was not possible to recruit the planned six to ten participants for each focus group, and ex-smokers and occasional care-givers (such as grandparents) were included. Group 1 attracted four participants, group 2 included three, and group 3 included two. All participants in groups 1 & 2 were female, while one participant was male and the other female in group 3.

Selected themes from the analysis of the groups are presented in Table 6, along with comments from participants exemplifying those themes.

Participants have been identified in extracts using group number and a letter corresponding to the order in which they first spoke during the group (e.g. participant 1A attended the first group and spoke first, while participant 2C attended the second group and spoke third).

Table 6 - Selected themes and example comments from focus group discussions

Theme	**Example comments**
Cynicism about government intentions and profit motive	"…the government are the ones that go on about the pollution, the ozone layer, all that stuff right? But they're the one that's permitted cigarettes to be made, cause obviously they make a profit off of the cigarettes, that's obviously why they're legal." (2A)
Air pollution is visible, smells and has a "feeling" which makes it unpleasant to be around	"Sometimes you don't even need to open your windows, you can tell by the dirt from the outside, you know?" (1B) "And the more you stay in Glasgow with all the air you can get sore heads, cause the last time I was there it was like smelly plastic and rubber burning..." (2A) "…if you walk somewhere and you go 'this place really smells bad and I don't want to be here', then it's probably a good, our instincts are probably quite good at saying get out of here cause this isn't good." (3B)
SHS is not as bad as other kinds of air pollution	"I would say - maybe a bit worse actually… your smoker comes and goes, don't they? I could come to your house, talk to you and have a cigarette if that's ok with you, ten minutes later I'm gone. Maybe in an hour or so all the smoke's gone out your house. But when a car's passing every two minutes, it's constantly coming into your property." (3A) "you would rather be smoking in your garage than have your car exhaust going when you've got the doors closed, so I guess that cars are more dangerous than cigarette smoke for you" (3B)

SHS is worse than other kinds of air pollution	"I think if you smoke inside because it's such a confined area I think it might be more dangerous than walking the streets with the cars" (1C) "if it's in a home environment, I think that second-hand smoking would probably be worse than anything else" (2A)
Vehicles are the most prominent source of air pollution	"make people walk home, get rid of emissions as much as you can from cars and industry, that's I think the main one." (1A) "whenever I'm driving my car and I'm stopped in traffic, maybe it's a nice day, I've got my window down or I've got the air conditioning on and there's a car in front of me, the fumes are immediately, I'll turn off the air con and put my window up cause I don't want to breathe in, cause you can smell it" (1D) "Even if [the participant's son] goes to his sister's in Kilmarnock he can comeback really quite poorly, and it's from the change in the air. But, I suppose with their buses and everything, think how many buses are in Glasgow, one every five minutes? That's like 900 buses from all the bus stations so it's gotta be really bad." (2A)
SHS can be visible, particularly in residue, and it is disgusting	"I smoked in the house, and when I cleaned things, the nicotine that came off it was absolutely disgusting and I don't know why that never put me off smoking but it didn't and it's disgusting, the yellow stuff, and you think that's lingering in your house" (1C)
Urban areas are more polluted than rural areas	"I keep harping back to my grandkids cause I haven't got young kids anymore. They live in a big town and they're always out, my daughter won't keep them in cause they're two boisterous little boys so they're always out, but like I'm saying, they're the ones that seem to be having the health issues…" (1C)

	“It's not so bad here, in the rural areas. See when you start going into Glasgow and Edinburgh, that's when you smell it, you can tell, you get tired” (2C)
Individual action can help indoor air but outdoor air is governed by politics and community action	“you can smoke outside … you can make that choice and then, I suppose, but there's things like cars and stuff, it's hard” (1A) “I don't think there's an awful lot we can do as individuals apart from being aware of it and keep pushing for more and more to be changed, and... for the government to put these things in place and get a cleaner air” (1C)
E-cigarette vapour is a cause for concern, and may not be any better than cigarette smoke	“even with these vape cigarette things as well, I don't see how that's less pollution than a normal cigarette, to be honest… the amount of smoke, you're like how the hell can that be better?” (2A). “There's not as much smoke as there is coming from them, but it's disgusting” (2C)

4.3.3.1 *First impressions of air pollution*

Following introductory remarks, focus group discussions began with a general question about the first thing participants thought of after hearing the words "air pollution". Participants interpreted this question in different ways – some listed various potential causes of air pollution, while one participant described their reaction to experiencing air pollution, calling it "disgusting" (2A).

4.3.3.2 *Sources of air pollution*

When participants spoke about causes of air pollution, they generally listed outdoor air pollutants (including vehicles, industry and agriculture) rather than indoor pollutants. After further discussion indoor sources were usually mentioned.

Vehicles were very commonly referred to as an important cause of air pollution, and were a frequent topic of discussion throughout all three groups. Emissions from diesel engines were a particular source of concern

Living on or near a road was a concern from this perspective as well: "when you're staying in the big cities and when you've got your windows open as well, all that pollution can go into your house. Cause you've got the big trucks and all that driving…" (2C)

Industrial pollution was also mentioned, sometimes in the context of electricity production or oil refining: "power plants and that, they're all creating pollution" (3A). As these focus groups took place in a rural setting, participants did not have experience of nearby industrial pollution, viewing this as an issue in cities and larger towns.

Forms of indoor air pollution mentioned included boilers, a particular concern because of fears about carbon monoxide, referred to as an "invisible killer" (1C), and indoor coal fires, a number of which had recently been replaced in housing authority homes in one of the villages where the focus groups took place, and which participants implicated in poor air quality: "I stayed up here in 2002 and a lot of people had coal fires, then I moved away in 2007 and I came back … they started taking out coal fires, and over the past few years the air has been a lot easier" (2A).

Allergens such as pollen were also seen as a form of air pollution by some participants: "My grandson, he has eczema, but he's allergic to grass, cause he's got, see him he's covered, cause he's just been rolling in the grass. so again, is that an air pollutant? To some, but not to everybody." (1C)

Some participants referred to e-cigarette aerosol as a potential cause of poor air quality, referencing the large clouds of smoke seen when newer e-cigarette devices are used: "when you see the amount that comes off! I know it's bad what comes off a cigarette, but what comes off one of them vapes, it's like a cloud.” (1C) E-cigarette aerosol drew direct comparison with SHS, with participants questioning whether it was safe to be around, particularly as these products are relatively new:

Participants expressed concern that e-cigarettes may be no healthier than combustible cigarettes: “if I'm giving up cigarettes I'm not suddenly going to start vaping cause I don't know what that's doing to- at least I know what a cigarette's doing to me!” (1C).

In the second group, a local waste dump with a particularly bad odour was held to be a source of air pollution:

> 2A: Well look up there, they've built one of those, it was meant to be a landfill, and they've dug it out… and it's now full of stagnant water. Smelly. It's stinking! See when the wind blows, it's horrible.
>
> 2C: It's like raw sewage, the smell.
>
> 2A: There's nothing in it apart from, just, like rain water.
>
> 2B: That's what we smelled the other week, that's what that was.
>
> Interviewer: So that smell, do you think that's associated with air pollution?
>
> 2A: Yeah, definitely. It's really bad.
>
> Interviewer: So do you think that would have a big effect on your health?
>
> 2A: I would say so.

This was not the only time that odour was linked to air pollution. On several occasions, participants referred to the smell of air pollution as a reason to be concerned by a particular source, including cars and ambient pollution in cities and towns. One participant stated explicitly that smell was a viable way to determine the level of risk of air pollution: “if you walk somewhere and you go "this place really smells bad and I don't want to be here", then it's probably a good, our instincts are probably quite good at saying get out of here cause this isn't good” (3B).

4.3.3.3 Relative harm of different forms of air pollution

Multiple participants mentioned carbon monoxide as the perceived worst form of air pollution, due to concerns about the gas indoors and produced by vehicles, sometimes due to personal knowledge of people affected by it. This could colour perceptions of the health risks of different sources of air pollution, with participants in the third group agreeing that carbon monoxide meant "cars are more dangerous than cigarette smoke" (3B). Carbon monoxide was thought of as undetectable, unlike other potential causes of air pollution at home: "You can't smell it. Like if you have a gas leak you can smell that. And you can actually see it." (2B).

Most participants expressed the view that SHS is more harmful to health than other forms of air pollution, particularly in a confined space: "it's the people in my house, if I'm smoking in the house that are inhaling my smoke, and it's in a confined areas to me that's probably more dangerous" (1C).

Some participants took the view that outdoor air pollution, particularly in the form of vehicle pollution, is more harmful than SHS exposure: "obviously there's more cars and that going past the windows than there's people smoking a cigarette in your, directly in front of you". (3A)

Participants mentioned confined spaces as a health hazard outdoors as well as indoors. In one exchange in group 3, participants indicated that the tall buildings of a high street could create a confined space for vehicle-related pollution: "yeah, and the main road doesn't have any built up things on either side, where in a town you've got the buildings, so that kind of traps the [inaudible] as well" (3B). Another participant likened this situation to "being in a box with the lid open." (3A)

In general, health effects from both SHS and other forms of air pollution were perceived as primarily respiratory, with asthma a particular concern: "the coal fire went for my wee boy's asthma" (2C). Children and older people were seen as especially vulnerable to health harm: "I think the younger spectrum or the older spectrum would be mostly affected, rather than like twenties-thirties, below that and above that, they would be affected the most." (2A). In the case of children this was associated with a perception that air pollution affects healthy development: "it's affecting how they grow" (1A).

Health effects were generally thought to be long-term rather than acute, building up over years to have a serious impact on health and wellbeing: "you'll suffer gradually" (3A). This was a matter of concern, particularly in the context of young children: "I won't be around forever. Which is understandable. But I think ahead. And I think "right I've got me grandkids", the youngest one's six weeks old, so if you going on years from now, what's she going to be suffering with all the fumes and that in the air, what you breathe whether you smoke or drive or whatever. Everybody's gonna, you're gonna suffer.” (3A).

4.3.3.4 Is SHS distinct from “air pollution” as a category?

This was a matter of debate for participants. Generally, participants made a distinction between indoor and outdoor air pollution, with SHS considered a problem for health indoors but not outdoors: “second-hand smoke to me is in a confined space, it's not inside, cause they're telling you to take it right outside, so therefore it's evaporating into the air… second-hand smoke to me is, it's inside, when it's all compacted and can't get out anywhere, and it lingers for hours” (1C).

SHS was held to be a local, indoor issue: “you don't think of it going further up, polluting the full air… know it affects you round about, but you don't think in the wider picture” (1D). By contrast, outdoor air pollution was thought of as totalising and unavoidable: “at the end of the day, air travels round the whole world, that's the point… clouds travel, pollution travels” (2A). Some participants expressed resignation regarding outdoor air pollution: “it's never gonna go away” (3A).

Generally, participants identified SHS as the worst cause of poor air quality in homes: “if we're talking about inside and outside, you’ve gotta go to the smoking” (1C).

4.3.3.5 Priorities for reducing air pollution

When asked to suggest high priority actions to reduce air pollution, participants frequently mentioned switching transportation from cars to methods of active travel: “I'd probably make people walk more, take their bikes, unless it was a necessary journey like for work that's very far away”. (1B)

These participants were critical of those who travel by car unnecessarily, often citing examples from their own experience: “there's actually a neighbour who lives across the road, and the shop from my house is literally ten, fifteen second walk, and I've actually seen him driving to the shop. I'm like ‘c'mon, man!’” (1B). Nonetheless, participants defined some level of car use as acceptable: “I mean don't get me wrong, I'm a driver, but I don't go out every day of the week” (3A). This may have reflected the rural setting of this research, where cars were seen as a necessary part of everyday life for most participants.

4.3.3.6 Individual vs collective action on air pollution

In general, participants viewed air pollution as an issue which would need to be solved collectively, not individually: “I don't think there's an awful lot we can do as individuals apart from being aware of it and keep pushing for more and more to be changed, and... for the government to put these things in place and get a cleaner air” (1C). Government action was observed to be necessary to achieve meaningful change by several participants: “I'd say that you need to reduce vehicles on the road .So the government need to say right, if you have a car, it can't be no older than so-and-so” (3A).

Participants frequently expressed cynicism about government efforts to reduce smoking-related harm compared to other causes of air pollution, in common with comments analysed in the earlier phase of this research: “at the end of the day no-one can tell anyone to smoke or not smoke. If cigarettes weren't available, the government didn't give the go ahead to make cigarettes in the first place, then this wouldn't be a problem” (2A).

These efforts were sometimes regarded as ineffective and tokenistic when, in general, it wasn’t perceived that air pollution is in decline: “They're supposed to be reducing the emissions of the diesel and the petrol and all this lot, and the smoking ban and everything, but kids are still suffering with asthma, so the pollutants are still in the air, we don't seem to be getting rid of them, we don't seem to be making the air any better.” (1C). Profit motives were highlighted as a reason for this lack of effective action: “the company want to sell their product [cars] don't they, and they're gonna do anyway they can to make that happen” (3A).

4.4 Discussion

Air pollution was linked to a range of sources, most commonly vehicles, both in comments and focus groups. Sources varied from the general (vehicle or industrial pollution) to those affecting homes or small areas (coal fires or boilers).

Responses from online commenters and participants in focus groups demonstrated a high awareness of issues around outdoor air pollution, with responses often criticising the quality of the outdoor air even in fairly rural settings where outdoor air quality was likely to be good. Previous research has described personal understanding of air pollution as driven by personal experience such as smell [166], a link made by several participants in this study. Focus group participants generally perceived a difference between pollution in outdoor air and indoor air, although they believed that the former could affect the latter. SHS was usually seen as a specific issue rather than a manifestation of wider concerns around air pollution. However, SHS was clearly seen to impair indoor air quality in a way comparable to (and generally more severe than) vehicle-related pollution. Future research could test this using educational tools designed specifically to compare SHS and vehicular pollution, such as a video developed in an Italian study in 2015 [99]. The comparability of health effects from tobacco smoke and other types of air pollution has been seen previously in the literature, with one study in the northeast of England in 2003 suggesting that participants considered active smoking a worse contributor to diseases such as lung cancer than air pollution, but that air pollution was a greater mediator of asthma than smoking [167].

Participants expressed the view that indoor air could be affected by the quality of outdoor air. For this reason, the design of interventions to promote smoke-free homes through air quality feedback should consider ways to demonstrate that poor air quality is caused by SHS, rather than outdoor sources.

Not all forms of air pollution were viewed equally. In particular carbon monoxide was viewed as a far more severe health hazard than other pollutants – a reasonable view given the serious acute effects of exposure. Future research could explore the level of understanding of different forms of air pollution, such as particulate matter vs carbon monoxide.

Air quality feedback interventions could also explore the use of carbon monoxide monitoring as a tool to promote smoke-free homes, but care should be taken not to conflate the detectable but low levels of the gas present in SHS with the high and quickly deadly levels mentioned by participants in these focus groups.

Individual action was not seen as a substitute for wider governmental or social action in tackling air pollution overall, and some cynicism was expressed regarding the government’s willingness to reduce smoking while deriving tax revenue from tobacco. However, focus group participants generally accepted the idea that indoor air pollution could be reduced, particularly by avoiding SHS in the home. This may indicate that personal health interventions designed to link SHS exposure to air pollution indoors could provide effective messages to reduce smoking indoors.

4.4.1 Strengths and limitations

This is the first study to compare perceptions of SHS and outdoor air pollution directly, and the first to analyse an internet discussion thread for this purpose.

The large sample of comments available in the discussion thread element of the work was a positive feature, allowing a wide range of opinions to be represented in the research. However, the lack of "back and forth" in the thread, as well as the short lengths of most comments, meant that there was little in-depth engagement on or debate of the ideas raised by participants.

No direct information was available about the demographics of commenters on the BBC News website. However, analysis of other internet comments sections' demographics has suggested that commenters are more likely to be younger, male and unemployed than the general population, and may be more politically engaged (possibly commenting to express their political views) [168]. This demographic may have resulted in bias, with commenters unaware or unconcerned with issues more salient for women or other socioeconomic groups, for instance.

The focus group element of this research was limited due to the rural setting and small sizes of the focus groups available. This may have impacted the range of views expressed – those in rural areas may be less inclined to be concerned about outdoor air pollution due to the relative cleanliness of their air, for instance, or may regard cars more favourably than those who live in cities due to their ubiquity in a setting where public transport is impractical (and by extension express less concern about vehicle-related air pollution).

4.4.2 Conclusions

SHS and outdoor air pollution were viewed separately by a sample of internet commenters and focus group participants, rather than on a continuum of types of air pollution. While most focus group participants viewed SHS as more harmful than outdoor air pollution, some participants and internet commenters viewed SHS and outdoor air pollution as broadly comparable sources of harmful pollutants. This is in contrast to the scientific evidence - that SHS leads to higher concentrations of particulate matter indoors than are reached outdoors in the UK, even in urban environments. Information and education about the relative impact of SHS and outdoor air pollution may result in changes in attitude, prompting smokers to reduce smoking indoors and thereby reducing harm.

For this reason, comparisons between SHS and outdoor air pollution could be a potent behaviour change tool for interventions promoting smoke-free homes.

5 Developing and testing an air quality feedback intervention to encourage smokers to make their homes smoke-free

This chapter contributes to research questions 2 & 3:

- *Can giving people in socioeconomic groups associated with high exposure to SHS accurate, personalised information about the effects of SHS on air quality influence their decisions to keep their homes smoke-free? (RQ2)*
- *Does giving that information in different forms influence views of SHS and air quality? (RQ3)*

and objectives 3 & 4:

3. *Develop an air quality-based smoke-free homes intervention featuring new behaviour change techniques, visualisations and software*
4. *Test the impact of those novel elements of the intervention first in a pilot study and then in a larger trial across a number of European cities (TackSHS)*

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5.1 Developing an air quality feedback intervention building on previous research

Note - The author's contribution to this research included elements of the experimental design, visualisation development, pre-intervention qualitative research, preparation and interpretation of quantitative results and interpretation of qualitative results. The rapid literature reviews and intervention mapping process were carried out by other members of the research team as detailed in the Acknowledgements section on page 15.

5.1.1 Introduction

Previous air quality feedback intervention studies [72,114,120] have been small scale pilots designed to test the feasibility of using air quality monitoring technology in behaviour change interventions. As such, they have not had significant involvement from behaviour change scientists in their development, and the technology used faced a range of challenges.

The most prominent example in the literature at the beginning of this study, REFRESH [72], included feedback of PM data over one day in one arm of the study. While this was a small-scale feasibility study, it demonstrated the potential of air quality feedback as a route for the promotion of smoke-free homes. However, the air quality monitor used in this study (the TSI Sidepak) was identified as noisy and expensive, and therefore unsuitable for follow-up research.

Another air quality feedback intervention study was ongoing at the University of Aberdeen while this research was undertaken. The First Steps to Smoke-Free study (FS2SF) [169] was a randomised controlled trial which took place in South Lanarkshire, Scotland. This study was closely related to REFRESH, although it used a different PM monitor and longer baseline and follow-up measurement periods.

Concerns had been raised by researchers involved in these two studies that the materials given to participants were not optimised for their use and understanding. Following a baseline period, participants received printed sheets displaying information about their air quality (such as the mean concentration over time) and a graph of measured $PM_{2.5}$ concentration over time – 24 hours in the case of the REFRESH study, six days in the case of FS2SF. These sheets had been designed only by researchers, with little involvement from the target groups for the interventions or people who work closely with them.

In order to realise the full benefits of air quality feedback, it was decided to develop a new intervention building on previous work with the addition of new elements – the AFRESH project. Engagement with the relevant client group would allow for the creation of more effective visualisations and information about SHS. Behaviour change theory and engagement with relevant professionals could underpin the relevant elements of the intervention.

5.1.2 Methods

5.1.2.1 Monitor selection and measurement considerations

The REFRESH study used TSI Sidepak AM510 optical particle counters to provide data about smoking in the home. This monitor is widely used in exposure assessment of $PM_{2.5}$ [170] but is relatively expensive (around £2,000 per monitor) and produces a loud, high pitched whine when operating.

A different monitor, the Dylos DC1700, has been identified in the literature as an effective low-cost PM monitor suitable for air quality feedback interventions [148]. This monitor may be more acceptable due to its lower cost and low-power, quiet fan system (which is quieter than the Sidepak's pump). Unlike the Sidepak, the Dylos does not report concentrations of $PM_{2.5}$, instead providing estimated particle counts per cubic foot. Counts of all particles over 0.5µm in diameter and counts of all particles over 2.5µm in diameter are reported. Previous research in smoking homes has led to the development of an equation which converts Dylos particle counts to estimated $PM_{2.5}$ mass concentrations (Equation 1) [171]. This approach allows Dylos readings to be compared to relevant air quality guidelines for exposure to $PM_{2.5}$, such as the WHO guideline exposure limit of 25µg/m^3 over 24 hours [79].

$$PM_{2.5} = 0.65 + 4.16 \times 10^{-5}(Dylos\ total\ particle\ count - large\ particle\ count)(particles\ per\ ft^3) + 1.57 \times 10^{-11}(Dylos\ total\ particle\ count - large\ particle\ count)(particles\ per\ ft^3)^2$$

Equation 1 - conversion equation from Dylos particle count to estimated SHS $PM_{2.5}$ mass concentration

The Dylos DC1700 had been selected for the concurrent FS2SF research project [169] and so was well known to members of the research team.

5.1.2.2 Intervention mapping

Intervention development was carried out through an intervention mapping exercise [156], a six step protocol for designing effective behaviour change interventions. This process was led by other members of the research team, but elements described in this section contributed to it. Components contributing to the intervention mapping exercise are set out in Table 7.

Table 7 - Actions taken at each intervention mapping step

Step	**Components**
1: Needs assessment	• Short literature reviews conducted • Planning group/expert panel convened
2: Creating matrices of change	• Determinants of behaviour listed in matrices including knowledge and behaviour goals
3: Theoretical methods & practical strategies	• Methods to achieve change listed for each behavioural determinant
4: Programme development	• Seven semi-structured interviews with health professionals with experience of air quality monitoring • Three focus groups with smokers from disadvantaged communities in Lanarkshire, Scotland • Development of revised visualisations of air quality feedback • Development of AFRESH programme document
5. Programme implementation plan	• This step was not conducted
6. Evaluation plan	• This step was not conducted

5.1.2.3 Expert panel

Using pre-existing contacts from previous research on air quality feedback interventions, an expert panel of five members was recruited to discuss the development and requirements of the intervention, in line with the principles of intervention mapping in which a planning group is convened [156]. The panel was composed partially of individuals with experience of previous interventions using air quality feedback (two members), and partially of people working with the target client group (smoking parents of young children) (three members).

The expert panel members were interviewed informally for their experiences and thoughts on proposals for the intervention, and surveyed on several potential methods of visual feedback.

5.1.2.4 *Software development*

The Dylos DC1700 is supplied by its vendor with software to download data logs and visualise this information. However, this capability is minimal – the data is downloaded to a text file and is not converted from Dylos particle counts to $PM_{2.5}$ mass concentrations, and only a very basic visual representation of the data is produced. Converting Dylos data to estimated $PM_{2.5}$ concentrations required the use of Microsoft Excel (Microsoft Corporation) or similar software to import and convert data logs and produce graphs or other visualisations. Producing a report to be provided to a participant could then require the manual use of a template in Microsoft Powerpoint, a laborious process.

As these tasks were time-consuming but not complicated, it was decided to automate them through the use of specially developed software. Software development was carried out by the author using the Python 2.7 programming language [172].

5.1.2.5 *Visualisation development*

Previous studies on air quality feedback developed only a minimal method of displaying and feeding back air quality intervention, without the participation of potential clients.

Air quality information must be presented in a way that both participants and intervention deliverers can understand if its potential benefits are to be realised. Through work with other researchers and use of the health visualisation toolkit VizHealth [173], candidate visualisations were developed based on previously used graphs of air quality information. These included graphs of fairly complex information (such as minute by minute $PM_{2.5}$ data over the entire recording period) as well as simpler information about average $PM_{2.5}$ levels, colour-coded using the US EPA air quality index [174].

5.1.2.6 *Focus groups*

To test the visualisation methods and determine attitudes to air quality feedback, three focus groups were held at two locations with members of the intervention client group – parents (with young children) who smoke or who live with a smoker. Participants were questioned about their understanding of smoking and air quality and their perceptions of different methods of visualising air quality information. Examples of this feedback are appended (Appendix II).

5.1.3 Results

5.1.3.1 Expert panel

The expert panel suggested a number of improvements to the intervention design.

Panel members suggested that the information given during the original REFRESH trial, both in written and verbal form, could be too complicated for some members of the target group. The materials used in other research were described as unattractive, with a great deal of small text and too much focus on numerical data, which could be difficult for participants with limited numeracy or literacy.

Some members of the panel recommended that the number of contacts required between those delivering the intervention and those receiving it be minimised, to make it simpler for care professionals to carry out the intervention.

Panel members with direct experience of using the Dylos DC1700 raised concerns about its low download speed (which frequently resulted in waits of fifteen minutes or more when downloading data from a monitor). It was not possible to alter this due to the limitations of the inbuilt RS232 serial interface.

5.1.3.2 Software development

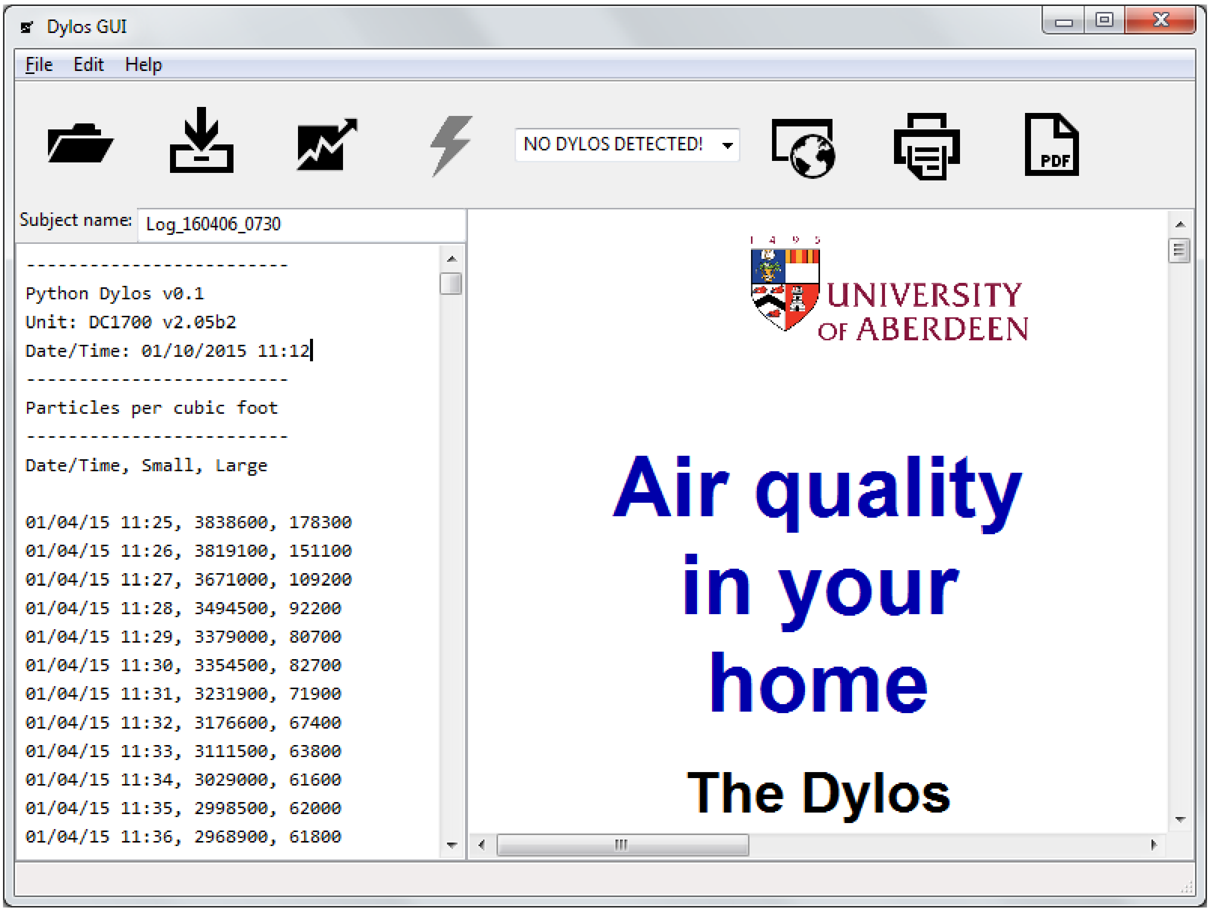
The AFRESH software (Figure 5) as developed by the author using feedback from the AFRESH project's expert panel, as well as informal feedback from third sector organisations and others involved in using air quality interventions in the past.

The AFRESH software replicates the functionality of the vendor-distributed Dylos Logger software by downloading a fully compatible data log from the Dylos monitor. However, it can additionally apply the conversion equation (Equation 1) to produce a Microsoft Excel compatible CSV file containing estimated $PM_{2.5}$ concentrations, and PDF reports containing a variety of personalised visualisations of air quality. Customisable templates can be used to provide different pieces of information using different visualisations (examples are shown in Appendix II). This can provide different feedback to different client groups – for instance, younger smokers may not remember pubs and bars before Scottish smoke-free legislation came into effect in 2006, but older smokers may remember the smoke and associated air pollution [175], making references to those conditions relevant to one group but irrelevant to the other.

This system also allows for the translation of templates to permit the use of the software in non-English-speaking countries.

As part of the work done on using goal-setting as part of the AFRESH intervention, the software can produce comparisons of logs from different times.

Figure 5 - The AFRESH software displaying a raw Dylos DC1700 air quality log (left panel) and a generated report (right panel)



The AFRESH software is freely available online for use or modification [176]. Source code is available under the GNU General Public Licence [177].

5.1.3.3 Focus groups – visualisation development

Three focus groups (one in Lesmahagow, South Lanarkshire, and two in Edinburgh) were recruited to discuss the development of the intervention and the visualisations. Participants broadly approved of the candidate visualisations, with some preferring a graph (to show change over time) and others preferring a colour-coded image showing their home's position on a simplified version of the US Environmental Protection Agency's air quality index (AQI) [174]. A hybrid version, showing a graph combined with coloured dots representing the AQI over each hour, was described as confusing. The visualisations as used in the final intervention are displayed in Appendix II.

5.1.3.4 Intervention design - the AFRESH Programme

Insights from this work, along with three rapid literature reviews conducted by other researchers, were used to prepare the "AFRESH Programme", a document setting out the steps and information required to carry out the AFRESH intervention. The AFRESH Programme is available in Appendix III.[1] Programme production is a component of the intervention mapping process [156]. The full intervention programme emphasises a range of new elements developed from the intervention mapping process. Goal-setting and planning materials were designed to assist participants to achieve a smoke-free home, supported by contacts carried out by the care professionals running the intervention.

The AFRESH intervention proposes between five and seven contact episodes using six programme modules over the course of one month. These contacts involve two home visits and a further three to five telephone or in-person discussions. The home visits involve the installation of a Dylos monitor in the participant's home twice, for six days at the start of the month and six days at the end. After the initial measurement period, data from the monitor is given to intervention participants using the previously described report format, the information is discussed using AFRESH programme module 2, and facilitators, barriers and planning are considered using the relevant modules of the AFRESH programme. Two to four weeks later the Dylos is installed once again, and further feedback is given to the participant, along with the opportunity to review progress and changes made since the first installation. The intervention programme is represented diagrammatically in Figure 6.

5.1.3.5 Care professional training

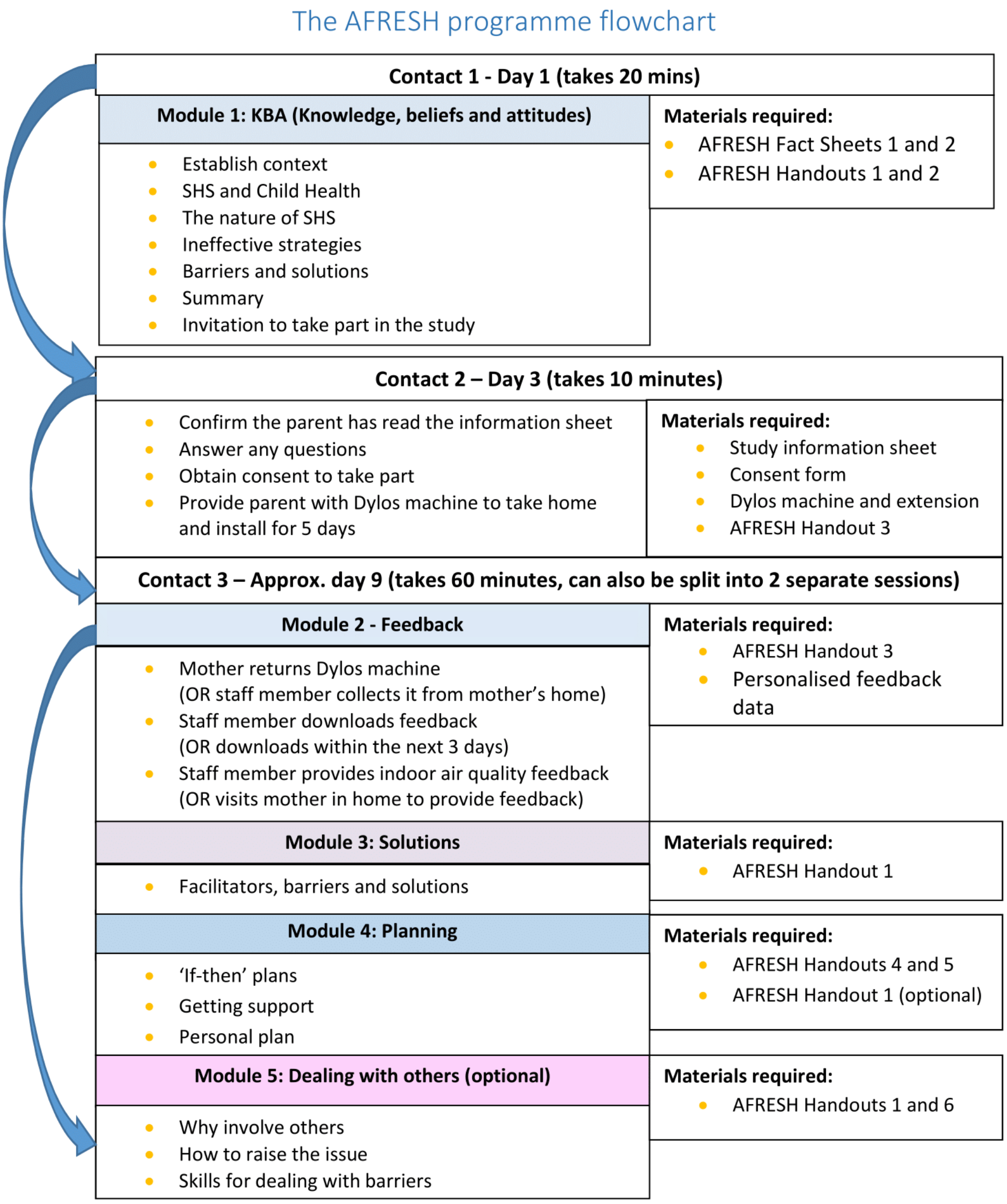
An online training version of the programme was developed in collaboration with the charity ASH Scotland [178]. This training was designed to be used by workers carrying out the intervention.

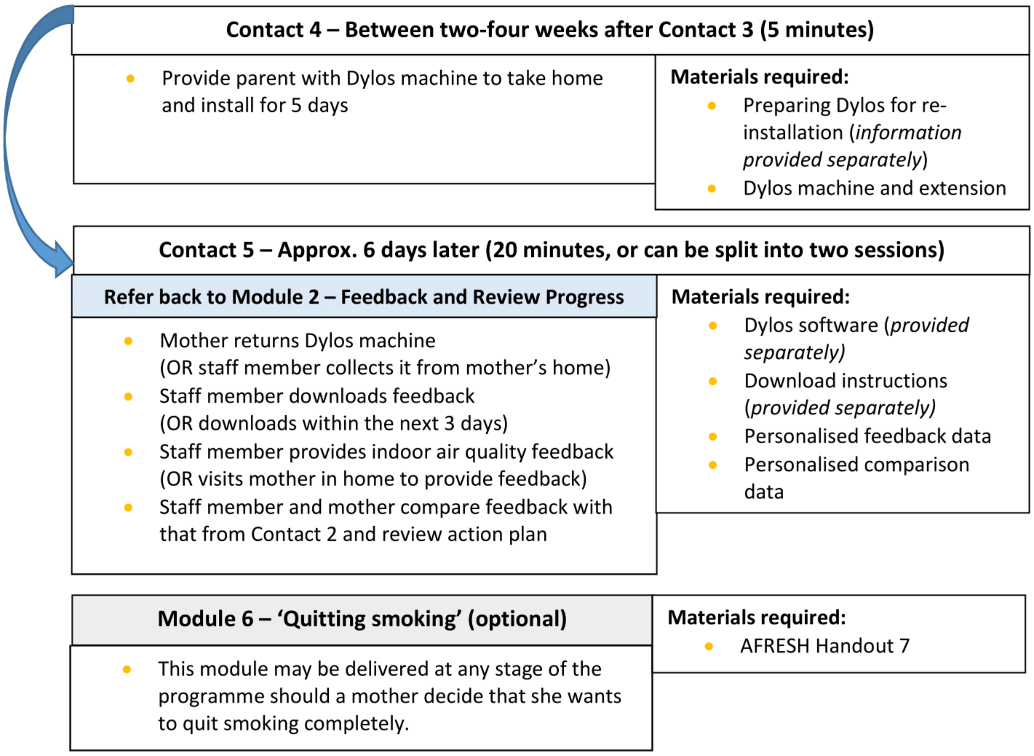
The training programme is divided into three units, each of which is designed to be completed in around one hour. Unit 1 covers general information about second-hand smoke, unit 2 provides

[1] Please note that the AFRESH Programme is not the exclusive work of the author but a collaborative work between multiple members of the research team on the AFRESH project. The author's contribution to the development of the programme is set out in the main text of this thesis.

details on carrying out the AFRESH intervention, including advice on contacts and descriptions of each AFRESH module, and unit 3 demonstrates the use of the Dylos DC1700 monitor and the AFRESH software to produce air quality feedback reports.

Figure 6 - the stages of the AFRESH programme





5.1.4 Discussion

The intervention and materials developed were considered suitable for testing by members of the AFRESH project research team. The intervention as designed was therefore tested in a feasibility study in South Lanarkshire, described in the next section of this chapter.

Many of the elements designed in this study, including visualisations and several modules of the AFRESH programme, were later used as components in the Measuring for Change intervention, discussed in chapters 6 & 7 of this thesis.

5.2 Using air quality monitoring to reduce second-hand smoke exposure in homes: the AFRESH feasibility study.

*Note – This section is an edited form of a paper published previously as Dobson R, O'Donnell R, de Bruin M, et al. Using air quality monitoring to reduce second-hand smoke exposure in homes: the AFRESH feasibility study. Tob Prev Cessat 2017;**3**. doi:10.18332/tpc/74645* [179]. *The published text of that paper is available in Appendix IV. The author's contribution to this research included elements of the experimental design, visualisation development, pre-intervention qualitative research, preparation and interpretation of quantitative results and* *interpretation of qualitative results. The rapid literature reviews and intervention mapping process were carried out by other members of the research team.*

5.2.1 Introduction

Measurement of fine particulate matter or $PM_{2.5}$ has been used as a proxy for the presence of second-hand smoke [57,175]. Indoor air quality monitoring and feedback has been explored as a potential motivator in interventions to encourage parents to keep smoke-free homes [72,120,121] with some success.

Air quality feedback has been reported to cause a feeling of shock in study participants, leading to a desire to change smoking behaviour [155]. But the methods used to deliver this information have not been developed with the participation of individuals in intervention target groups, and may therefore have failed in maximising ease-of-understanding among participants from low socioeconomic groups, who may have lower levels of numeracy and literacy.

This section describes testing the feasibility of using a novel air quality feedback intervention in four homes in Scotland, the results of the intervention in those homes and its perceived utility and acceptability to participants and those delivering it. It also discusses the recruitment of third sector organisations to participate in this study, and the implications of this experience on the effectiveness of similar interventions.

5.2.2 Methods

5.2.2.1 Development of the Intervention

Intervention mapping [156] was used to develop a change-based intervention, using air quality feedback to promote smoke-free homes. The full development process is discussed in section 5.1.

In consultation with three focus groups with people in the target group, a report format was created including a graph of $PM_{2.5}$ over time on the last day with coloured hourly averages and an overall average visualisation using our air quality index. This last figure was developed using the VizHealth visualisation toolkit [173].

Custom software [176] was developed to allow easy and quick download and processing of data and the preparation of air quality reports. This software, named AFRESH, is available under an open source licence for free download.

Care professionals taking part in the intervention were trained over two sessions of around 1 hour 30 minutes each. The first gave general information about second-hand smoke and its effects on health and air quality, while the second involved in-depth information about the intervention. Following this training session, an online course was developed to allow others to use the intervention.

5.2.2.2 AFRESH Intervention

The AFRESH intervention involves delivering personalised air quality information and feedback to parents from socio-economically deprived settings who do not live in smoke-free homes. The intervention is designed to be delivered by support workers at third-sector organisations working directly with individuals in those circumstances, therefore widening the potential group of people who can deliver it from healthcare workers as used in previous research [72]. The intervention is designed to be light-touch and simple to deliver using a low-cost monitor to reduce expenditure [148].

In the AFRESH intervention, a parent living with a child under the age of six who lives in a smoking home is invited to participate by a care professional already known to them. Following informed consent the parent is provided with basic information about SHS and given an air quality monitor to place in their home for approximately five days. Placement of the monitor can be carried out either by the participant or the worker enabling flexibility in delivery of this first stage depending on the model of interaction typical for the care professional, resource and staff-time available. Following the five day period, the monitor is returned to the worker. The air quality information is downloaded and a report prepared using custom software.

This report is given to the participant by their support worker, and a discussion takes place on planning for a smoke-free home. This can include techniques to talk about the issue with other smokers in the home and, if desired, support to quit smoking entirely (though quitting is not the focus of the programme).

Two weeks to one month later, the monitor is returned to the participant’s home for a further period of approximately five days to record more air quality data. The monitor is again returned to the worker, and a second report is produced along with a report comparing the initial, baseline reading with the follow-up reading. A discussion then takes place between worker and participant about successes and challenges in keeping a smoke-free home.

No control group was included in this pilot study, as the primary objective was to determine the feasibility of conducting the intervention in this setting rather than to detect any effect on participants' behaviour.

5.2.2.3 Recruitment

An initial target of 20 participants between two centres was set at the beginning of the study. Six centres were approached to take part in the research, through pre-existing relationships with research staff. These centres were identified as working in the third sector (though often with statutory funding or support) and employing workers in direct, personal and regular contact with members of the target population. Some had participated in air quality monitoring work before, while others had not.

Of these six centres, only one finally participated in the study. Others declined or dropped out for a number of reasons: staff turnover (one centre), lack of resources or staff time to carry out the intervention (two centres), and inability to recruit sufficient members of the target population (one centre) were cited.

Ethics

Ethical approval for this study was given by the College Ethics Review Board of the School of Medicine, Medical Sciences and Nutrition at the University of Aberdeen (reference: (CERB/2016/5/1367).

5.2.3 Results

5.2.3.1 Quantitative results

Participants in four homes underwent the intervention. Results from those homes are presented in Table 8.

Table 8 - Results of air quality monitoring in homes

Participant ID	**Baseline average $PM_{2.5}$ (μg/m³)**	**Follow-up average $PM_{2.5}$ (μg/m³)**	**Change (μg/m³)**	**Change (%)**
AFRESH_01HV	11	9	-2	-18
AFRESH_02HV	59	48	-11	-19
AFRESH_03HV	12	6	-6	-50
AFRESH_04HV	239	201	-38	-16

Average $PM_{2.5}$ levels fell for all four participants following the first measurement, but the small sample size precluded statistical significance of this effect. No participant had average $PM_{2.5}$ levels which fell from a level above the WHO guideline to a level below.

5.2.3.2 Participant perceptions of the intervention

> *"Well, the first results were coming up as hazardous, and that made me think 'I'm not doing them[my children] any good. Even though I'm smoking downstairs at night, and the kids are asleep in bed upstairs, I'm not doing them any good."*
>
> \- AFRESH_02HV

Three of the four participants consented to take part in semi-structured interviews by a member of the research team to discuss their experience of the intervention.

Two participants saw declines from harmful levels. One of these participants (AFRESH_02HV) reported that the intervention process was useful, and suggested that the planning process had made it possible to reduce not only smoking inside but the number of cigarettes smoked.

The other, AFRESH_04HV, referred to a sense of pride in reducing their home's average $PM_{2.5}$ level, although they were sceptical that second-hand smoke was seriously harmful to their child. They suggested placing the monitor in their child's bedroom in order to receive more relevant and impactful information about the impact of smoking indoors.

Participants reported understanding visualisations well, although the relative risk of different $PM_{2.5}$ concentrations may not have been clear. One participant believed that an average $PM_{2.5}$

level of 239µg/m^3 – in the “unhealthy” range using the AFRESH air quality index and almost ten times the WHO’s recommended upper limit for a 24 hour average - was “*not as bad as it could have been*”, while accepting that “*to a non-smoker, a result like that would look terrible*”.

5.2.4 Discussion

5.2.4.1 Recruitment

Recruiting centres to take part was problematic. Concern was expressed over the multi-step nature of the intervention and the implication this would have for staff time. Even centres which initially expressed eagerness to take part were sometimes unable to do so. This reflects the high workload, limited resources and short-term funding cycles of the type of organisation approached. Working with better-funded statutory bodies or recruiting participants directly may ameliorate these issues in future work.

Fewer participants were recruited than anticipated. This reflected staff changeover at the participating centre and funding problems preventing the recruitment of an additional member of staff whose presence was anticipated during the planning of this work.

5.2.4.2 Feasibility of the intervention

This small feasibility study demonstrated that the AFRESH intervention could be used in the setting of a small charity working with individuals in low socioeconomic groups, and that participants could understand, interpret and accept the results of air quality monitoring performed in this way.

Although all participants saw reduced average $PM_{2.5}$ levels in their follow-up measurements, neither of those who had harmful levels at baseline reduced their average level to below the WHO guidance value at follow-up. It is possible that carrying out the follow-up stage of the intervention repeatedly over a longer period of time may motivate participants to continue making changes to their smoking behaviour, and give feedback on the effectiveness of different approaches.

The coloured banding system was generally well-received, but participant comments suggest that lowering the highest “hazardous” band could provide a greater incentive to make a change for those with very high levels of $PM_{2.5}$ in their home, by reframing their average level as within the most harmful category. Placing the monitor in a child’s bedroom could also help to overcome scepticism and reinforce the danger of second-hand smoke in the home.

5.2.4.3 Conclusions

Overall, those participants and workers recruited to take part in the intervention found the AFRESH programme acceptable and useful. Second-hand smoke levels were observed to fall modestly in all four homes where the intervention was employed, although the small sample size made statistical analysis of this decline impossible. Working with small community-based third sector organisations presents challenges and it is likely that these would be a significant barrier to using this model more widely to promote smoke-free homes. Future research could involve direct recruitment of participants by researchers and other efforts to reduce the time required in delivering the programme to those who express interest.

5.3 Analysis and conclusions

5.3.1 Conducting the study

Recruitment of both centres and participants was difficult and slower than expected. The reluctance of centres to take part can partially be explained by the lack of funding attached to this part of the study – the centres themselves had no financial incentive to take part, and in a third-sector environment where funding is scarce, unfunded projects may take a lower priority. While conducting this trial in a "real world" environment was a strength of the study, this presented a difficulty given the short (18-month) timeframe available. Future research of this kind should incorporate recruitment partnerships into the initial grant application or recruit through another method.

The AFRESH intervention requires between five and seven episodes of contact between participant and support worker. For workers with heavy workloads or those who work in rural areas with participants who live far away (or who have limited mobility), this could be difficult to achieve. An intervention with fewer contact points would be easier to conduct in those circumstances. A future study could allow researchers to conduct the intervention itself, reducing pressure on any third-sector organisation involved in recruitment.

5.3.2 Acceptability and success of the intervention

In those households which did take part in the study, acceptability of the intervention materials was high, suggesting that the AFRESH Programme could be used effectively to promote smoke-free homes. In interviews participants highlighted the goal-setting elements of the programme as particularly useful.

However, one participant referred to very high levels of $PM_{2.5}$ as *"not as bad as it could have been"*, suggesting that the impact of higher concentrations was not always completely understood or accepted by those taking part in the intervention.

Future air quality interventions could make use of the goal-setting elements of the programme, but should aim to reduce the number of physical contact points required to conduct it.

6 Developing the TackSHS ‘Measuring for Change’ intervention

This chapter contributes to research questions 2 & 3:

- *Can giving people in socioeconomic groups associated with high exposure to SHS accurate, personalised information about the effects of SHS on air quality influence their decisions to keep their homes smoke-free? (RQ2)*
- *Does giving that information in different forms influence views of SHS and air quality? (RQ3)*

and objectives 3 & 4:

3. *Develop an air quality-based smoke-free homes intervention featuring new behaviour change techniques, visualisations and software*
4. *Test the impact of those novel elements of the intervention first in a pilot study and then in a larger trial across a number of European cities (TackSHS)*

6.1 Background

Previous air quality interventions, including the AFRESH intervention detailed in chapter 5, have generally used a model of delayed feedback, providing participants with a printed report on their air quality after a monitoring period is complete. While this is relatively simple to achieve, it means participants do not have regular access to information about their air. Furthermore, this approach requires time- and labour-intensive contacts between the workers conducting the intervention and each participant – with at least five person-to-person contacts this was estimated to require two hours of staff time per intervention, not counting travel time to the participant’s home or any additional preparation time (see AFRESH Programme flowchart, Figure 6). This made the AFRESH intervention more difficult to conduct.

Only one previous intervention trial has provided participants with real-time feedback on their air quality. This intervention, developed and tested at San Diego State University [115,117,120] involved the use of a customised Dylos monitor with LEDs and speakers to produce specially designed auditory and visual warnings [151] when detected particle levels exceeded certain levels (beginning at 15,000 particles/0.01 ft^3). While this provided more rapid feedback than other intervention designs, comparison of recent results to past results within the home was limited to a maximum of four in-person counselling sessions over several months, rather than providing more frequented automated comparisons. This may have impacted the ability of participants to set goals to reduce SHS indoors. Additionally, this intervention required the use of two Dylos monitors (one in the living area of the home, the other in a bedroom) along with custom equipment to produce warnings and transmit data to researchers, increasing the cost of the intervention.

In order to build on these previous intervention studies in a lower-cost intervention, it was decided to develop an intervention which used near-real-time feedback combining internet-based air quality monitoring with text and email messaging. This required the development of a suitable internet-based air quality monitoring system.

In 2016 results from the First Steps to Smoke-Free (FS2SF) study became available [169]. This randomised controlled trial gave feedback to participants following several days of monitoring in the home in a similar manner to the AFRESH intervention (though without the use of the AFRESH visualisations and programme). FS2SF did not demonstrate a significant reduction in SHS in intervention homes, unlike other studies using similar forms of air quality feedback [117,125]. Reasons suggested for this failure included the demographics of the recruitment group, who were in the lowest quintile of the Scottish Indices of Multiple Deprivation (SIMD) and who may have found it particularly difficult to smoke outdoors. Qualitative interviews revealed that many participants lived in flats, often many storeys up, and could not leave their young children for the length of time required to have a cigarette outside.

Taking these concerns into account, it was decided to develop a lighter touch intervention incorporating elements of goal-setting and real-time feedback, and which involved screening for motivation, capability and opportunity as characterised in the COM-B model [180] of behaviour change, to ensure that participants were able and motivated to change their behaviour.

This study took place as part of the TackSHS consortium, a multinational research project funded by the European Union's Horizon 2020 funding scheme. The TackSHS research project comprised research organisations across Europe working on 11 work packages on issues around exposure to second-hand smoke and e-cigarette aerosol. This research formed work package 4 of the TackSHS project, and included five research organisations in four countries: the University of Stirling, Stirling, Scotland; the Catalan Institute of Oncology (ICO), Barcelona, Catalonia; the National Cancer Institute (INT), Milan, Italy; Istituto per lo Studio, la Prevenzione e la Rete Oncologica (ISPRO), Florence, Italy; and George D. Behrakis Research Lab, Athens, Greece.

This study represents the first smoke-free homes intervention to incorporate the remote delivery of objective feedback on SHS levels in the home, and the first to use both air quality feedback and mobile health techniques.

This chapter presents an expanded paper mapping out the development and testing of a system to provide real-time feedback of SHS concentrations to study participants and a section on the methods used in the eventual use of this technology in a multi-centre trial to encourage parents to adopt a smoke-free home.

6.2 Monitoring second-hand tobacco smoke remotely in real-time: a simple, low-cost approach

*Research in this section was supported by a Daniel Turnberg Travel Fellowship award from the Academy of Medical Sciences (grant number DTF009\1173). The author's contributions to the research included all elements of RAPID monitor development and testing. This section is an expanded version of a manuscript published as Dobson R, Rosen L, Semple S. Monitoring secondhand tobacco smoke remotely in real-time: A simple low-cost approach. Tob Induc Dis 2019;**17**. doi:10.18332/tid/104577* [181]. *The full text of that published paper is provided in Appendix V.*

6.2.1 Introduction

Previous air quality feedback interventions have generally involved the use of feedback generated after monitors have been retrieved from homes, leaving a gap between the smoking behaviour and the resulting feedback [125,127]. It may be valuable to deliver this feedback more quickly to demonstrate the positive effect on household air quality on the reduction of smoking.

Previous research by our group [148,179] and others [120,149] has used the Dylos DC1700 (Dylos Inc, CA, USA) successfully to monitor fine particulate matter ($PM_{2.5}$) as a surrogate for SHS. The Dylos is a relatively inexpensive and widely used optical particle counter, considered to be well-suited for monitoring in homes. However, it has no internet capability and has numerous other limitations, including a small internal memory with a maximum data capacity of just over six days.

Now with the advent of the "internet of things" [182] networked monitors can provide a similar function, reporting data over the internet and allowing analysis and feedback in real-time, even when a monitor is still on site. However, these monitors are of variable quality and are generally dependent on a local WiFi connection rather than sending data over a mobile network [183]. A device that can use a local mobile phone signal instead can be installed more quickly, avoids the security implications of connecting to a study participant's home network and does not rely on the presence of a fixed internet connection (important in lower socioeconomic status households in the developed world and in the global south).

It was decided to develop a prototype networked monitor based on the Dylos DC1700, using commercially available components. This monitor would send Dylos data to a website via mobile internet access, allowing real-time access and feedback on air quality in the home.

6.2.2 Materials and methods

6.2.2.1 System design

The Raspberry Pi computing board [184] is a small (87.1mm × 58.5mm) inexpensive computer (currently retailing for approximately 33 GBP), useful for embedded computing, particularly where manufacturing a new device would be unnecessary, undesirable or unaffordable. While small, the computer can run sophisticated, modern software in a manner similar to a PC. To allow connections to the internet, the latest model, the Raspberry Pi 3 B, comes equipped with both an Ethernet port and a WiFi chip.

As it clearly suited our needs, the Raspberry Pi was selected to form the computing portion of our monitor. For identification purposes, the combined monitoring system has been named "RAPID" (a combination of the terms "Raspberry Pi" and "Dylos").

Although the Raspberry Pi does not include a method of accessing the internet over the mobile phone network, devices are available off the shelf which allow it to do so. This would allow for a wholly autonomous monitor which would require only electrical power to send data for as long as required. For our purposes Huawei wireless access equipment (Huawei Technologies Co. Ltd.) was selected, as it is widely available and compatible with the Raspberry Pi.

The Dylos DC1700 is a direct-reading low-cost optical particle counter, a class of instruments which detect light scattered by a laser to estimate particle size and number in the air [81]. The Dylos estimates counts of particles larger than 0.5μm in diameter (total particle count) and particles larger than 2.5μm in diameter (large particle count) per 0.01 cubic feet of air taken in [148]. In addition to recording them in its internal memory, the Dylos DC1700 reports these particle counts each minute over a 9-pin RS232 serial port in the following format:

<total particle count/100>,<large particle count/100><end of line>

These data can be converted to an estimated $PM_{2.5}$ concentration through the use of a pre-existing equation [171].

By design, particle count data can be read each minute by a computer using a serial cable. The Raspberry Pi does not have a serial port, so a USB-Serial converter cable was used. Previous experience has determined that those cables containing an FTDI conversion chip are most reliable, so these cables were selected for this project.

Software to record, convert, send, receive and store air quality data was developed using the Python 2.7 programming language [172]. The PythonAnywhere cloud programming service [185] was used to host the website to receive data and store it in a database. Source code and further information on the RAPID system has been made available online by the authors [186]. Source code is available under an open source and free software licence.

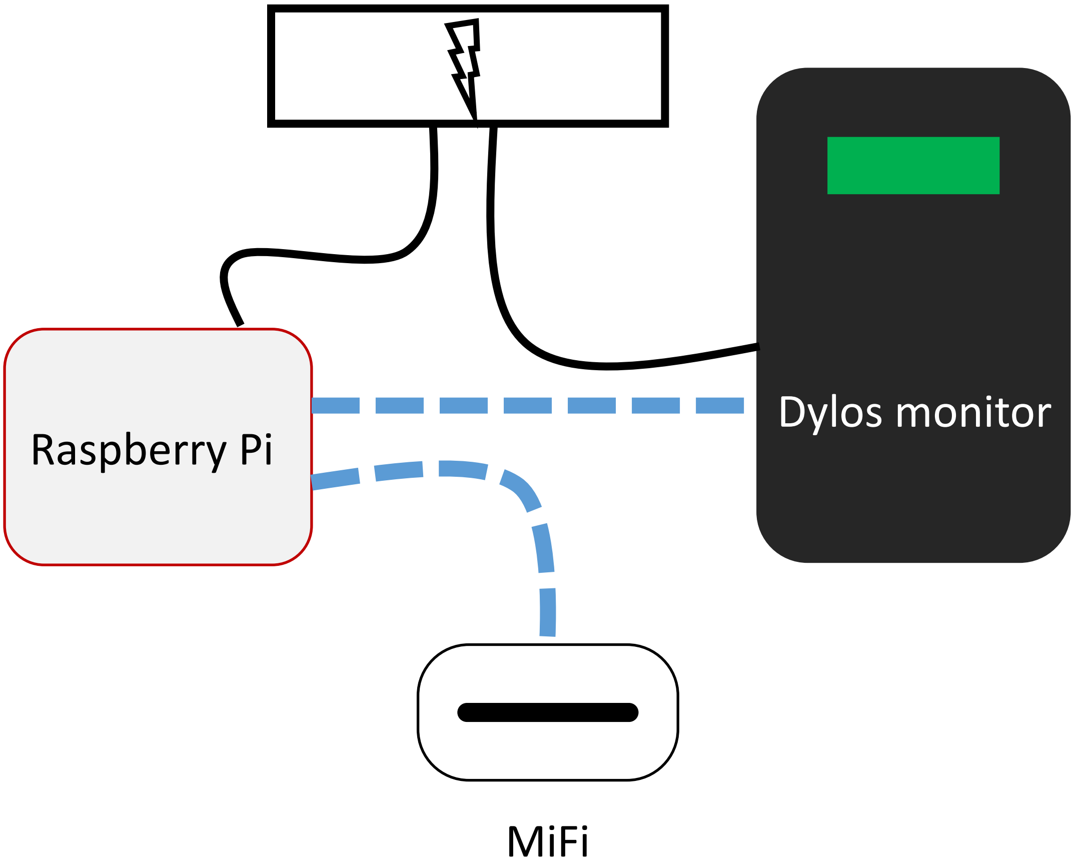
6.2.2.2 Monitor production

Four RAPIDs were produced using four Dylos DC1700 monitors, four Raspberry Pi 3 computers and four 16GB microSD cards. For mobile internet access, three Huawei E5330 MiFi units and one Huawei E3533 wireless dongle were used, along with SIM cards for Israel's Partner mobile network. The total cost of the component parts to 'retrofit' a Dylos DC1700 device to a RAPID was approximately 98GBP each (excluding SIM cards).

RAPIDs were produced as follows. A microSD card loaded with a Raspberry Pi-compatible operating system (Raspbian Linux) was installed in the Raspberry Pi. The custom RAPID software was then installed and set to launch as soon as the Raspberry Pi was powered on. This software was set to send data to a server running custom software designed to store the information in a database, and a unique identifier was given to the RAPID to ensure that data could be downloaded reliably later.

The Raspberry Pi was then connected to a mobile internet device and (if applicable) the WiFi network name and password were saved. The Dylos was powered on and plugged in to the Raspberry Pi using the serial-USB cable, and the Raspberry Pi was restarted to check that the completed device functioned. A diagram of the complete RAPID system is shown in Figure 7.

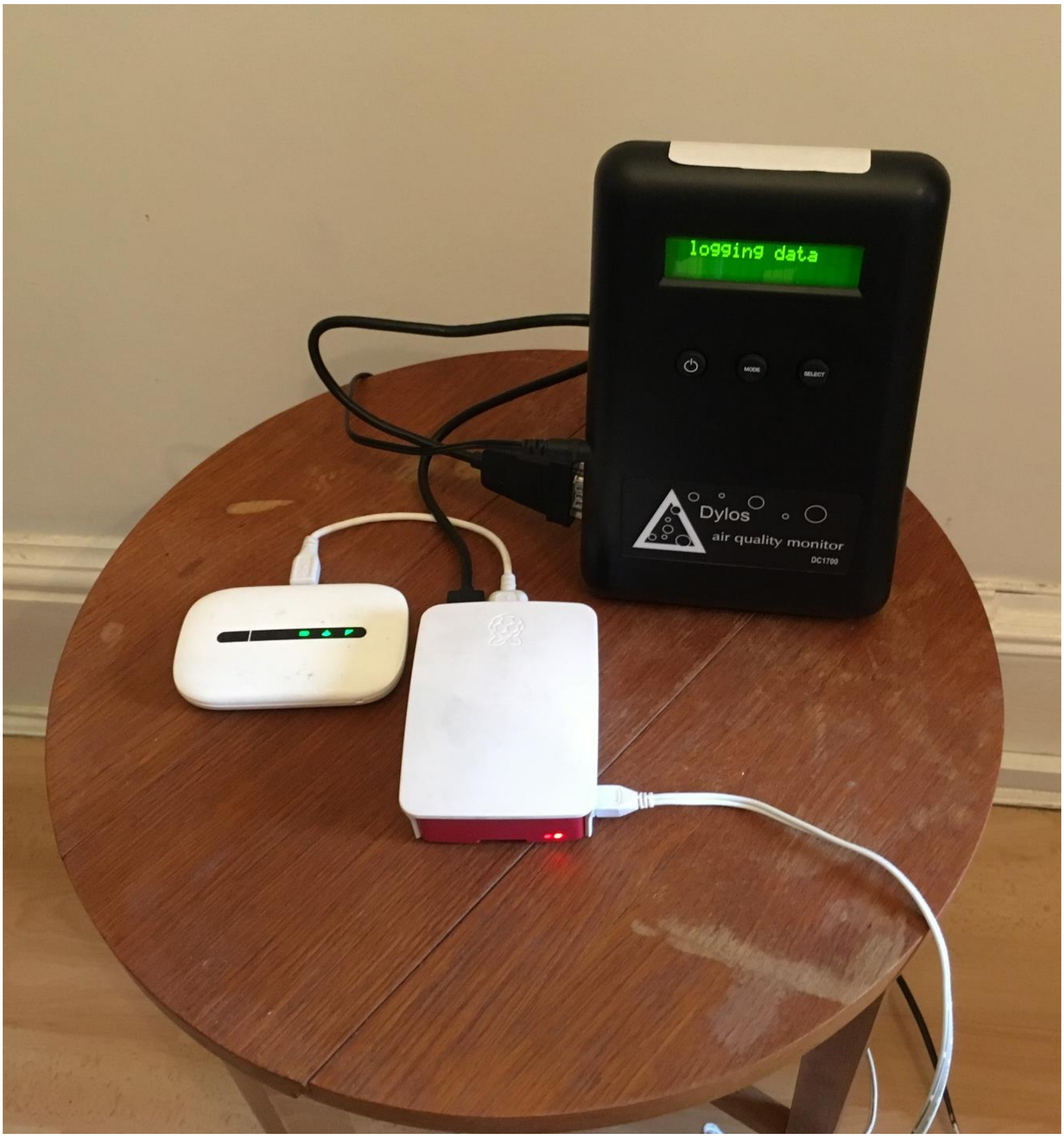
Figure 7 - a diagram of the RAPID monitoring system, incorporating a Dylos DC1700 air quality monitor, a Raspberry Pi computing board and a "MiFi" providing internet access. Data cables are shown with blue dashes while power cables are shown in solid black.



6.2.2.3 Installation in homes

The four RAPID monitors were installed in eight homes during July and August 2017 for periods between four days and 18 hours to six days and six hours (the maximum memory capacity of the Dylos) at a time, depending on participant availability. Installation took place at variable times of the day. Monitors were installed in the main living area of the home (the living room or, in one case, a kitchen used as the main living space). Monitors were placed at least 30cm from walls, at least 30cm above the floor and as far as possible from windows (depending on the placement of electrical sockets in the room). A RAPID monitor installed in this manner in the author’s home is shown in Figure 8. Ethical approval was provided by the Tel Aviv University Ethics Committee (25 June 2018).

Figure 8 - a RAPID monitor installed and functioning.



6.2.2.4 Data analysis

Data from the Dylos's internal memory and the RAPID system were compared to test the reliability of the internet connection system. Following a period of monitoring in each home, data was downloaded conventionally from the memory of each Dylos. These data were cleaned and compared to the data received and stored on the internet using the RAPID system over the same time period.

Outcome variables were the arithmetic mean and median $PM_{2.5}$ concentrations in each home using each method of data retrieval. Wilcoxon signed-rank tests were carried out to compare the mean and median $PM_{2.5}$ concentrations recorded by each method, to determine whether significant data were lost by using the RAPID server-based data retrieval method compared to the onboard memory of the Dylos. Additionally, Spearman correlation coefficients were calculated for mean and median concentrations derived from each retrieval method. IBM SPSS Statistics software was used to conduct statistical tests [187].

6.2.3 Results

6.2.3.1 $PM_{2.5}$ in smoking and non-smoking homes

Monitoring took place in two homes in Haifa, two in Jerusalem, three in Tel Aviv and one in Be'er Sheva. Four homes were inhabited by smokers who reported that they lived indoors, while four reported no smokers.

Results from homes are available in Table 9. Smoking homes had higher mean and median concentrations of $PM_{2.5}$, but no significant difference was detected in a Mann-Whitney U test (p=0.686 in means, p=0.486 in medians). This may be due to the small sample of homes in which data was collected.

6.2.3.2 RAPID system testing

Averaged over the eight homes, 0.57% of data was lost when using the RAPID system compared to the Dylos onboard memory – equating to six hours and eight minutes of data lost over 44 days of measurement. No more than 2.4% was lost in any monitoring period, while the longest single period of data loss was 1 hour 45 minutes.

The close relationship between mean PM concentrations from the remote server and the Dylos local memory can be seen in Figure 9, showing the mean $PM_{2.5}$ concentrations recorded during the period of measurement using both methods, and Figure 10, a Bland-Altman plot of the differences between each measurement. Using Wilcoxon paired-rank tests no significant difference was detected between the means or medians collected using the RAPID and the onboard memory of the Dylos (p=0.327 and p=0.093 respectively). Spearman correlation coefficients showed near-perfect relationships between RAPID and Dylos data for both mean and median concentrations (ρ = 1.000 and ρ = 0.929 respectively).

Table 9 – Mean and median $PM_{2.5}$ concentrations detected using the RAPID system in homes where smoking was and was not permitted, and geometric means of arithmetic mean and median $PM_{2.5}$ concentrations.

Home ID	**Smoking status**	**Mean $PM_{2.5}$ concentration (μg/m^3)**	**Median $PM_{2.5}$ concentration (μg/m^3)**
BE_03	Smoking permitted	82.01	13.92
HA_04	Smoking permitted	30.85	15.32
JE_03	Smoking permitted	7.10	6.05
TA_04	Smoking permitted	7.10	6.33
HA_01	Smoking not permitted	9.27	7.75
JE_05	Smoking not permitted	8.08	6.89
TA_01	Smoking not permitted	6.77	6.21
TA_02	Smoking not permitted	7.14	5.90
All smoking permitted homes		18.90	9.51
All smoking not permitted homes		7.76	6.65

Figure 9 - Mean $PM_{2.5}$ recorded in homes using RAPID and Dylos internal memory, showing the close relationship between the two.

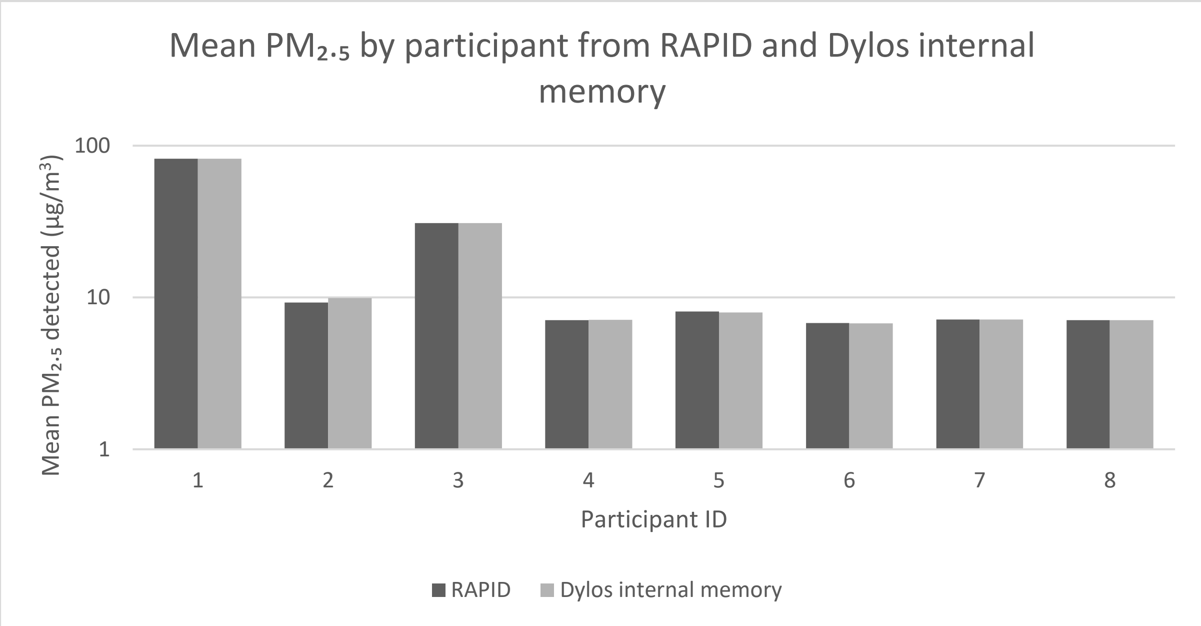
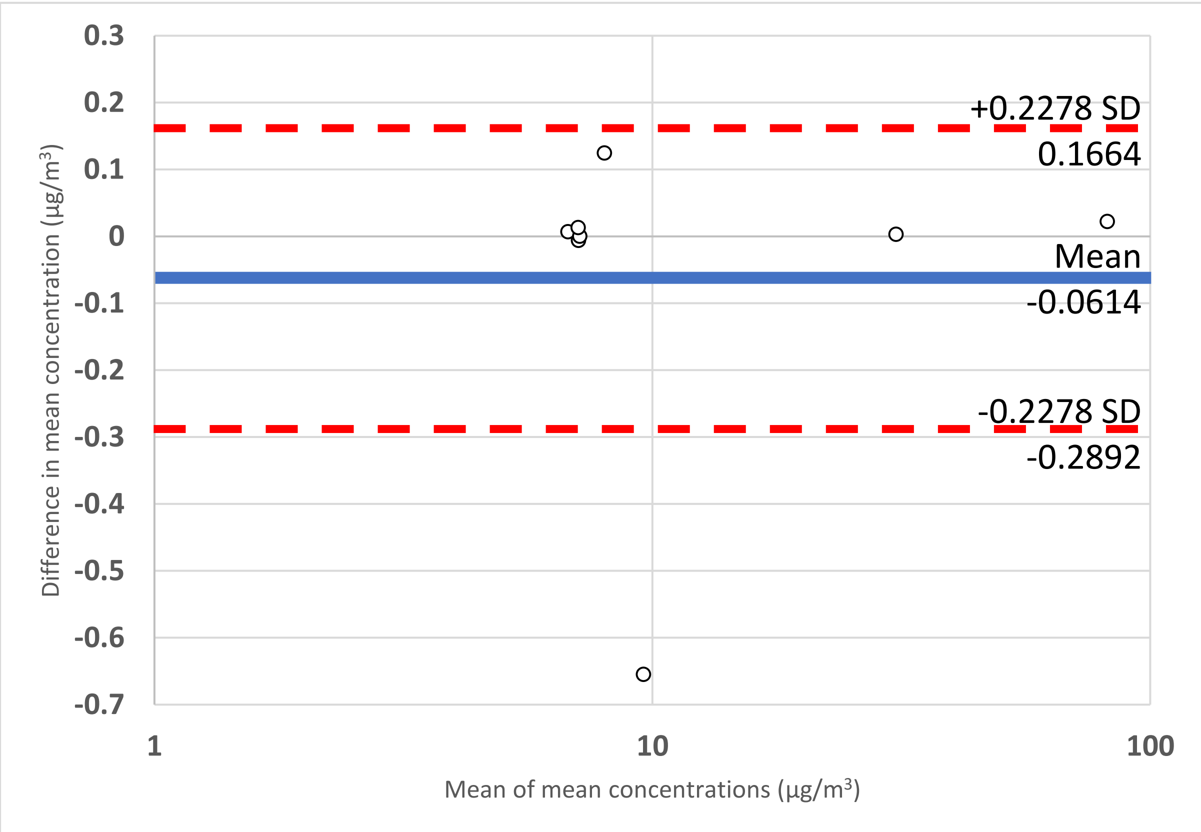


Figure 10 - Bland-Altman plot of mean concentrations from Dylos and RAPID against the differences between each measure.



6.2.4 Discussion

The results show that it is possible to use low cost monitors combined with inexpensive, off-the-shelf consumer technology to reliably monitor $PM_{2.5}$ in real-time in homes. This technology could be adapted for use in smoker behaviour modification interventions with relative ease.

6.2.4.1 Advantages

Data obtained from the online server using the RAPID system were highly reliable when compared to conventional Dylos onboard memory records, demonstrating that little information was lost when being sent over the internet.

The components used to make the RAPID are widely available and inexpensive, and could therefore be accessed in many settings. The Dylos DC1700 has been widely used and research groups with existing monitors could ‘retrofit’ their Dylos devices into RAPIDs for lower cost than purchasing a new monitor with these features.

The core Raspberry Pi software could be customised to incorporate other monitors and sensor technology, such as humidity and temperature sensing.

6.2.4.2 Disadvantages

Although errors were rare, they did occur, and could be more common in areas with poor mobile network coverage. This could be remedied by the option of connecting the RAPID to a conventional home WiFi connection.

Due to the short design period, the software used in this version of the RAPID suffered from a number of bugs which could have contributed to data loss. More recent unpublished research using these devises have resulted in substantially improved reliability.

Data loss may have occurred due to temporary failure of the mobile connection equipment or a slow internet connection (causing the RAPID software to “time out” the connection with the remote server rather than remain connected indefinitely, pausing data recording). Updates made to the RAPID software following the study period allow the system to store and re-send data which did not reach the server due to a failed internet connection.

The present form of the RAPID has used ‘off-the-shelf’ components and a number of connecting cables. The RAPID can therefore be disabled if a component is accidentally disconnected. This may not be obvious to the participant in a study due to the complexity of the device. Future work could easily remedy these problems by designing an enclosure for the Raspberry Pi and wireless access components of the device.

It should be noted that the Dylos DC1700, like all similar monitors, cannot specifically identify the source of $PM_{2.5}$ it detects. Even with the addition of RAPID components and functionality the monitor can only be used to detect $PM_{2.5}$ as a proxy for SHS. This could be advantageous if the equipment is to be used in other settings – for instance, for monitoring household air pollution or biomass smoke – but should be considered in the design of studies monitoring exposure to SHS. Other methods of recording information about indoor air pollution (such as diaries and data from monitoring stations on outdoor air) should be considered when using the RAPID to mitigate against this disadvantage. Additionally, it may be possible to use features of the particle size distribution of SHS (which predominantly consists of particles of 0.2-0.25μm in diameter [188]) to detect SHS with better specificity [189].

6.2.4.3 Summary

Monitoring SHS remotely in real time is feasible without a large financial investment. This holds potential for intervening to reduce exposure to tobacco smoke and for research.

6.3 The Measuring for Change intervention – development of an air quality feedback intervention using real-time monitoring and mHealth techniques

Research in this section was supported by a grant from the European Union's Horizon 2020 programme (grant number 681040) as part of the TackSHS project. Intervention development was a collaborative process between members of the research team, and fieldwork was conducted by a range of researchers at four research institutions around Europe. The author's contributions included software development, contributions to study and intervention design, visualisation and message development, liaison with overseas centres and protocol development.

6.3.1 Introduction

The Measuring for Change intervention was designed to build on previous experiences of air quality feedback interventions, including the AFRESH intervention (chapter 5), First Steps to

Smoke-free [127], and published studies from other countries at the time development took place (from November 2016) [120,121,149] .

The intervention used newly developed internet-connected monitors and regular SMS- and email-based feedback to promote keeping a smoke-free home. It was hypothesised that the inclusion of these elements, and of new stage of change-based recruitment techniques (recruiting participants who had the motivation, opportunity and capability to achieve smoke-free homes), would promote smoke-free homes more effectively than comparable interventions (and, in particular, more effectively than the First Steps to Smoke-free intervention). Information about the design and development of the intervention is given below.

6.3.2 Methods/Design

6.3.2.1 Ethics & trial registration

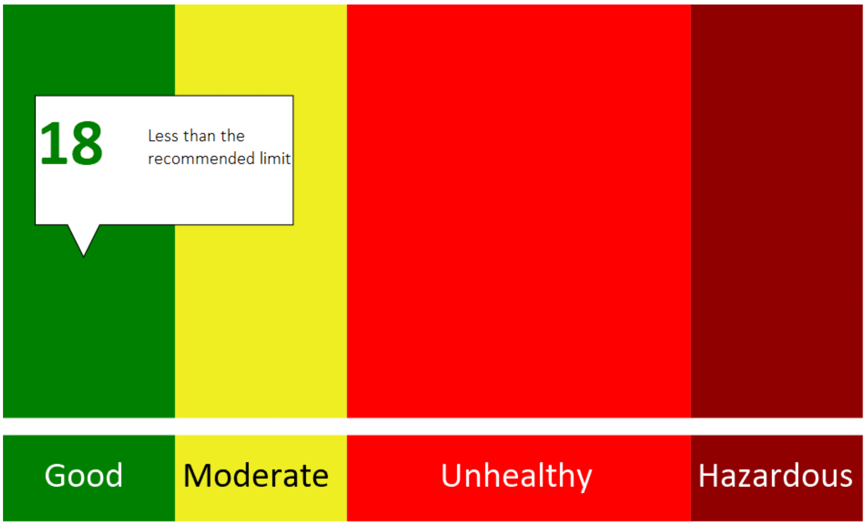
Ethical approval for the study was provided in the first instance by the College Ethics Review Board of the School of Medicine, Medical Sciences and Nutrition at the University of Aberdeen (CERB/2016/12/1412). Each research centre outside of Scotland applied for and received ethical approval from a local and applicable ethics board.

The study was registered on ClinicalTrials.gov (Identifier: NCT03151421).

6.3.2.2 Study design

The monitor was installed in the participant’s home for 30 days. Monitoring with no feedback took place during the first seven days (the pre-intervention period). Between days 8 and 23 (inclusive), one automatically generated SMS message giving information about the air quality in the home was sent to the participant each day. On days 8, 16 & 22 emails containing a graph of air quality over the past seven days and a graphical representation of the mean air quality in that time (Figure 11) were sent. On days 9 & 23 participants received a 15 minute phone call from a member of the research team, asking additional questions about their progress and offering them the chance to ask questions about the intervention process.

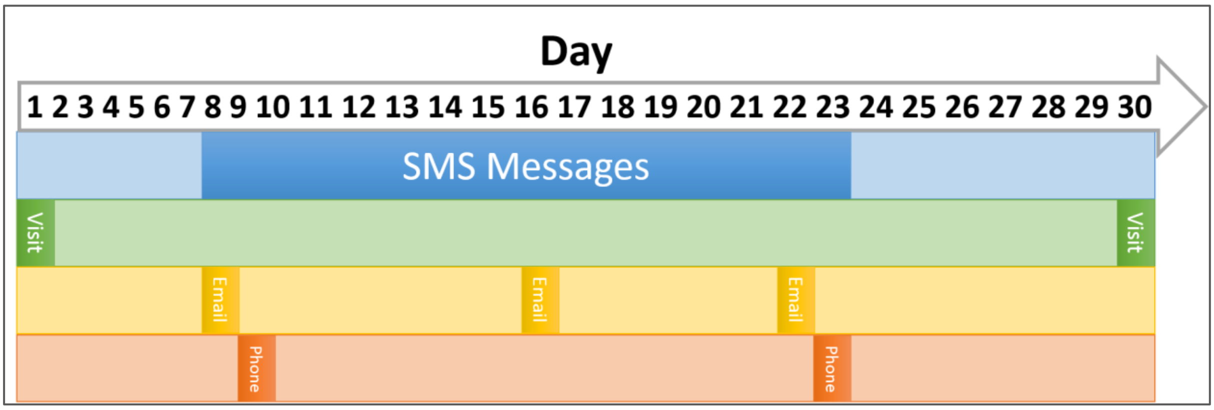
Figure 11 - Mean air quality visualisation as used in Measuring for Change emails.



The primary outcome measure was change in mean $PM_{2.5}$ between baseline monitoring period (day 1 – day 7 inclusive) and follow-up monitoring period (day 24 – day 30). Secondary outcome measures included self-reported home smoking rules between baseline and follow-up and stage of change from recruitment to day 23.

Figure 12 shows the design of the intervention with contact points on each intervention day.

Figure 12 - Intervention components over the course of an intervention.



6.3.2.3 Recruitment

To ensure adequate power for the study, an overall recruitment target of 160 was set across all five centres. Centres in Scotland, Athens and Barcelona were set targets of 40 recruits, while INT (Milan) and ISPRO (Florence) were set targets of 20. Although inclusion and exclusion criteria remained the same in each centre, specific recruitment strategies varied to take account of different circumstances in each country.

Recruitment in Scotland involved two strands – engagement with staff at local community centres in Edinburgh and recruitment through targeted advertisements on the Facebook and Instagram social media networks (both of Facebook Inc., Menlo Park, California).

Staff engagement strategies used pre-existing and new contacts at community centres run by Edinburgh City Council to explain the study to staff members, who were then asked to refer potential participants to the research team.

Social media advertisements were targeted to individuals living in and around Edinburgh (and later expanded to include Fife, West Lothian, Stirling and Glasgow). Facebook's advertising tools allow for the selection of some demographic characteristics (such as age) and some algorithmically determined interests or characteristics, such as having an "interest" in smoking or parenthood. These options were selected to increase the likelihood that individuals in relevant circumstances would see the advertisements. Potential recruits saw an advert giving basic details of the study (an example is shown in Figure 13). If interested, they could select a "learn more" option to see more details and complete a short form giving their name, phone number, email and city or town of residence. A member of the research team would then contact them by telephone or email to invite them to learn more and complete a stage of change assessment.

6.3.2.4 Inclusion and exclusion criteria

To be eligible to participate, individuals had to smoke indoors or live with someone who smoked indoors, take care of a child under 16 at least once a week, have regular access to the internet and have no plans to move home for two months from first contact with the research team.

Following a previous air quality intervention study conducted in Scotland in which many participants were unable to make a substantial change to their smoking behaviours [127] this intervention was designed to target those who were motivated and capable to make their homes smoke-free. For this reason the COM-B model of behaviour change [180] was used to develop a stage of change assessment questionnaire to identify those potential participants who had made substantial progress in terms of stage of change (as conceptualised in the transtheoretical model [152]).

The COM-B model represents the components of a behaviour change intervention as necessarily affecting Capability, Opportunity and Motivation to change Behaviour. These components can be seen as close to the hub of a "behaviour change wheel", with specific intervention functions (such as education or environmental restructuring) arranged further out, and policy areas to be affected around the edge of the wheel [180]. This model allows for the identification of relevant methods to affect specific behaviours. This questionnaire is available in Appendix VI.

Figure 13 - A Facebook advertisement as shown to participants in Scotland. The format of the ad would change depending on the type of device used to view it - this version would be shown to recruits using a web browser on a PC or laptop.

Potential participants were asked to assess whether smoking in the home was a problem for themselves or anyone living in their home, asked when they might change their behaviour, asked how realistic it would be to make their home smoke-free, and how realistic it would be to reduce the amount of SHS in the home (on a scale where 0 represented “not realistic at all” and 10 represented “extremely realistic”). A further free-form question asked about barriers and facilitators to making the home smoke-free, focusing on practical issues such as other smokers living there and access to outdoor space.

Participants were ineligible to participate if they indicated that smoking was not a problem in the home, or if their answer to how realistic making the home smoke-free would be was less than or equal to 2. These criteria were adopted to allow the intervention to focus on those who were likely to make a substantial change to their behaviour. A previous air quality feedback study in Scotland, First Steps to Smoke-Free, saw no effect in either the intervention or control groups [127]. Qualitative interviews conducted with participants in that study found that, while many had the motivation to change their behaviour, they frequently lacked the opportunity to do so (due to inability to leave their children alone for any length of time, for instance). For this reason, it was decided to concentrate in this research on participants who did have the capability to make change.

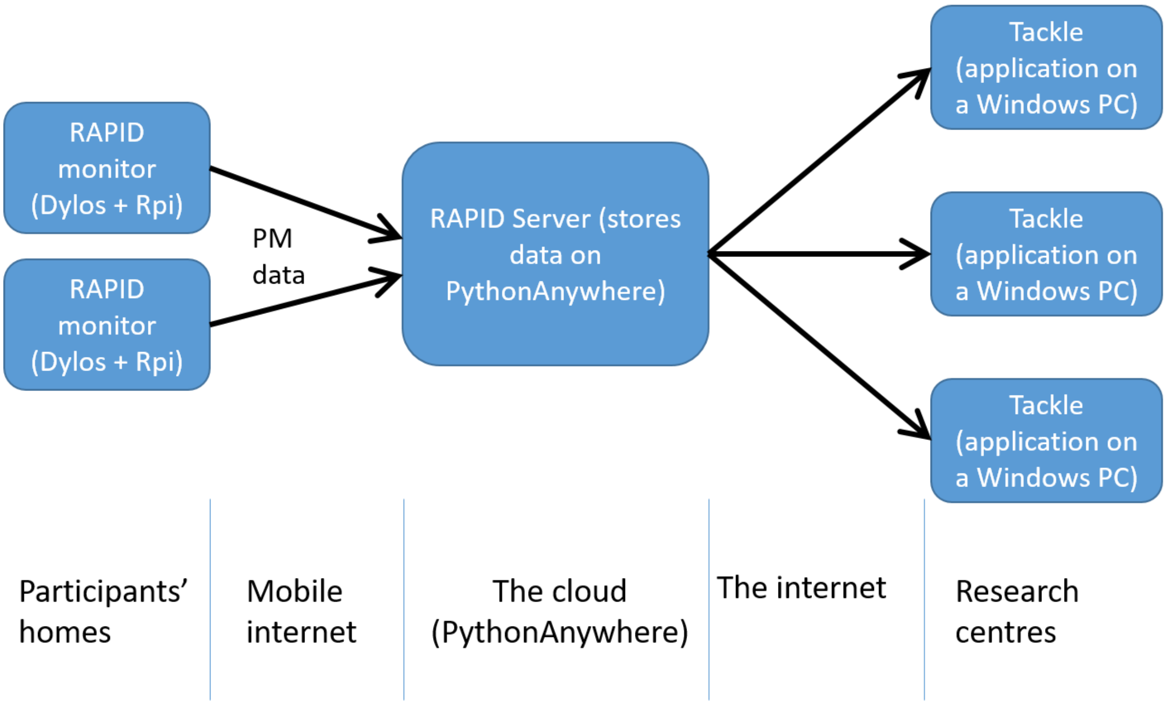
6.3.2.5 Non-smoking participants

Recruits could be eligible to take part in the study if they lived with an adult smoker but didn't smoke themselves. In this case, the intervention was delivered as with a smoking participant with researchers using elements of the AFRESH Programme (Appendix III) to provide assistance on communicating messages about SHS in homes to other householders.

6.3.2.6 Monitoring strategy

The RAPID monitor discussed earlier in this chapter was used to provide continuous internet-connected air quality monitoring in each intervention household for thirty days. Monitors were installed in the main living area of the house (generally a living room or dining room/kitchen) at a height of at least one metre from the floor, and away from any open windows or obvious sources of particulate matter (such as cookers). These criteria were chosen to ensure that monitoring represented the most commonly used room in the home where participants would spend most of their waking hours, and to ensure that air would be able to circulate around the device. The data model for air quality data upload, storage and download is shown in Figure 14.

Figure 14 - Data model for RAPID data storage and download. Data can also be accessed directly online using a web gateway. All data access requires a valid security key, but no personally identifying information is stored online.



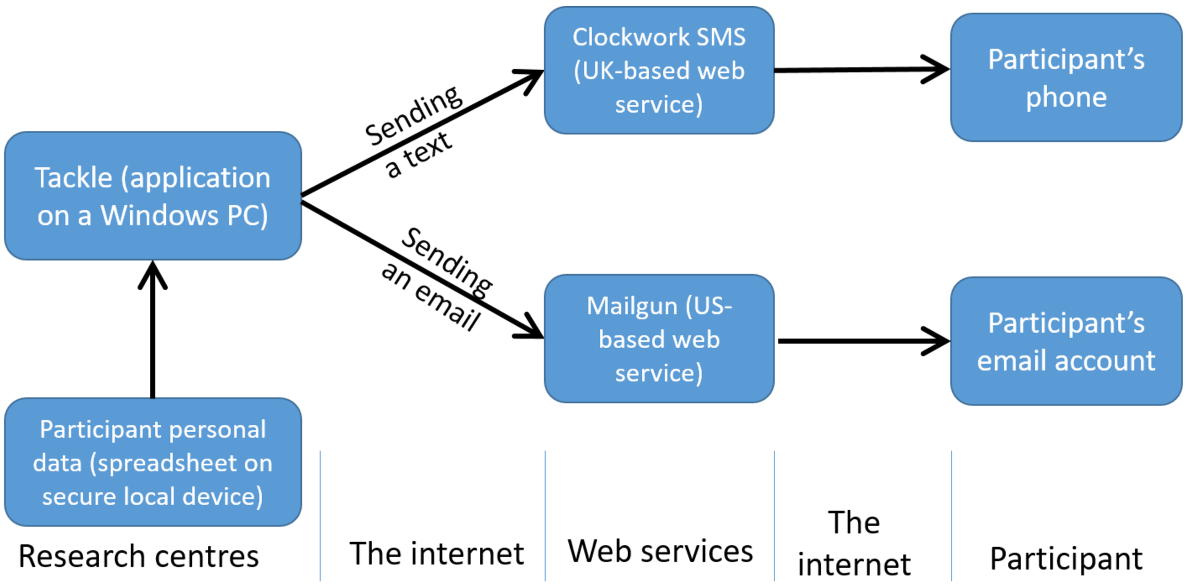
6.3.2.7 *Software to conduct the intervention*

Specialist software was written by the author to carry out the intervention. The "Tackle" software allows SMS messages and emails to be generated and sent to participants as detailed in the intervention protocol. SMS messages and records of phone calls can be stored in a specialised log to be examined later.

Tackle accesses data stored on a PythonAnywhere server, automatically downloading the required data for each intervention being carried out. It can then auto-generate SMS messages in the local language (from a provided spreadsheet of SMS components) and emails (using an HTML template file). These messages can then be sent using services such as ClockworkSMS (Mediaburst, Manchester, UK), Twilio (Twilio Inc., San Francisco, USA) and Mailgun (Mailgun Technologies, Inc., San Francisco, USA).

In order to ensure participant privacy is maintained as far as possible, Tackle uses a local file to store sensitive participant information (such as names, phone numbers and email addresses). This information is only available to researchers in each individual centre. The data model for sending communications can be seen in Figure 15.

Figure 15 - Data model for sending messages using Tackle. Information is downloaded from the server hosting air quality information and used to generate messages with appropriate values. These are then sent to intervention participants using web services.



All software used in the project was developed in Python 2.7 [172]. The Flask framework [190] was used to develop the server backend. The Chromium Embedded Framework [191] was used to provide an interface for Tackle.

The source code for Tackle (written in the Python 2.7 programming language [172]) is available online [192]. As the software is highly customised to the intervention and platforms used in this study, it may be difficult to run successfully in other environments. Future work could develop the Tackle platform for simpler installation and use if this intervention is adopted in practice.

6.3.2.8 SMS and email messages

Messages were generated automatically using Tackle following pre-defined templates. SMS messages were made up of a selection of components, some based on the air quality of the participant's home, others randomly selected. A message would first give the estimated $PM_{2.5}$ concentration in the home over the 24 hours before the message was generated. It would then give a comparison to the estimated concentration over the previous seven days (higher, similar or lower) followed by a comparison to $PM_{2.5}$ concentrations in smoke-free homes as measured in a relevant urban area (Edinburgh, Milan, Florence, Athens or Barcelona). Finally, a short piece of advice on keeping a smoke-free home derived from the Scottish Government's Right Outside campaign [100] was appended. Example messages can be seen in Table 10.

Text message components are available in Appendix VII. Where appropriate, these components were translated into the local language. Participants in Milan were sent messages in English.

6.3.2.9 Telephone counselling

Brief counselling by telephone was included as an element of the intervention. Participants were telephoned on two occasions (at day 9 and day 23). These days were chosen to allow participants to receive and read emails on days 8 & 22, and consider questions and thoughts during that time.

Telephone counselling was semi-structured, including a questionnaire mirroring elements of the initial stage of change questionnaire given at recruitment to track changes in motivation to change (Appendix VI). Calls lasted approximately fifteen minutes. Additional questions were asked about success of efforts to keep a smoke-free home and any particular successes or failures participants had noticed. Participants were asked about the status of previously identified barriers and facilitators, with guidance given on overcoming barriers using advice drawn from the AFRESH programme (Appendix II). Questionnaires are given in Appendix VI.

6.3.2.10 Qualitative interviews

Eight qualitative interviews were conducted in Scotland with participants who had completed the intervention. These interviews focused on participant experience of the intervention process and their views on its effectiveness.

Table 10 - Example text messages as generated from the templates.

Example message	**Circumstances**
The second-hand smoke level in your home was 74 over the last 24 hours. This is higher than the average over the previous seven days. This is higher than a smoke-free home in Edinburgh. Consider using nicotine replacement therapy when you know you'll be indoors for a long time.	A home in which smokers have not successfully reduced SHS levels to around the smoke-free home value
The second-hand smoke level in your home was 14 over the last 24 hours. This is lower than the average over the previous seven days, well done! This is about the same as a smoke-free home in Edinburgh. Children exposed to second-hand smoke at home are more at risk of coughs, colds, ear problems and chest infections.	A home where change has successfully been made on at least one day, with the previous seven day average substantially greater than the local smoke-free homes value. A positive message ("well done!") is included where there has been a reduction compared to the last seven days.
The second-hand smoke level in your home was 21 over the last 24 hours. This is about the same as the average over the previous seven days. This is about the same as a smoke-free home in Edinburgh. Opening a window or smoking in just one room isn't enough - are you able to take your smoking right outside?	In this home, smoking has been reduced to leave SHS-related $PM_{2.5}$ levels broadly in line with the smoke-free home value in Edinburgh.

6.3.2.11 Smoke-free home benchmarks

All indoor spaces, whether or not smoking takes place there, have a background level of $PM_{2.5.}$ This can be associated with activities in a home (such as cooking or vacuuming) and with ambient outdoor air pollution (related to vehicle pollution, industry and natural factors). In order to provide a general point of comparison between smoking-permitted and smoke-free homes in SMS messages, an estimated value for $PM_{2.5}$ in homes where smoking is not allowed was required.

Ambient air pollution varies in locations around the world. As this study was conducted in five cities across Europe with variable levels of air pollution (Table 11) specific comparison values were required for each study centre.

Table 11 - Yearly mean $PM_{2.5}$ concentrations according to the World Health Organisation's Global Ambient Air Quality Database, 2018 [193] *and smoke-free homes benchmark values generated for this study. No benchmark is provided for Barcelona as this centre did not begin the study within the timeframe of this thesis.*

Study city	**Country**	**Yearly mean $PM_{2.5}$ concentration (μg/m^3)**	**Smoke-free homes benchmark**
Athens	Greece	20	15.3
Barcelona	Catalonia	14	-
Edinburgh	Scotland	7	11
Florence	Italy	15	17
Milan	Italy	27	20.3

Each centre conducted five-day measurements in five smoke-free homes within their study area to determine a comparative 'smoke-free home' value (the arithmetic mean of those measurements). In addition to the generation of this benchmark, these measurements were used as an opportunity to train researchers in the operation of the RAPID monitors. The smoke-free homes benchmarks used in the study are shown in Table 11.

For Edinburgh, data from a pre-existing study of 25 smoke-free homes (described in chapter 8) was used to generate the smoke-free home benchmark.

6.3.2.12 Monitor calibration

Each Dylos monitor used in the study was individually calibrated to allow a suitable k-factor to be applied, improving the accuracy of the device's measurements. Calibration was conducted in Milan with the assistance of researchers at the National Cancer Institute of Italy (INT) as part of work package 7 of the TackSHS project.

Calibration of 30 Dyloses took place against a BAM-1020 continuous particle monitor (Met One Instruments, Inc., Grants Pass, Oregon), a high-precision instrument frequently used for regulatory purposes. Dyloses were collocated with the BAM-1020 and three fans in an office owned by INT. Volunteer smokers were asked to smoke in this room for one hour, with the monitors left running for 6 hours. Two calibration sessions were conducted in June and September 2017, the first with 17 Dylos monitors, the second with 13.

Generation of k-factors was conducted by dividing the mean BAM-1020 generated $PM_{2.5}$ concentration by each Dylos' estimated $PM_{2.5}$ concentration (as derived from a previously developed equation designed to estimate SHS-related $PM_{2.5}$ mass concentration from Dylos small particle number concentration data) [171].

k-factors were generated for 29 of these instruments, with one failing calibration due to erroneous readings. A further three Dylos monitors were calibrated against a previously calibrated Dylos monitor in February 2018, in order to provide each centre with enough equipment to conduct the study.

6.3.2.13 Questionnaires

In addition to stage of change questionnaires given at recruitment, day 9 and day 23, participants were given baseline and follow-up questionnaires at first and last home visits. Questions deal with details about the home (such as design and garden space), smoking rules indoors, other residents of the home and their smoking behaviour and knowledge about the health effects of SHS.

These questionnaires are available in Appendix VI.

6.3.2.14 Statistical analysis

The primary outcome measure for the study was change in mean concentrations between baseline and follow-up measurements in homes. Additionally, percentage change in mean concentrations between baseline and follow-up measurements and the percentage of time spent above 25μg/m^3 were analysed. These changes were tested for significance using the Wilcoxon signed-rank test, suitable for non-normally distributed data, such as measurements of home $PM_{2.5}$ concentrations (which are lower-bounded). Results were tested as a whole and grouped by centre (although it was not expected that changes within individual centres would be statistically significant), by housing type, by access to garden space and by self-report of behaviour change. Pearson correlation coefficients were used to detect a relationship between stage of change at recruitment and reduction in $PM_{2.5}$ concentration.

Additionally, self-reported changes between baseline and follow-up survey were examined using the Wilcoxon signed-rank test, as was stage of change from recruitment to day 23.

7 Measuring for change: results of an air quality feedback intervention study in four European countries

This chapter contributes to research question 2:

- *Can giving people in socioeconomic groups associated with high exposure to SHS accurate, personalised information about the effects of SHS on air quality influence their decisions to keep their homes smoke-free? (RQ2)*

and objective 4:

4. *Test the impact of those novel elements of the intervention first in a pilot study and then in a larger trial across a number of European cities (TackSHS)*

Note - the author's contribution to this research included leading on the technical elements of the experimental design, visualisation development software/hardware development and data analysis. The author was also involved in conducting the intervention with other members of the TackSHS study team (as detailed in the Acknowledgements section on page 15).

7.1 Background

The air quality feedback intervention described in chapter 6 was tested in a multi-centre trial, part of the Horizon 2020 TackSHS programme (forming work package four of twelve within that larger study). TackSHS is a multi-centre collaboration focused on the health effects of SHS and second-hand e-cigarette aerosol. The research programme includes studies assessing the population-level harm of SHS across Europe, assessing exposure to SHS outdoors, assessing the health impact of second-hand e-cigarette aerosol and measuring that aerosol in homes where e-cigarettes are used, among other areas of interest.

At the time of developing the TackSHS intervention air quality feedback intervention trials to encourage smoke-free homes had taken place only in one country in a limited geographical area [72,110,114,120,121]. This may have the effect of limiting the variety of housing and smoking behaviours present during the study period. This research took place in five locations across four European countries – Scotland, Catalonia, Italy and Greece – representing a variety of home and outdoor environments. At the inception of this study, most air quality feedback interventions had used delayed means to provide feedback (with the exception of one trial in Armenia which directly demonstrated the impact of smoking one cigarette on $PM_{2.5}$ in indoor air [114] and a pilot study in San Diego using a laptop to provide visual and auditory warnings of SHS detected by a Dylos DC1100 PM monitor [120]). No studies on interventions had up to this time used mHealth techniques to deliver feedback, making this trial unique.

7.2 Results

7.2.1 Recruitment

Recruitment by centre is shown in Table 12. Due to conflicting commitments, ICO in Barcelona were unable to complete recruitment as originally scheduled. This recruitment is ongoing (at the time of writing March 2019) with the goal of being completed later in 2019; for the purposes and timeline of this PhD the data collected in the four centres by the end of December 2018 is presented and analysed.

Recruitment involved an initial contact by telephone, during which potential participants were given information on the study, assessed against inclusion criteria and asked to complete a stage of change assessment (as described in chapter 6) to determine whether they were ready to change the smoking behaviour in their home. This process was conducted incorrectly in Milan, with no stage of change assessment conducted at first contact with participants. This could have resulted in participants unready to make behaviour changes taking part in the intervention study.

Those who passed the stage of change intervention were then scheduled for a home visit, at which point written informed consent was obtained, a baseline survey completed and a monitor installed. At the University of Stirling, 18 recruits passed the stage of change assessment and were scheduled for home visits but then dropped out before those visits could take place, usually with no further contact or reason given. This may have been related to the differences in recruitment method used in this centre compared to others (specifically the use of Facebook advertising for recruitment at Stirling). By comparison, only three potential participants who passed the stage of change assessment dropped out before the start of the intervention at other centres, where recruitment was conducted using conventional advertisements and word of mouth at universities.

Table 12 - Recruitment by centre, incorporating the total of those who were eligible to take part in the study following a stage of change assessment and those who completed the intervention. Note that other project commitments led to a delay in Barcelona beginning the project, which is now scheduled to finish later in 2019.

Centre	Fieldwork start and end dates	Initial recruitment target	Participants passing inclusion criteria	Participants completing the intervention
Athens - Behrakis Lab	April 2018 – November 2018	40	21	20
Barcelona - ICO	*	40	*	*
Florence - ISPRO	April 2018 – March 2019	20	6	3
Milan – INT	April 2018 –December 2018	20	20	18
Stirling - UoS	November 2017 – September 2018	40	44	27
Total	**November 2017 – March 2019**	**160**	**91**	**68**

7.2.2 Intervention outcomes

7.2.2.1 Data quality and cleaning

Data integrity was generally high with a median loss of 0.62% of data per home, although occasional monitor failures and dropped minutes of data occurred causing some greater data loss. Results from one participant in Stirling were lost due to a monitor failure early in the follow-up period (SC_37), while another participant (SC_34) was withdrawn from the study due to unusual activity associated with the RAPID monitor’s wireless internet device. Results from two recruits in Milan (HO_15 and HO_18) and one recruit in Florence (FI_03) were unavailable due to monitor failures.

Custom Python 2.7 scripts were used to clean data downloaded from the online system. Table 13 shows descriptive statistics of this cleaning process by centre. In all, a median of 4.5 hours of data (IQR=2,127 minutes) was lost from each participant over the course of the monitoring period, made up of both individual minutes of data which were not successfully transmitted and longer periods where a monitor connection had been lost for an unknown reason, necessitating a system reboot by a participant, or where the instrument had been turned off. Some duplicate records were also sent by monitors due to software bugs. These were cleaned and therefore had no effect on the results of the study, but were included when calculating daily and weekly figures given to participants.

Table 13 - Results of data cleaning per centre and overall. Note that the sample from Florence was too small to generate interquartile ranges.

Centre	**Median records (minutes) missing per home (IQR)**	**Median percentage of records missing per home**	**Median duplicate records (minutes) per home (IQR)**
Athens – Behrakis Lab	452.5 (2446)	1.02%	145 (84)
Florence - ISPRO	34 (-)	0.08%	76 (-)
Milan – INT	1170 (5178)	2.57%	113.5 (105)
Stirling - UoS	83 (1466)	0.19%	81 (147)
Overall	**269 (2127)**	0.62%	**101.5 (109)**

7.2.2.2 Intervention programme fidelity

As the intervention required regular messages to be sent manually and contacts to be made with participants, it was possible that SMS messages and other contacts could be missed during the course of an intervention. The Tackle software used to send SMS messages kept logs of each SMS message sent over the course of the study. The median number of SMS messages missed from each centre are shown in Table 14. Note that in some cases (due to internet connection problems) SMS messages were sent manually in Milan, but records of this are not available.

7.2.2.3 Mean $PM_{2.5}$ concentrations at baseline and follow-up

Overall, there was a significant reduction in measured mean $PM_{2.5}$ concentrations in the follow-up periods compared to the baseline across all participants in the study (the primary outcome measure), with a median reduction of -17% (-3.8μg/m^3). Full results by each centre and combined overall can be seen in Table 15.

Table 14 - Median SMS messages which were not sent by centre

Centre	**Median missed SMS messages (IQR)**
Athens – Behrakis Lab	0 (0)
Florence - ISPRO	6.5 (3)
Milan – INT	12 (5)
Stirling - UoS	1 (2)
Overall	**1 (8)**

Declines in measured $PM_{2.5}$ occurred at each centre and overall. In total, 46/68 homes (66%) had reduced $PM_{2.5}$ concentrations at follow-up compared to baseline. Full data from each centre on the number of homes experiencing declining mean $PM_{2.5}$ is shown in Table 16. Overall, this suggests that the intervention resulted in the majority of homes in each centre reducing their smoking behaviour indoors.

A Wilcoxon signed rank test was conducted on the paired baseline and follow-up mean concentrations of all centres over the course of the intervention to determine whether these declines were statistically significant. This non-parametric test was chosen as the concentration data is not normally distributed, being skewed to the right as is typical for inherently-lower bounded $PM_{2.5}$ concentration data (and as can be seen in Figure 16).

Table 15 – $PM_{2.5}$ concentrations at baseline and follow-up by centre and overall. Note that the sample from Florence was too small to generate interquartile ranges.

Centre	**n**	**Median baseline mean concentration**	**Median follow-up mean concentration**	**Median change for paired samples (IQR)**	**Median change as a % of baseline (IQR)**
		(µg/m³)	(µg/m³)	(µg/m³)	%
Athens – Behrakis Lab	20	20	14	-3.2 (8.8)	-24 (50.7)
Florence - ISPRO	3	32	19	-4.8 (-)	-12 (-)
Milan – INT	18	17	14	-2.1 (13.2)	-18 (61.1)
Stirling - UoS	27	64	59	-8.3 (61.7)	-12 (65.3)
Overall	**68**	**31**	**27**	**-3.8 (20.2)**	**-17 (51.9)**

Table 16 - Participants experiencing and not experiencing declines in mean $PM_{2.5}$ in homes between baseline and follow-up by centre.

Centre	**Participants not experiencing declines in mean $PM_{2.5}$ (%)**	**Participants experiencing declines in mean $PM_{2.5}$ (%)**	**Total**
Athens – Behrakis Lab	6 (30%)	14 (70%)	20
Florence - ISPRO	1 (33%)	2 (67%)	3
Milan – INT	5 (28%)	13 (72%)	18
Stirling - UoS	11 (41%)	16 (59%)	27
Total	**23 (34%)**	**45 (66%)**	**68**

The result of this statistical test demonstrated that the median 17% fall in mean $PM_{2.5}$ concentrations was statistically significant (p=0.046). Due to the small sample sizes available, significance testing was not conducted on samples by centre.

An alternative method of determining statistical significance of change between non-normally distributed datasets is to log-transform that data (thus causing it to become normally distributed) and then conduct a parametric test (such as Student's t-test). This approach was conducted on baseline and follow-up $PM_{2.5}$ concentrations, with a paired t-test resulting in p=0.085 (above the presumed level of significance of p=0.05).

Mean $PM_{2.5}$ declined in most homes between baseline and follow-up at each centre. Figures 17 & 18 plots mean $PM_{2.5}$ at baseline and follow-up for each participant, by each centre and across all centres, graphically demonstrating the level of decline.

Figure 16 - Histograms showing the distribution of mean $PM_{2.5}$ concentrations at baseline and follow-up

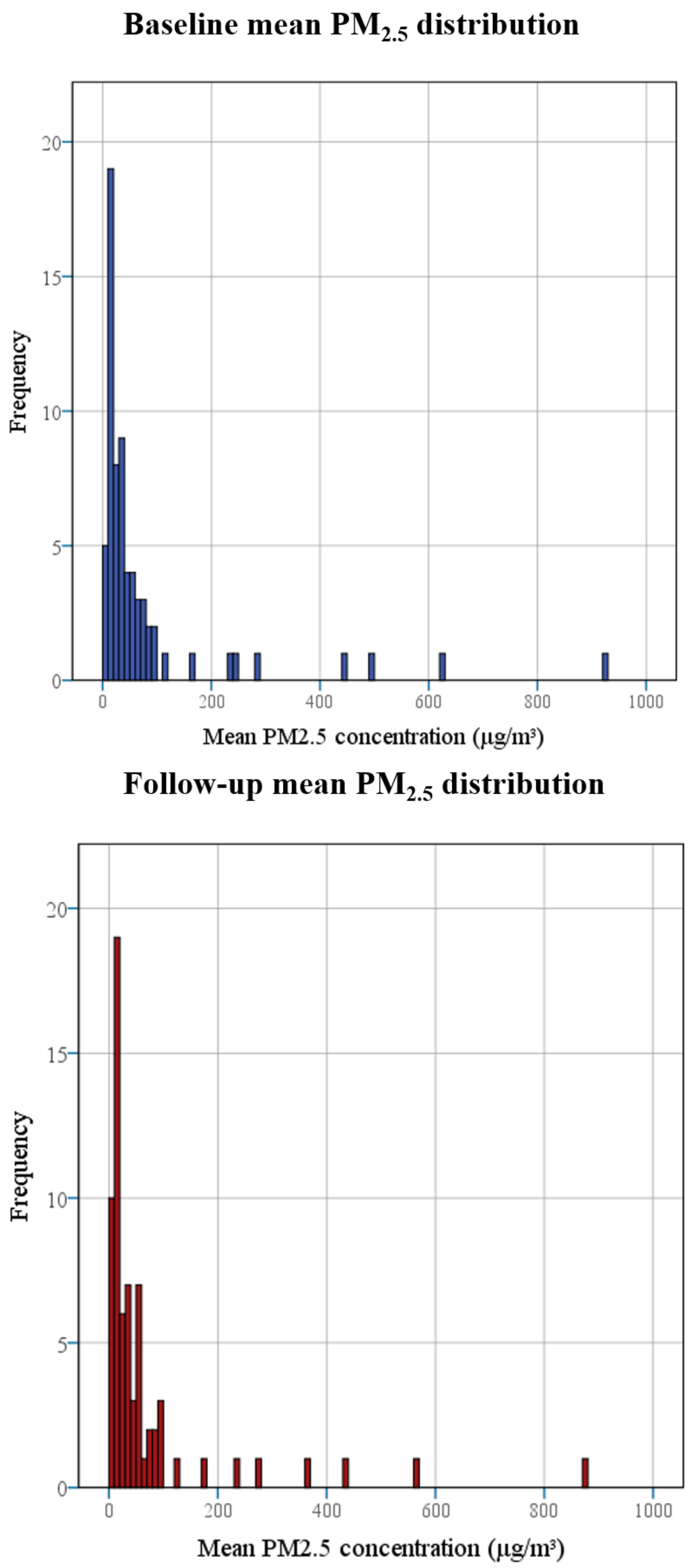


Figure 17 - Measured mean $PM_{2.5}$ concentrations during baseline and follow-up measurements in each participating home by centre. Results to the lower right of the identity line show declines in $PM_{2.5}$ concentration over the intervention period. Note the logarithmic scales on both axes to account for the variability in concentration in these homes.

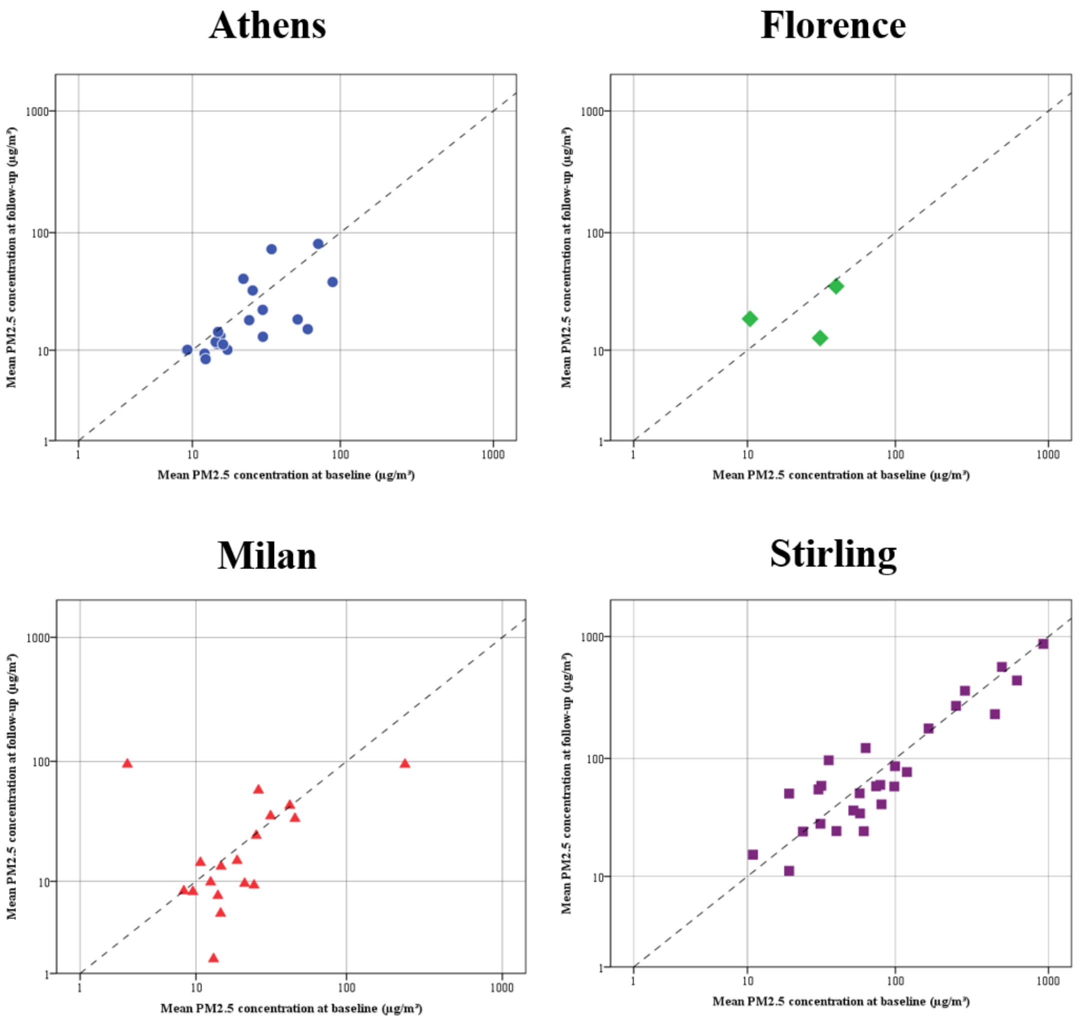
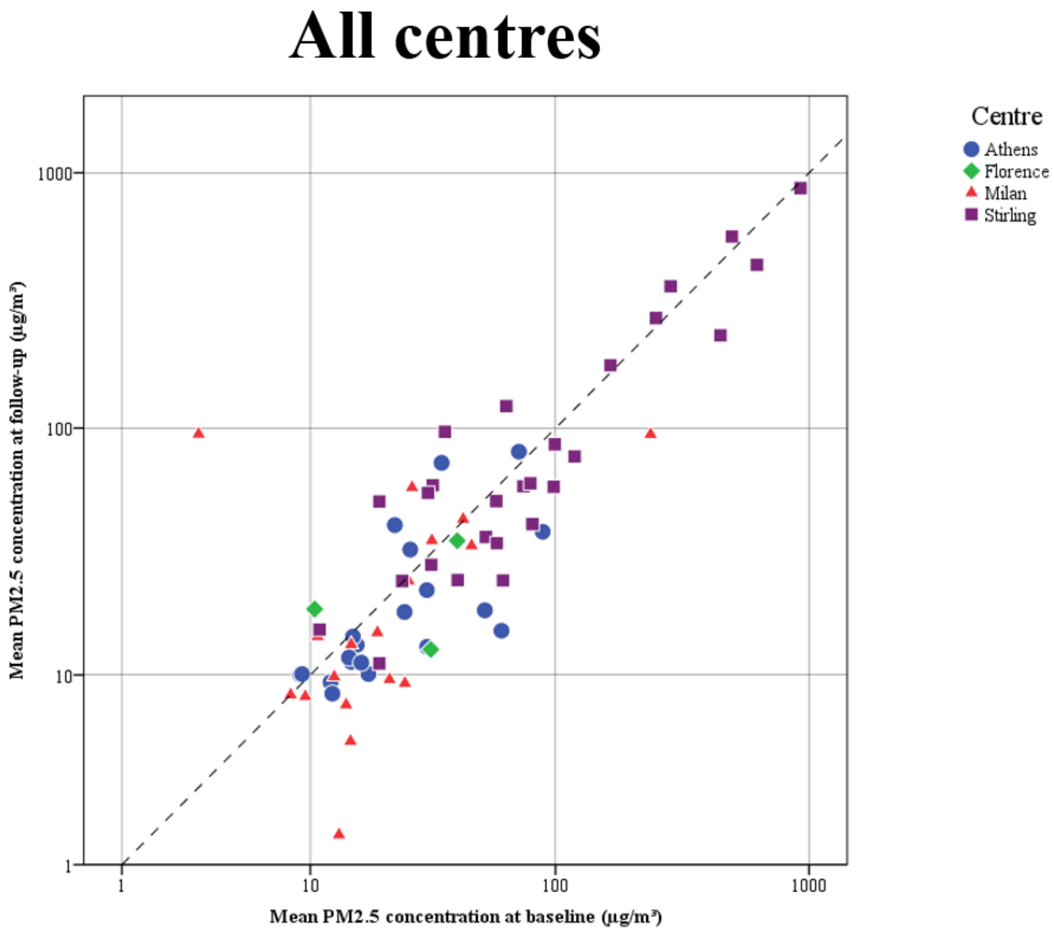


Figure 18 - Measured mean $PM_{2.5}$ concentrations during baseline and follow-up measurements in each participating home over all centres. Results to the lower right of the identity line show declines in $PM_{2.5}$ concentration over the intervention period. Note the logarithmic scales on both axes to account for the variability in concentration in these homes.



7.2.2.4 Seasonal effects

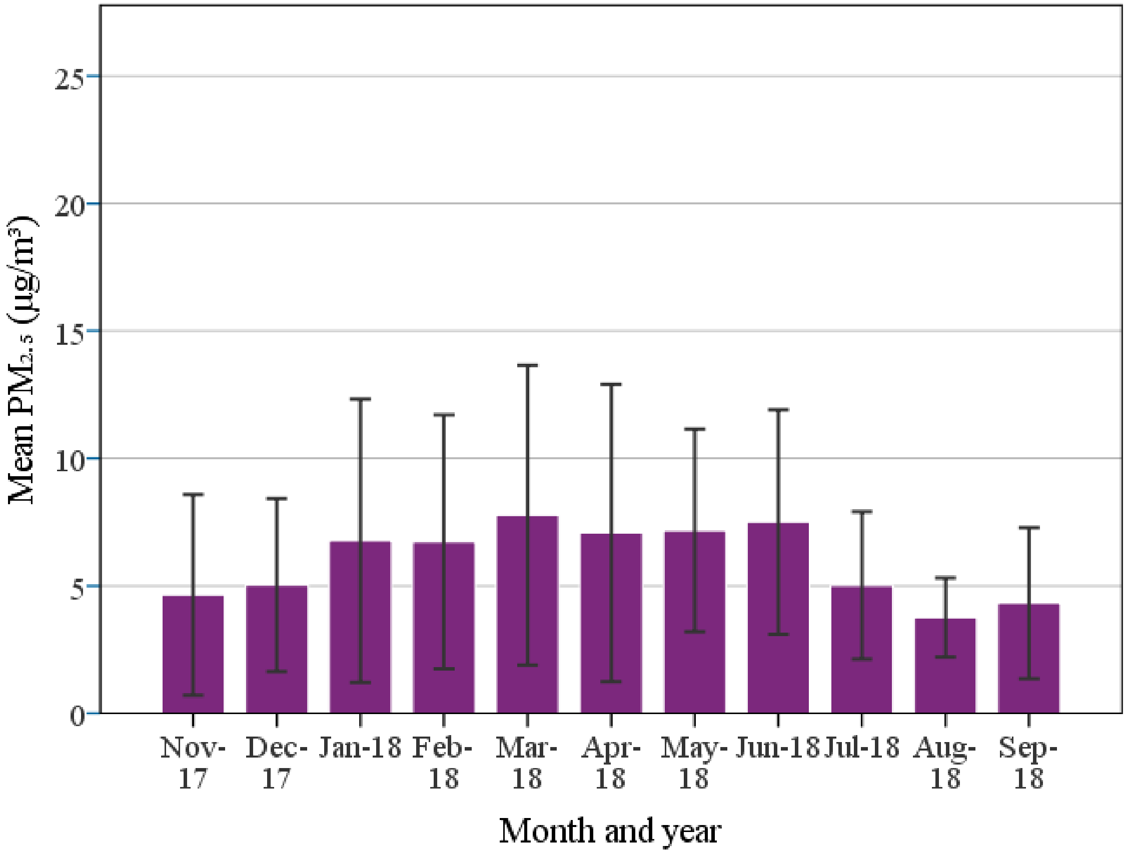
A range of factors can affect concentrations of $PM_{2.5}$ indoors over the course of the year. Where weather conditions change, human behaviour may change in response, for instance by closing or opening windows or doors affecting ventilation rates in the home, or by increased willingness to smoke outdoors in warmer summer months. It was not possible to control for these effects in this study.

One important potential seasonal source of error could be changes in outdoor $PM_{2.5}$ concentration. Seasonal variation affects $PM_{2.5}$ concentrations outdoors (and consequently indoors through infiltration) [194]. Over the course of a month-long measurement period significant seasonal variation could be a confounding factor – gradual changes in outdoor ambient concentrations could be confused for reductions in SHS indoors.

To determine whether seasonal variation could have led to declines in $PM_{2.5}$ concentrations indoors, outdoor monitoring data from Scotland during the intervention period was accessed and observed. Similar data was not accessible at other centres, but as Scottish data made up 40% (27/68) of total interventions in the study this would provide an indication of the presence or absence of seasonal effects on the intervention outcome measures.

Interventions in Scotland took place in and around Edinburgh. Three fixed-site gravimetric $PM_{2.5}$ monitoring sites were identified in this area – Edinburgh St Leonard's, Edinburgh St John's Road and Kirkcaldy – and hourly $PM_{2.5}$ concentration data downloaded from November 2017 (when the first intervention took place) to September 2018 (when the last intervention finished). Means for each hour were calculated and results collated by month (Figure 19).

Figure 19 - Mean $PM_{2.5}$ concentrations by month at three fixed site monitors in and around Edinburgh, Scotland over the course of this study. Error bars represent one standard deviation of the hourly mean.



No major seasonal variation was observed, with all monthly means within a narrow range between 4 & 8µg/m^3. Outdoor concentrations were very low compared to concentrations in homes (median baseline mean 64µg/m^3 in all Scottish homes, compared to 4.7µg/m^3 in outdoor monitoring). The median change detected in Scottish homes was -8.3µg/m^3, substantially greater than the largest month-to-month change in mean concentration of -2.5µg/m^3 (between June 2018, 7.5µg/m^3 and July 2018, 5.0µg/m^3).

A large majority (21/27) of interventions in Scotland occurred between January and June 2018, a period in which mean outdoor $PM_{2.5}$ concentrations were relatively stable. Only two interventions were conducted in any part in July 2018, and only one was conducted principally in August 2018 (the period over which $PM_{2.5}$ concentrations declined by the greatest amount).

Hourly interquartile ranges in each month ranged from 2.0 (in August 2018) to 5.34 (in April 2018). These large interquartile ranges demonstrate that intra-month variation was much greater than inter-month changes.

Similar fixed-site monitoring data was not available for other three centres in the study. The majority (16/20) of interventions in Athens occurred between April and August 2018, when days were becoming drier and warmer and hence $PM_{2.5}$ concentrations would be expected to be higher than outside of this period [195]. Seasonal effects cannot be ruled out in Milan, although 12/18 interventions there were completed within the summer months when $PM_{2.5}$ concentrations have been found to be lower in the Po Valley than in winter [196,197]. A similar (although milder) seasonal effect to that seen in Milan may operate in Florence [198], although the small number of interventions conducted there took place within three summer months making seasonal variation a lesser consideration.

7.2.2.5 Time over World Health Organisation guideline limits for $PM_{2.5}$

A secondary outcome measure in this study was change in the percentage of time where measured $PM_{2.5}$ concentrations exceeded the World Health Organisation's guideline indoor limit for $PM_{2.5}$ over 24 hours (25µg/m^3). The percentage of time at follow-up where $PM_{2.5}$ was measured to be above this concentration was compared to the percentage of time at baseline where this was so.

Overall, time spent over 25µg/m^3 fell by a median 5.1% from baseline to follow-up, representing more than one hour per day in which the median home was below that level following the intervention. Table 17 shows full data on percentage time over 25µg/m^3 from all centres and overall.

To test the significance of this result, a Wilcoxon signed rank test was conducted on pairs of the percentage of time at baseline and follow-up. The fall was statistically significant (p=0.022).

Table 17 - Time over WHO 24-hour limit on $PM_{2.5}$ indoors by centre and overall, along with change following the intervention.

Centre	**n**	**Median baseline % time over 25µg/m³**	**Median follow-up % time over 25µg/m³**	**Median change in % time over 25µg/m³**
Athens – Behrakis Lab	20	16.4	8.7	-8.6
Florence - ISPRO	3	53.5	19.6	-0.1
Milan – INT	18	24.7	15.0	-1.6
Stirling - UoS	27	56.0	46.6	-5.5
Overall	**68**	**36.0**	**28.9**	**-5.1**

7.2.2.6 Self-assessed ability to achieve a smoke-free home

Participants were asked to assess their ability to achieve a smoke-free home as part of the stage of change assessment used at initial recruitment to determine whether potential participants were prepared to make substantial changes to their smoking rules at home. This ability was measured using a self-rated 0-10 scale of a smoke-free home within the next two months, where 10 represented a participant who was "extremely likely" to make their home smoke-free, while 0 represented a participant "extremely unlikely" to make their home smoke-free. Participants were asked a similar question during day 9 and day 23 calls as a routine part of the intervention.

This data was only available for Athens, Florence and Stirling, due to poor intervention fidelity in Milan (where the stage of change assessment was not used at recruitment). Statistics by centre are available in Table 18. Overall, participants were more likely to report being likely to achieve a smoke-free home as the study progressed, but this may have been an artefact of less optimistic participants dropping out after recruitment or being unavailable for day 9 or day 23 phone calls.

Table 18 - Self-reported likelihood of achieving a smoke-free home within two months at three points in the study.

Centre	**Median self-rated achievability of a smoke-free home at recruitment (n)**	**Median self-rated achievability of a smoke-free home at day 9 (n)**	**Median self-rated achievability of a smoke-free home at day 23 (n)**
Athens – Behrakis Lab	8 (20)	9 (20)	10 (20)
Florence - ISPRO	8 (3)	7.5 (2)	9 (2)
Stirling - UoS	6 (26)	5.5 (17)	8 (16)
Total	**7.5 (49)**	**8 (39)**	**9 (38)**

Pearson correlation coefficients were calculated to determine whether higher ratings at recruitment indicated that participants were more likely to reduce SHS in their home, but there was no significant association with either of the objective outcome measures (change in mean $PM_{2.5}$ or change in percentage of time above the WHO $PM_{2.5}$ 24h guidance limit) as shown in Table 19).

Table 19 - Results of Pearson correlations between outcome measures and participant self-assessed stage of change at recruitment.

Outcome measure	**Pearson correlation with self-assessed stage of change at recruitment**	**P-value**
Change in mean $PM_{2.5}$ concentration	0.101	0.491
Change in percentage of time over WHO guideline limit	-0.005	0.975

7.2.2.7 Knowledge about SHS and intention to act

Knowledge about and intention to act on the harm of SHS was generally good. Participants were asked to rate seven statements on a five-point Likert scale (from “strongly agree” to “strongly disagree”). These answers were coded numerically, with answers reflecting the scientific consensus on the health risks of SHS, and an overall “knowledge/intention” score calculated for each participant who answered all questions. Statements and median answers by centre are presented in Table 20.

Results from each question and from overall knowledge/intention scores were tested against absolute change in mean $PM_{2.5}$ between baseline and follow-up and percentage time over the WHO guideline limit using independent-samples Kruskal-Wallis tests. Results of these tests are shown in Table 20.

No individual question was significantly associated with changes in these measures, nor was overall knowledge/intention score.

7.2.2.8 Change in measured SHS by self-reported behaviour change

Participants reported whether they had made any change in their behaviour in follow-up questionnaires, answering a yes or no question to that effect. Of those participants who completed follow-up questionnaires, 43/61 (70%) indicated that they had made a change to smoking behaviour in the home regardless of what it might be. All responding participants in Athens (20/20) indicated they had made a change, with most participants in Florence (2/3) and Stirling (15/20) reporting the same. A minority (6/18) of participants in Milan reported making changes to smoking behaviour in the home.

Mann-Whitney U tests were conducted to determine whether positive answers to this question were associated with greater reductions in detected $PM_{2.5}$ in homes or percentage time over the WHO guideline limit for $PM_{2.5}$. The results of these tests can be seen in Table 21. By this metric, self-reported change in behaviour did not have a significant association with reduced mean $PM_{2.5}$ concentration ($p=0.245$) or reduced time over 25µg/m^3 ($p=0.187$).

Table 20 - Median responses by centre and overall to questions on SHS knowledge and intention to act, along with median "knowledge/intention score".

Centre	**Median response to statement**							**Median overall knowledge/intention score**
	Inhaling other people's tobacco smoke poses a high risk to health	I would challenge someone smoking in a non-smoking area	The dangers of inhaling other people's tobacco smoke are greatly exaggerated	I would ask someone who smokes to smoke outside of my house	Children are more at risk from other people's tobacco smoke than adults	Exposure to other people's tobacco smoke can increase the severity of asthma in children	Other people's tobacco smoke can cause significant problems for children	
High knowledge/intention answer	Strongly agree (5)	Strongly agree (5)	Strongly disagree (5)	Strongly agree (5)	Strongly agree (5)	Strongly agree (5)	Strongly agree (5)	
Athens – Behrakis Lab	Strongly agree (5)	Strongly agree / Agree (4.5)	Disagree (4)	Agree (4)	Strongly agree (5)	Strongly agree (5)	Strongly agree (5)	29 / 35
Florence - ISPRO	Strongly agree (5)	Strongly agree (5)	No strong opinion (3)	No strong opinion / Agree (3.5)	Strongly agree (5)	Strongly agree (5)	Strongly agree (5)	30.5 / 35
Milan – INT	Agree (4)	Agree (4)	No strong opinion / Disagree (3.5)	No strong opinion (3)	Strongly agree (5)	Strongly agree (5)	Strongly agree (5)	28 / 35
Stirling - UoS	Agree (4)	No strong opinion (3)	No strong opinion (3)	Disagree (2)	Agree (4)	Agree (4)	Agree (4)	26 / 35
Overall	**Strongly agree (5)**	**Agree (4)**	**Disagree (4)**	**No strong opinion (3)**	**Strongly agree (5)**	**Strongly agree (5)**	**Strongly agree (5)**	**28 / 35**

7.2.2.9 Change in measured SHS by housing type

It was hypothesised based on previous research that housing type could affect ability to reduce smoking in the home, as those living in flats (particularly higher flats) face additional barriers compared to those who live in houses when leaving the home to smoke – the need to move through communal areas and travel down stairs, adding time and potentially making it more difficult to smoke outdoors. For this reason, participants were asked in the baseline questionnaire about their housing type: a detached house, a semi-detached house, a terraced house or a flat. Those who lived in flats were asked to provide the flat's floor.

Housing type was recorded incorrectly in Milan, with information on the height of flats not recorded. For this reason, all flat types were collapsed into one for analysis. Due to small sample size, all types of house were also combined for analysis. Mann-Whitney U tests were conducted on changes in mean $PM_{2.5}$ and percentage time over the WHO guideline limit for $PM_{2.5}$ at baseline and follow-up, but no significant differences were detected (p=0.931 and p=0.819 respectively).

7.2.2.10 Change in measured SHS by access to outdoor space

For similar reasons as in the case of housing type, it was hypothesised that the availability of outdoor space (a garden or balcony) could affect the ability of participants to reduce SHS in their homes, as those who do not have a private outdoor space to smoke in might find smoking outdoors more difficult than those who do.

Participants were asked during the baseline survey whether they had access to a private garden, a shared garden, a balcony or no form of outdoor space. 23 of 63 responding participants reported access to a private garden, while 22 had access to a shared garden and 36 had a balcony. Only one participant (from the Stirling cohort) indicated that they had no access to outdoor space of any of these kinds. Balconies were very common in Greece and Italy (where 36/42 participants reported access to them) but no participant in Scotland reported access to one, likely reflecting prevailing building standards and climatic conditions in each country.

As participants could have access to multiple kinds of outdoor space, binary variables were created for each type. A binary variable was also computed for participants who had access only to a shared garden (with no balcony or private garden) and a categorical variable computed representing the type of garden available to participants – private, shared, none or both private and shared. Independent samples Kruskal-Wallis tests were conducted on all variables to test the association between access to that type of space and change in mean $PM_{2.5}$ between baseline and follow-up and percentage time over the WHO guideline limit for $PM_{2.5}$. Results of these tests are given in Table 22. No category of access to outdoor space was significantly associated with greater improvement in the study's objective outcome measures.

Table 21 - Results of Kruskal-Wallis tests on the association between response to each knowledge/intention statement and outcome measures.

Knowledge/intention statement	**P-value, change in mean $PM_{2.5}$ concentration over intervention**	**P-value, change in time over WHO guideline over intervention**
"Inhaling other people's tobacco smoke poses a high risk to health"	0.517	0.434
"I would challenge someone smoking in a non-smoking area"	0.394	0.424
"The dangers of inhaling other people's tobacco smoke are greatly exaggerated"	0.311	0.391
"I would ask someone who smokes to smoke outside of my house"	0.629	0.858
"Children are more at risk from other people's tobacco smoke than adults"	0.206	0.566
"Exposure to other people's tobacco smoke can increase the severity of asthma in children"	0.662	0.610
"Other people's tobacco smoke can cause significant problems for children"	0.933	0.812
Overall knowledge/intention score	**0.150**	**0.125**

7.2.2.11 Worked example – a typical participating home

Participant SC_18 took part in the study in April and May 2018 as part of the Scottish cohort of participants where the intervention was delivered by researchers at the University of Stirling. Measured $PM_{2.5}$ concentrations in their home declined by 21% between baseline and follow-up, close to the overall median decline of 17%. The absolute decline in concentration in this home was 15.7µg/m^3, larger than the median absolute decline of 3.8µg/m^3.

SC_18 lived in a first-floor flat with their partner (a non-smoker) and their son. At recruitment, they rated their ability to make their home smoke-free in the next two months at 6/10, citing the difficulty of going downstairs from their flat to smoke as a barrier but the prospect of improved weather as summer approached as a potential facilitator.

A monitor installation date and time was arranged, a home visit conducted and a baseline survey completed by the participant. Over the seven day baseline period mean $PM_{2.5}$ was measured at 74.6µg/m^3, with 82% of measurement time exceeding the WHO guideline limit of 25µg/m^3. The intervention proceeded as planned (although the participant was not contactable for a telephone call on day 23, and SMS messages were not sent as intended on days 15 & 17).

Over the seven day follow-up period (from day 24 – day 30 inclusive) mean $PM_{2.5}$ was measured at 58.9µg/m^3, a reduction of 15.7µg/m^3 compared to the baseline period. The $PM_{2.5}$ concentration plot for this period is provided in Figure 20. Percentage time over the WHO guideline limit had declined to 67%, a fall of 15% compared to the baseline period. This represented an additional 25 hours during the follow-up period where $PM_{2.5}$ was below the guideline level, compared to the concentrations detected at baseline. In their follow-up questionnaire SC_18 reported having made changes to smoking behaviour in their home, suggesting that SHS was reduced following these changes. While these smoking behaviour changes and reductions in $PM_{2.5}$ concentrations were a positive step, the house was clearly not smoke-free by the end of the seven-day follow-up period.

Graphs of $PM_{2.5}$ concentration over the course of the baseline and follow-up periods are given in Figure 20.

Table 22 - Results of independent samples Kruskal-Wallis tests conducted in IBM SPSS v23 on the relationship between the types of outdoor space available to participants and the main outcome measures for the study. "Private garden", "shared garden" and "balcony" refer to binary variables indicating the availability of those types of spaces, while "only a shared garden" refers to a binary variable indicating whether a participant had access to a shared garden space and no other type of outdoor space. "Type of garden" refers to a variable with four categories, indicating whether a private garden, a shared garden, both or neither were available to participants.

Type of outdoor space	**P-value, change in mean $PM_{2.5}$ concentration over intervention**	**P-value, change in time over WHO guideline over intervention**
Private garden	0.383	0.612
Shared garden	0.908	0.878
Balcony	0.914	0.343
Only shared garden	0.624	0.133
Type of garden	0.807	0.768

7.3 Discussion

Based on the results of this study, the Measuring for Change intervention can reduce SHS concentrations in homes over the course of a month-long intervention. However, this reduction does not typically lead to participants having fully smoke-free homes, instead leading to significant but small reductions of about 17% in mean $PM_{2.5}$ concentrations and 5.1% in percentage time spent over the WHO guideline limit for $PM_{2.5}$ over 24 hours in the home. This is suggestive that the intervention leads to participants giving greater consideration to the impact of smoking on household air quality and/or the harms of SHS, but being unable to take the necessary steps to make the home entirely smoke-free all of the time.

7.3.1 Strengths and limitations

This study represents a wholly new approach to air quality feedback for smoke-free homes, incorporating novel mHealth techniques such as SMS messaging and internet-based feedback. Other studies of air quality feedback interventions have used either immediate [114,117] or significantly delayed [125,127] feedback. This study is the first to use a hybrid approach, combining near-immediate feedback through SMS messages with delayed, in-depth researcher-supported feedback through emails and phone calls.

As a quasi-experimental study rather than a randomised controlled trial, this study cannot definitively demonstrate causation. However, the effect size (a median decline in mean $PM_{2.5}$ concentration of 17% between baseline and follow-up periods) is similar to other published research on air quality feedback interventions [117,125] which included a control.

Unlike some other studies in this area, no non-air quality feedback elements such as nicotine replacement therapy [125] were included in the intervention, making this study a true test of air quality feedback as a method of promoting smoke-free homes.

Difficulties in recruitment across all centres led to a smaller sample size than intended. Further data from Barcelona that may become available later in 2019 has the potential to increase the sample size.

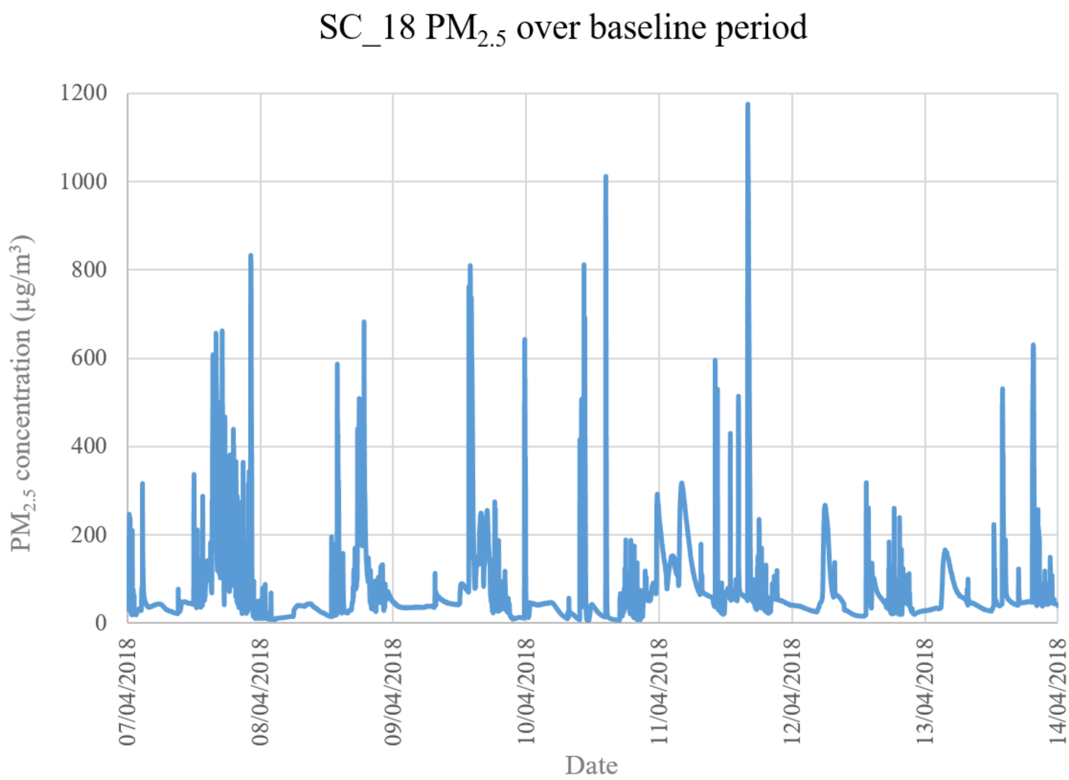
Intervention fidelity was not high across centres, particularly in Milan where stage of change data were not retained and SMS messages were sent less frequently than in other centres. The limited sample size means that this study is underpowered to detect differences between centres, but it should be noted that Milan had the lowest absolute decline in $PM_{2.5}$ of any centre ($-2.8\mu g/m^3$) .

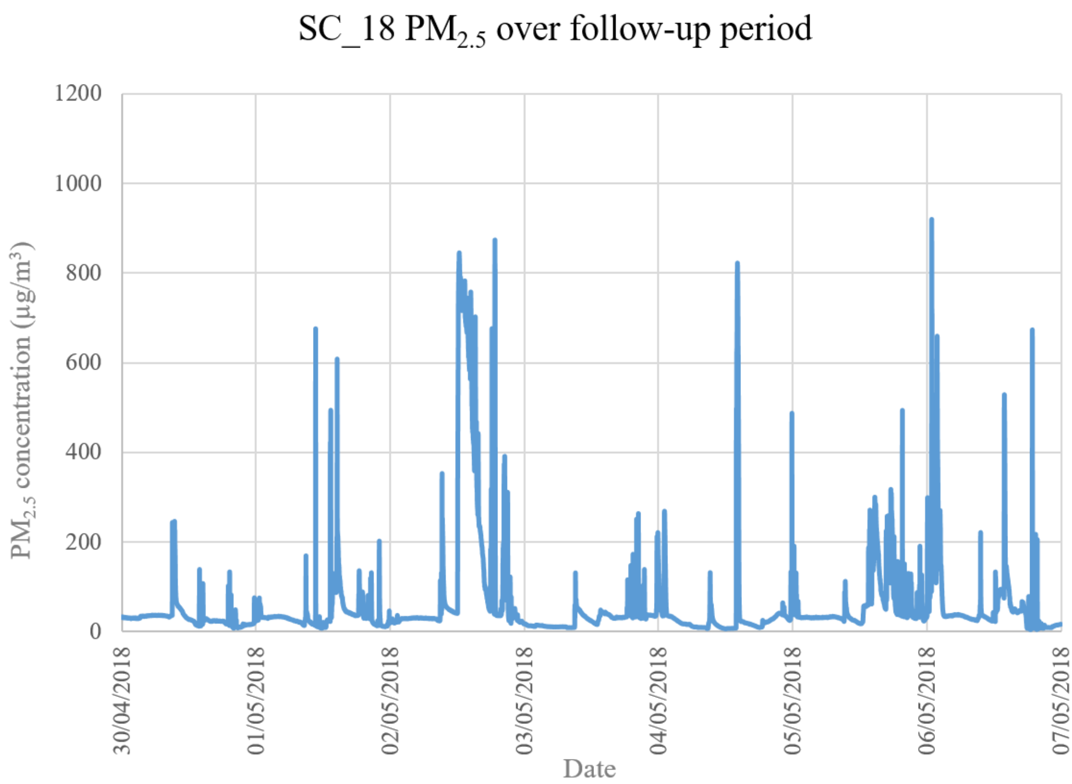
The RAPID monitor system performed well with an average of >99% of the time period measured recorded by the system. Occasional failures in monitoring required researchers to monitor the status of each monitor on a frequent basis. Due to the nature of the system, which included several components with external wired connections, it was possible for connections to be severed accidentally by knocking the device. Additionally, software errors occurred causing delays or failures in sending data to the server. These were partially remedied by ongoing development of the system during the course of the study, but were not completely eliminated. Using an alternative monitoring system with integrated long-term data storage and internet connection capabilities may reduce these problems further.

7.3.2 Alternative explanations for change

As this study did not include a control group, it is possible that $PM_{2.5}$ concentrations declined in homes for reasons not related to the intervention. The median change detected in $PM_{2.5}$ concentration between baseline and follow-up periods was statistically significant but small in absolute terms ($<5\mu g/m^3$).

Figure 20 - graphs of $PM_{2.5}$ concentration over time during SC_18's baseline and follow-up periods.





Seasonal variation in ambient air pollution could have accounted for some of this change, as the month-long measurement periods used could have reflected gradual changes in $PM_{2.5}$ concentration over this time (depending on the infiltration of $PM_{2.5}$ into homes in each setting, which may relate to building design and location among other factors). Comparison of intervention outcome measures with outdoor air monitoring data from Scotland does not reflect such a change, although it cannot be ruled out definitively in other centres due to a paucity of fixed-site monitoring data. Other seasonal effects could have contributed to this effect, such as increased ventilation with open windows during warmer summer months.

It is also possible that the recruitment criteria, which required participants to be willing to . However, the effect size observed was similar to a previous study which did not require participants to be prepared to make a change within their home [117]. Additionally, higher willingness to make a change at recruitment was not associated with greater likelihood to succeed in doing so (section 7.2.2.6). From the available evidence, the stage of change recruitment method appears to have had no effect on the results of this intervention.

Nonetheless, the lack of a control group in this study must be regarded as a serious limitation. Future research may be called for, conducting this intervention within a randomised controlled trial framework.

7.3.3 Future research

The air quality feedback intervention described in this study requires relatively frequent contacts and work by a researcher to send SMS and email messages and to conduct phone calls. It would be possible to automate the message components of the intervention such that a researcher or practitioner only needed to be involved when telephoning participants to discuss results. This could reduce the burden of the intervention on healthcare professionals' time in a real-world setting.

This intervention was conducted for 16 days (excluding baseline and follow-up periods) due to constraints in the available resources. One recent intervention [117] has involved feedback given to participants over three months. An intervention incorporating greater automation could potentially run in a home indefinitely, providing participants with continuous feedback on smoking indoors. This could allow participants to build habits, helping them to keep a smoke-free home. A longer period could also have tested the ability of the intervention to begin longer processes of change – it is possible that participants continued to change their behaviour gradually following the study, and that follow-up periods later (such as six or 12 months after the intervention period) could demonstrate greater change than observed in this study.

Non-tobacco sources of $PM_{2.5}$ exist in the home [88], so it is possible that under some circumstances other sources could be misidentified as smoking, reducing trust in the intervention. Techniques to more selectively identify SHS in the home could be used to increase trust and to measure the effectiveness of the intervention more accurately. This could involve real-time nicotine monitoring [90] or the use of new techniques to determine the source of emissions based on the detected sizes of particles emitted by different sources of pollution – an approach discussed in chapter 8 of this thesis.

Alternatively, interventions could be designed to address multiple sources of air pollution in the home, providing more general advice on improving indoor air quality such as by changing cooking method or improving ventilation. This approach may have benefits – epidemiological evidence suggests that all combustion-related $PM_{2.5}$ is harmful [199] – but could also come with risks if participants come to believe that actions such as frying food (a source of $PM_{2.5}$ [88]) are as harmful to health as smoking indoors.

7.3.4 Conclusions

An air quality feedback intervention using a hybrid of immediate and delayed feedback techniques can be a successful method of reducing SHS in the home over a short trial period, although it does not lead to wholly smoke-free homes.

8 Detecting smoking in homes using low-cost PM monitors

This chapter contributes to research question 4:

- *Can low-cost $PM_{2.5}$ monitors be used to differentiate SHS from other sources of PM, and thus provide more accurate information on the source or behaviour leading to poor air quality?(RQ4)*

and objective 5:

5. Develop a candidate algorithm to differentiate SHS-related $PM_{2.5}$ from other sources, and recruit participants in a small study of smoke-free homes to provide data to test that algorithm with smoking home data

8.1 Background

$PM_{2.5}$ monitoring is not specific for SHS [91]. Many other potential sources of $PM_{2.5}$ exist in the home, including cooking fumes, wood stoves and the use of incense or candles, among others [88]. It is therefore possible that air quality feedback interventions using $PM_{2.5}$ monitoring could lead to incorrect results in environments where other sources of $PM_{2.5}$ exist.

Providing reliable information to participants is a central part of air quality feedback interventions. Objective feedback relies on accurate information about the impact of SHS on home air quality, both to detect it and in order to promote change. If this is not possible, the intervention cannot function – for instance, in one study on the feasibility of a smoke-free homes intervention in Israel, statistical noise in $PM_{2.5}$ concentrations over time led to researchers abandoning the air quality feedback component of the intervention [126,149].

It would therefore be useful to be able to classify detected $PM_{2.5}$ as smoking-related or non-smoking-related in order to conduct air quality feedback interventions. This may be possible due to the distinctive particle size distribution of second-hand smoke, which peaks at particles below 0.2μm in diameter [188]. The Dylos DC1700 provides some data on particle sizes, and could therefore be used for this purpose.

Future work may include analysis of smoking-related peaks by shape - as smoking-related PM is generally produced quickly and remains in the air for long periods of time [89], it may be possible to use peak shape to identify smoking events. Other sensors, such as newer real-time nicotine sensors [90], could also be incorporated to allow more reliable detection of nicotine.

8.2 "How do you know those particles are from cigarettes?": An algorithm to help differentiate second-hand tobacco smoke from background sources of household fine particulate matter

Note – this section is an edited form of a paper published as Dobson R & Semple S. "How do you know those particles are from cigarettes?": An algorithm to help differentiate second-hand tobacco smoke from background sources of household fine particulate matter. Environ Res 2018;166:344–7. doi:10.1016/j.envres.2018.06.019. The text of the manuscript as published is provided as Appendix VII.

8.2.1 Introduction

$PM_{2.5}$ has been widely used as a proxy to quantify indoor concentrations of SHS in many settings including bars, homes and vehicles [75,76] as reliable measurements can be taken easily and affordably over time using optical particle counters, in contrast to the high cost and complexity of more specific methods such as air nicotine measurement. However, other activities in these settings can also generate $PM_{2.5}$. These can include cooking emissions, combustion such as candle burning or the use of solid fuels for heating, and aerosols such as deodorants and hair sprays [200]. These sources can produce high concentrations of PM within a home which could be confused for SHS in interpretation.

Parents in previous intervention trials have been observed to deny and challenge messages about the risk of SHS [153], and if feedback wrongly identifies non-SHS sources as being smoking activity this is likely to weaken the effectiveness of such approaches and make the participant question the validity of the measurement method. Developing reliable and accurate information on PM concentrations that are specifically linked to SHS is therefore important in the development of effective interventions.

The particle size distribution of tobacco smoke is known to skew towards fine and ultrafine particles [188]. The mean diameter of particles in tobacco smoke has been measured as 0.27μm (in the case of mainstream smoke) and 0.09μm (for sidestream smoke); smaller mean diameters than those associated with common household activities like frying, cleaning and the movement of people, and other sources [201] while still producing a sustained increase in particle mass concentration over time [89]. The particle size distribution of tobacco smoke has been observed to be further skewed towards smaller particles than those of candles and incense, common sources of combustion-related PM indoors [202].

The Dylos DC1700 provides data on both the fine and coarse fractions of particulate matter in the form of particle counts for particles larger than 0.5µm and particles larger than 2.5µm. It may therefore be possible to use this particle size information to distinguish between different sources of PM in a home, and potentially to classify homes as smoking or non-smoking.

This research uses particle concentration data measured in homes to develop and test a rule-based approach to determine whether tobacco was smoked in the home during the monitoring period. This information could be useful in providing air quality data to support behavioural interventions designed to encourage smokers to keep their homes smoke-free.

8.2.2 Methods

8.2.2.1 Measuring mass concentrations and particle counts in homes

Previously reported methods [148] were used to assess $PM_{2.5}$ concentrations in homes. From previous work by our group [169], time resolved $PM_{2.5}$ data were already available from 116 smoking homes. Data from non-smoking homes were collected in the course of this research. Minute-by-minute particle counts reported by the Dylos DC1700 monitor were converted to estimated $PM_{2.5}$ concentrations using a previously developed equation (Equation 1).

Also, the large particle percentage, consisting of the particles larger than 2.5µm as a percentage of the total particles detected, was calculated for each minute of measurement for use in the algorithm.

8.2.2.2 Algorithm development

A four-step algorithm was developed to classify homes as smoking or non-smoking based on one day or more of Dylos-recorded data by excluding data points which were unlikely to be related to smoking. This algorithm was designed to use the ratio of large to small particles detected by the Dylos as a “signature” for the presence of SHS. Additional steps were intended to reduce noise in the data caused by brief fluctuations in levels of PM.

For each home:

1. Remove data where $PM_{2.5}$ concentration is below 5µg/m^3. This step is intended to account for low ambient concentrations of $PM_{2.5}$ which are not related to SHS. 5µg/m^3 was chosen as indoor $PM_{2.5}$ has been shown to correlate to 79% of ambient $PM_{2.5}$ in similar conditions [203], while the average ambient $PM_{2.5}$ concentration in Scotland has been modelled at 6.6µg/m^3 [204].
2. For each minute of data, calculate the percentage of the total detected particles which are larger than 2.5µm in diameter. Remove data where the percentage of large particles is greater than a threshold (described throughout as the 'Large Particle Threshold' or LPT).
3. Remove data where a peak lasts for fewer than three minutes, to account for random fluctuations compared to the sustained impact of SHS on indoor air quality [89].
4. Take the percentage of minutes in the log where data has not been removed in one of the steps above. This can be used as an "SHS score" to classify the home as smoking or non-smoking if the score is above a cut-off (determined experimentally).

8.2.2.3 Statistical analysis

Use of the algorithm relies on two factors: the LPT which best indicates smoking, and the best-performing cut-off value for the SHS score, over which a log can be classified as smoking. Receiver operating characteristic curves were used to determine these factors.

ROC curves are a common method for determining the efficacy of a diagnostic test [205]. In an ROC curve, a test is carried out on a set of records, and its specificity and selectivity are plotted. This allows comparison between different tests using the area under the curve (AUC) of this plot – a mathematical representation of the overall effectiveness of the test. Tests which classify records more successfully than random have AUC values greater than 0.5, while a hypothetical perfect test would have a value of 1.0.

Variants of the algorithm using LPTs between 0.1% and 4.0% (stepped up in 0.1% increments) were applied to the full dataset of logs and the categorisation results plotted on an ROC curve using IBM SPSS v24 [187]. The LPT which resulted in the highest AUC was selected, and the curve analysed to find the SHS score cut-off which maximised selectivity and specificity. An ROC curve was also generated using the mean $PM_{2.5}$measured in each household as a predictor of smoking status. Custom Python 2.7 scripts were developed to apply the algorithm to Dylos data logs.

8.2.2.4 Smoke-free homes data collection

Participants working at three health charities in Scotland were recruited. Only people living in homes where smoking or e-cigarette use was not permitted were eligible to participate in the study. A target of 30 people was set as achievable with the time and resources available.

Participants were given a Dylos DC1700 monitor and an instruction sheet asking them to install and run the monitor for 48 hours in their main living space, elevated above floor level and away from doors and windows. This mirrored instructions given during previous studies of personal exposure to SHS [206]. Participants were also asked to keep a diary of events which could cause elevated PM in the home, including cooking and heating use.

After the monitoring period, the Dylos was returned to the research team and data was downloaded from it. A short report on air quality in the home was prepared for the participant and emailed to them, along with any relevant information on reducing air pollution in their home. The monitor's memory was then cleared prior to use with the next participant.

8.2.2.5 Smoking homes data

The pre-existing smoking homes dataset comprised minute-by-minute measurements from 116 homes, each spanning approximately 5 days, taken from the First Steps 2 Smoke-free (FS2SF) study [169]. Participants in that study self-reported that smoking took place regularly within the home. No data on other events which could affect air quality was available from these homes.

8.2.2.6 Ethics

Ethical approval for this study was given by the College Ethics Review Board of the College of Life Sciences and Medicine at the University of Aberdeen (reference number CERB/2016/3/1320).

8.2.3 Results

8.2.3.1 Estimated $PM_{2.5}$ concentrations in smoking and smoke-free homes

For the smoke-free home data collection part of the study 27 participants were recruited, with 25 of those completing the study. Homes were monitored for a mean of two days, eight hours and six minutes (ranging from one day, 20 hours and 45 minutes to three days, 13 hours and 32 minutes). Two participants withdrew or were unable to provide 24h of data.

When compared to the existing data from 116 smoking homes the 25 smoke-free homes had significantly lower concentrations of $PM_{2.5}$, with a geometric mean of 5.2µg/m^3 (geometric standard deviation (GSD) ±2.16), compared to 37.6µg/m^3 (GSD ±3.0) ($p<0.001$, natural logs compared with a one-tailed Student's t-test).

Mean large particle percentages were also significantly different, with a geometric mean in smoke-free homes of 7.49% compared to 3.56% in smoking homes ($p<0.001$, natural logs compared with Student's t-test).

8.2.3.2 Classifying homes algorithmically

Potential large particle percentages were selected based on previous research on the particle size distribution of SHS [188]. The algorithm was applied to the whole dataset using LPTs between 0.1% and 4.0%, incremented by 0.1%. The resulting output was plotted as an ROC curve to determine the LPT which maximised AUC. An LPT of 1.8% was most successful, with an AUC of 0.945. ROC curves of selected LPTs are shown in Figure 21.

8.2.3.3 Comparison with classification by $PM_{2.5}$ concentration

An ROC curve was plotted using the results of the algorithm along with the mean $PM_{2.5}$ concentrations of each home (Figure 22).

The AUC for selection using mean $PM_{2.5}$ was 0.937, while the algorithm classification attained 0.945. Both methods were highly successful in classifying homes, with the algorithm more successful (although this was not statistically significant).

8.2.3.4 Determining the SHS score classification cut-off

Coordinates of the curve values were examined to determine the best-performing SHS score. The value 1.455% maximised sensitivity (0.974) and specificity (0.88) and was therefore selected (Table 23). Using this value, the algorithm classified only 3/116 smoking and 3/25 non-smoking homes incorrectly.

Figure 21 - Receiver operating characteristic curve comparing algorithm classification using selected large particle thresholds.

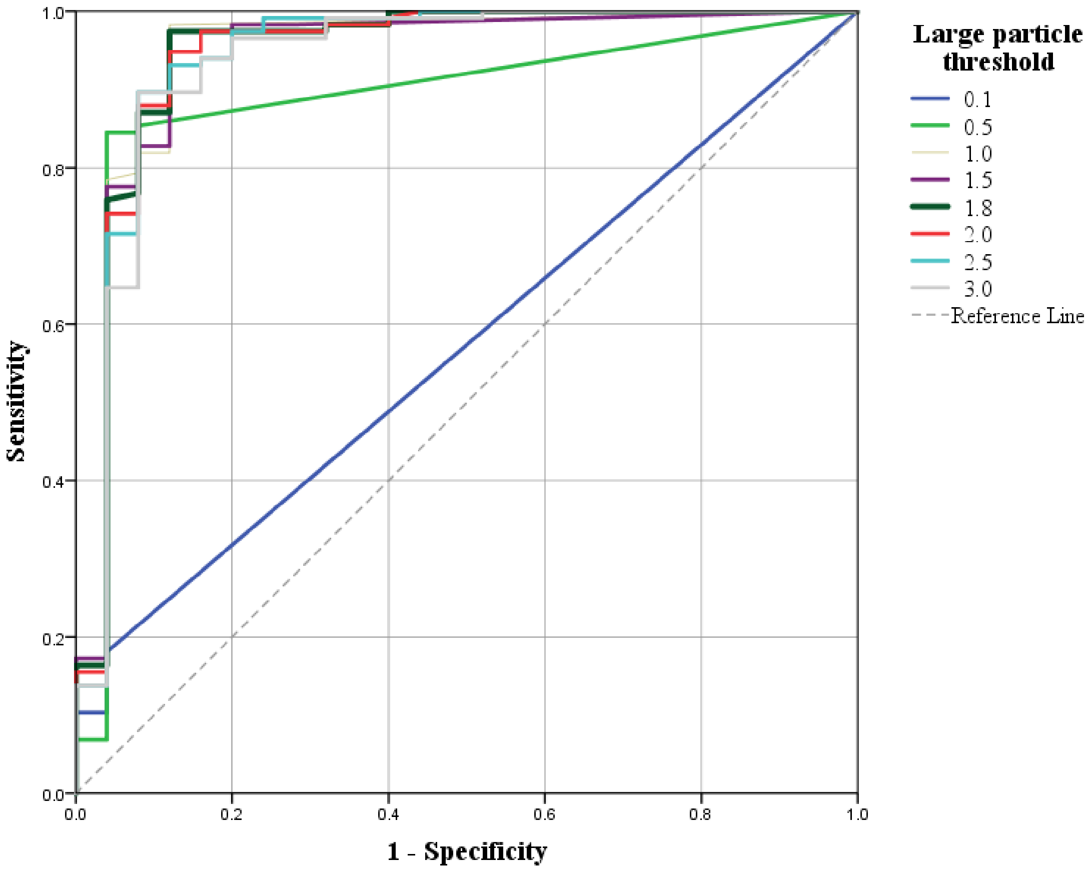


Figure 22 – Receiver operating characteristic curve comparing home classification using the algorithm with home classification using mean $PM_{2.5}$ in a home. Mean $PM_{2.5}$ classification refers to the use of mean $PM_{2.5}$ concentrations in isolation as a score to classify homes as smoking or smoke-free. Algorithm classification refers to the use of steps 1-3 of the algorithm to produce an SHS score which was used as a classifier. Curves approaching the upper left corner of the chart represent effective classifiers. Sensitivity refers to the number of true positive smoking homes identified, while 1 – specificity refers to the number of false positives identified. Coordinates of the curve were analysed separately to decide on an SHS score cut-off point which would best indicate a smoking home.

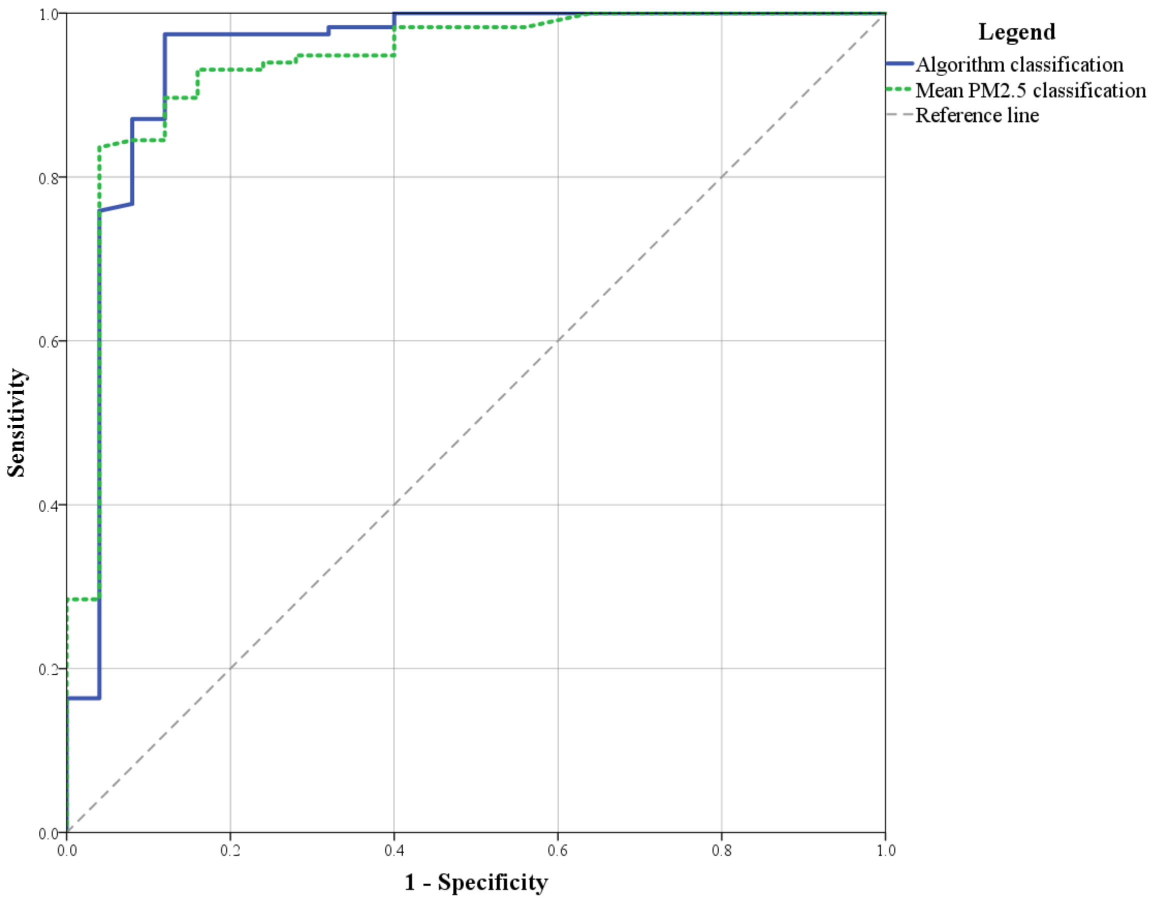


Table 23 - Sensitivity and 1 - specificity values for selected proposed SHS scores using the algorithm with an LPT of 1.8%. The value 1.455% maximised sensitivity and specificity.

SHS score (%)	**Sensitivity**	**1 - Specificity**
0.005	1.000	0.400
0.015	0.991	0.400
0.025	0.983	0.400
0.050	0.983	0.360
0.140	0.983	0.320
0.225	0.974	0.320
0.380	0.974	0.280
0.530	0.974	0.240
0.580	0.974	0.200
0.915	0.974	0.160
1.455	0.974	0.120
1.840	0.966	0.120
2.005	0.948	0.120
2.115	0.940	0.120
2.920	0.931	0.120
4.245	0.922	0.120

8.2.4 Discussion

It is possible to apply a simple algorithm to Dylos DC1700 particle number counts in order to predict with a high degree of certainty whether smoking occurred in a home during a multi-day monitoring period.

Previously, data from a similar monitor has been used to develop a logistic regression model to distinguish SHS from non-SHS sources of PM [207]. In this study, a large particle threshold of 1% was identified as indicative of SHS, similar to the threshold identified in this paper.

$PM_{2.5}$ is a well-recognised marker for SHS [76] which has been used in a number of behavioural interventions [72,120,149]. PM sensors are well-developed, easily portable and inexpensive, allowing them to be used in a wide range of settings where it may be useful to measure SHS. This need not be limited to homes – for instance, this technique could be used to promote smoke-free public places laws.

8.2.4.1 Limitations

The limited number of measurements available from smoke-free homes made it impossible to determine whether the algorithmic approach was statistically superior to an approach based purely on the use of logistic regression analysis on the mean level of $PM_{2.5}$. A follow-up study in further smoke-free homes may determine this.

Although the classification rate established by the algorithmic approach was high, one in eight of the smoke-free homes tested was still mis-classified. These false positives could cause intervention participants who have succeeded in keeping their homes smoke-free to be told that they have not done so, potentially reducing their trust in the intervention.

Scotland has relatively low levels of outdoor particulate air pollution. The large particle threshold and score values developed in these circumstances may not hold true in countries with high levels of coarse particle pollution (including dust storms or other natural particulate pollution) [208]. Further research should be carried out in these conditions.

In step 1 of the algorithm we have assumed that 79% of ambient PM will infiltrate, leading to an ambient $PM_{2.5}$ concentration indoors of around $5\mu g/m^3$. Values below this concentration are therefore excluded from the result. Infiltration of ambient PM varies greatly depending on building ventilation and other factors, and so this assumption is unlikely to hold true generally. Furthermore, measurements in settings where ambient PM is significantly higher than $6.6\mu g/m^3$ may cause few data points to be excluded at step 1, affecting the results of the algorithm. Further research is most likely necessary to test the algorithm in a variety of other settings, and to test the assumptions implicit in step 1. It may be beneficial to generate a specific “ambient $PM_{2.5}$” value for the time periods in which measurement takes place.

The results of this research can only be applied directly to the Dylos DC1700, with its two size bins. It may be possible to adapt the algorithm to other optical particle counters with multiple size bins, but research would be needed to measure their agreement with the size classifications made by the Dylos.

In general, optical particle counters are limited instruments compared to more labour- and time-intensive methods of detecting and quantifying PM, such as gravimetric methods. A wide range of factors can affect their results, including relative humidity [82], aerosol composition and the age of cigarette smoke in the air [209]. The particle number to mass concentration equation used in this study has been developed with reference to SHS aerosol only, so mass concentrations calculated by this method should be considered as estimates or approximations of exposure.

The effectiveness of the algorithm may be impeded in settings where there are other significant sources of $PM_{2.5}$, such as open flames. Similarly, high concentrations of PM_{10} in outdoor air could impede the effectiveness of the algorithm, raising the percentage of large particles measured by the monitor. This would be a particular concern in countries with high levels of outdoor air pollution.

No attempt was made to directly compare the use of classification simply on the basis of mean $PM_{2.5}$ concentrations in homes with the use of the algorithm. The algorithm developed is intended to provide complementary information to $PM_{2.5}$ concentrations using particle size data rather than necessarily replace them. Future work with a larger dataset could test the effectiveness of both algorithm and $PM_{2.5}$ concentrations separately and together.

8.2.4.2 Implications

Due to the well-known health implications of $PM_{2.5}$ in air and of SHS, particularly for children, interventions to reduce the number of homes in which smoking takes place are of importance in improving public health, with several recent studies describing the use of the Dylos DC1700 monitor [120,148,149].

While most people are well aware that SHS is harmful, many smokers blame other factors such as outdoor air pollution when presented with evidence of poor air quality in their homes. Researchers developing air quality feedback interventions for smoke-free homes or smoking cessation should consider incorporating this classification method to reinforce the specific danger of SHS.

Although this study took place solely in homes, the algorithm could be used to detect SHS in other indoor environments such as bars, casinos and other workplaces. This could be useful in assessing occupational exposure to SHS, and in providing evidence for advocacy for comprehensive smoke-free legislation.

8.3 Further work on algorithmic detection of SHS

This algorithm has been tested on data from homes in Scotland, a country with notably low levels of ambient $PM_{2.5}$ [193].Climatic conditions can affect air quality monitoring, with temperature and humidity prone to affect the reliability of optical particle counters [82].

Furthermore, it was not possible to use the First Steps to Smoke-free dataset to identify the times at which smoking took place in homes, as there was no diary or other source of information on smoking times accompanying the air quality data. Therefore the ability of the algorithm to detect the times at which smoking took place was not tested.

In order to further test the algorithm it was decided to collect new measurements in homes in a country with a different climate, and to collect data from both smoking-permitted and non-smoking-permitted homes to test the algorithm's ability to identify periods of time in which cigarettes were smoked.

8.4 Identifying smoking in homes using low-cost particulate monitoring – validating an algorithmic approach in a new environment

8.4.1 Introduction

Second-hand smoke (SHS) is a significant cause of ill-health in both adults and children [23]. Smoking indoors causes elevated levels of many air pollutants and has been linked to illnesses such as lung cancer, heart disease and diabetes. Children are worse affected than adults, and childhood SHS exposure can contribute to conditions including inner ear infection, meningitis and sudden infant death syndrome.

In recent years, attention has turned to methods of reducing smoking in the home by parents and caregivers, with the aim of reducing children's exposure to SHS and improving their health. Several complex interventions involving home air quality feedback have been developed for this purpose [65]. In these interventions, information about SHS-related pollutants in the air is given to participants to motivate or persuade them not to smoke in the home. The most commonly used marker of SHS in these interventions is fine particulate matter ($PM_{2.5}$), which is closely associated with SHS and easily measured using low-cost air quality monitors [75]. One such monitor is the Dylos DC1700 which has been used in several related studies [117,126,171,179].

SHS is usually the greatest source of $PM_{2.5}$ in the home where it is present in the developed world. The fact that $PM_{2.5}$ is not, however, exclusive to cigarette smoke – other sources of $PM_{2.5}$ can be present in the indoor environment, such as cooking, can complicate attempts to carry out air quality feedback interventions, as was found in one feasibility study in Israel [149]. To prevent the possibility of wrongly inferring smoking activity within a home based on elevated $PM_{2.5}$

concentrations, it would be valuable to be able to identify additional discriminating factors to help identify whether smoking has taken place in a home during a given time period.

One of the key identifying features of SHS particulate is the size distribution of the generated aerosol which has been shown to have a median diameter of between 0.1 and 0.2μm, thus allowing a ‘fingerprint’ to be created to identify when household $PM_{2.5}$ is likely to contain SHS [210]. Clearly the air in any given home will be a complex mixture of aerosols from a variety of sources: one of which may be the contribution from smoking. Previous research has been carried out to develop an algorithm which used the particle size distribution of SHS to predict the likelihood that homes are ‘smoking-permitted’ or ’smoke-free’ [189]. This was based on a series of rules around the concentration of $PM_{2.5}$ measured and the ratio of coarse to fine particulate as measured by the Dylos DC1700 (Dylos Corporation, Riverside, CA). However, this algorithm has been tested only in homes in Scotland and differences in ambient air pollution (such as the presence of larger dust particles associated with dust storms) and/or differences in climate including temperature and humidity may interfere with the effectiveness of the algorithm. This paper presents a study designed to test that algorithm in homes in Israel, and to attempt to use it to identify smoking-permitted from smoke-free homes.

8.4.2 Methods

8.4.2.1 Ethics

Ethical approval was provided by Tel Aviv University Ethics Committee.

8.4.2.2 Locations

This research was carried out over a five week period in Israel in July and August 2017. Smoking-permitted and smoke-free homes were sought in four cities around the country (Tel Aviv-Yafo, Jerusalem, Be’er Sheva and Haifa) reflecting different climactic conditions to allow for differences in temperature, humidity and ambient pollution. Table 24 provides typical environmental conditions experienced in these four cities during July and compares them to those found in Edinburgh, Scotland where the original algorithm was tested.

Table 24 - Typical environmental conditions in July in cities where the algorithm was tested Data from the Israel Meteorological Service [205], the UK Met Office [206] and the World Health Organisation Ambient Air Quality Database [193].

Location	**Mean air temperature in July (min – max, ºC)**	**Mean relative humidity in July (measured at 12:00 mid-day local time)**	**Mean rainfall in July (mm)**	**Ambient $PM_{2.5}$ concentration, annual (µg/m^3)**
Beer Sheva	20.5-32.7ºC	38%	0	25
Haifa	23-31.1ºC	56%	0	20
Jerusalem	17.8-27.6ºC	40%	0	28
Tel Aviv	23-29.4ºC	64%	0	24
Edinburgh	11.5-19.1ºC	78%	61.3	7

8.4.2.3 Inclusion and exclusion criteria

Participants were asked about their home smoking rules at first contact and categorised as having smoking or smoke-free homes. Smoking homes were those where smoking was permitted indoors (not just on a balcony or other outdoor area), and where a smoker lived. Smoke-free homes were those where no smoking was permitted indoors. Those who had variable smoking rules, such as permitting outside guests to smoke on occasion, were excluded.

8.4.2.4 Recruitment

Two smoke-free homes and two smoking homes were sought in each of four cities, for a total of sixteen participants. Recruitment took place opportunistically through colleagues at Tel Aviv University. Potential participants were approached by researchers and given information on the nature of the study. If they were interested, a date for further discussion and installation was set.

8.4.2.5 Air quality monitoring

Four Dylos DC1700 (Dylos Corporation, Riverside, CA) particle monitors were used to measure and log particulate concentrations. Four Lascar EL-USB-2 monitors (Lascar Electronics, Whiteparish, UK) were used to measure relative humidity (RH) and temperature. Following the monitoring period data logs were downloaded using custom software. Particle number counts measured by the Dylos in two size fractions were converted into estimated $PM_{2.5}$ mass concentrations using a previously described equation [171].

8.4.2.6 Monitor installation

Monitors were installed in the main living area of each home, either a living room or a combined living room and kitchen space. Monitors were elevated at least 30cm above the floor and were placed at least 30cm from a wall. Monitors were installed for periods of between four and six days.

8.4.2.7 Diary data

Participants completed diaries giving information on common air pollution sources in the home, including any form of combustion, cooking activity, canned aerosol use and smoking. Days were divided into nine two-hour periods between 5AM and 11PM and one six-hour period from 11PM to 5AM for each day. Participants marked events which occurred during each period with a tick or cross. Diaries covered four to five days of monitoring time, depending on when installation occurred.

8.4.2.8 Statistical analysis

A previously developed algorithm [189] was used to classify Dylos data logs from each home as smoking or non-smoking depending primarily on the number of large particles detected (those >2.5µm in diameter) as a percentage of the total number of particles detected (including those with diameters between 0.5 and 2.5µm) across the sampling period within each home.

This classification algorithm has four steps:

1. Discard data where estimated $PM_{2.5}$ concentration is below $5\mu g/m^3$
2. Discard data where the large particle percentage is over a threshold of 1.8%
3. Discard data which is not part of a continuous data period four or more minutes long.
4. Take the final number of minutes remaining as a percentage of data minutes in the original log to generate a ‘SHS score’. A cut-off value of 1.45% was found to be most effective in classifying homes in Scotland. Put another way the algorithm predicts a smoking-permitted home if it finds that more than 1.45% of total minutes of measurement had the $PM_{2.5}$ concentration $>5\mu g/m^3$ AND the large particle percentage is <1.8% (after ignoring very short periods where these two criteria are satisfied).

A worked example of the algorithm using data from this research is available in Appendix IX.

In addition to analysis carried out on whole logs, each air quality data log was split into calendar days (including partial days) and into diary periods as described above. Descriptive statistics, including arithmetic means and medians of estimated $PM_{2.5}$ concentration, were calculated for each log, each calendar day and each period, broken down by location and smoking status.

Diaries were compared with arithmetic mean $PM_{2.5}$ concentration measured in the home during each period, and Student's t-test was used to compare each air quality event and mean $PM_{2.5}$ concentration.

The SHS detection algorithm was applied to each whole log, calendar day and period (where smoking status information was available from a diary).

8.4.3 Results

8.4.3.1 Recruitment

16 participants were recruited, four from each target city. In Jerusalem three smoke-free homes and only one non-smoking home were recruited, while two smoking and two smoke-free homes were recruited to the study in Tel Aviv, Be'er Sheva and Haifa. Two homes did not provide diary data – one smoking home in Haifa and one smoke-free home in Jerusalem.

8.4.3.2 PM concentrations in homes in Israel

Estimated mean $PM_{2.5}$ concentrations were significantly higher in smoking homes (mean=30.4µg/m^3, standard deviation=28.78) than non-smoking homes (mean=7.9µg/m^3, standard deviation=1.24) ($p=0.034$). Higher variance and standard deviation were observed in smoking homes, in line with previous observational studies.

There were no significant differences in mean $PM_{2.5}$ concentrations indoors between the various cities where monitoring took place, though the study was likely underpowered to detect any differences which did exist.

8.4.3.3 Humidity

Geometric mean of RH across all measurements was 52.5%. RH was lowest in Be'er Sheva and highest in Haifa, but there was no significant difference between locations (possibly due to a lack of power in the study). The highest RH value recorded overall was 80.5%, while the median highest value in each log was 71.5%.It is unlikely that correction for this factor would make a substantial difference to the results as previous research has reported that optical particle counters remain accurate up to around 75% humidity [211,212].

8.4.3.4 $PM_{2.5}$ concentration as a marker for SHS vs other pollutants over periods

Two data logs which did not have reliable diary data (one smoking and one non-smoking) were excluded, as were periods which did not have associated diary data (such as where the monitoring period continued for longer than the number of days in the diaries). A total of 604 periods from 14 homes were analysed. An example of the data collected over one day in a smoking home is shown in Figure 23.

Mean and maximum $PM_{2.5}$ concentrations are higher in smoking periods than non-smoking periods, while mean large particle percentages were significantly lower, as hypothesised.

Both mean and maximum $PM_{2.5}$ concentrations were closely associated with SHS during individual periods, but not large particle percentage.

8.4.3.5 Detecting SHS in the home

All 9 non-smoking logs were correctly predicted using the SHS detection algorithm, while 5 of 7 smoking logs were correctly predicted. The positive predictive value (PPV) was 5/5 (100%) while the negative predictive value (NPV) was 9/11 (82%) indicating excellent sensitivity and very good specificity.

Smoking status information was available for a total of 77 days during the study, of which 54 were smoke-free and 23 smoking. The algorithm correctly predicted 49/54 smoke-free days (91%) but correctly predicted only 13/23 smoking days (56%). Here the PPV was 72% (13/18) while the NPV was 83% (49/59) showing moderate values for both sensitivity and specificity. Cross-tabulations are given in Table 25.

The algorithm performed poorly when applied to the shorter periods. While non-smoking periods were well-identified (NPV = 437/501, 87.4%), many false positives were reported (PPV = 40/104, 38.5%) (Table 26).

Figure 23 - example data from one day in a smoking home in Be'er Sheva, showing estimated $PM_{2.5}$ concentration and large particle percentage over time, with black vertical lines indicating the start of each period. Large particle percentages can be seen to drop precipitously during peaks associated with smoking events.

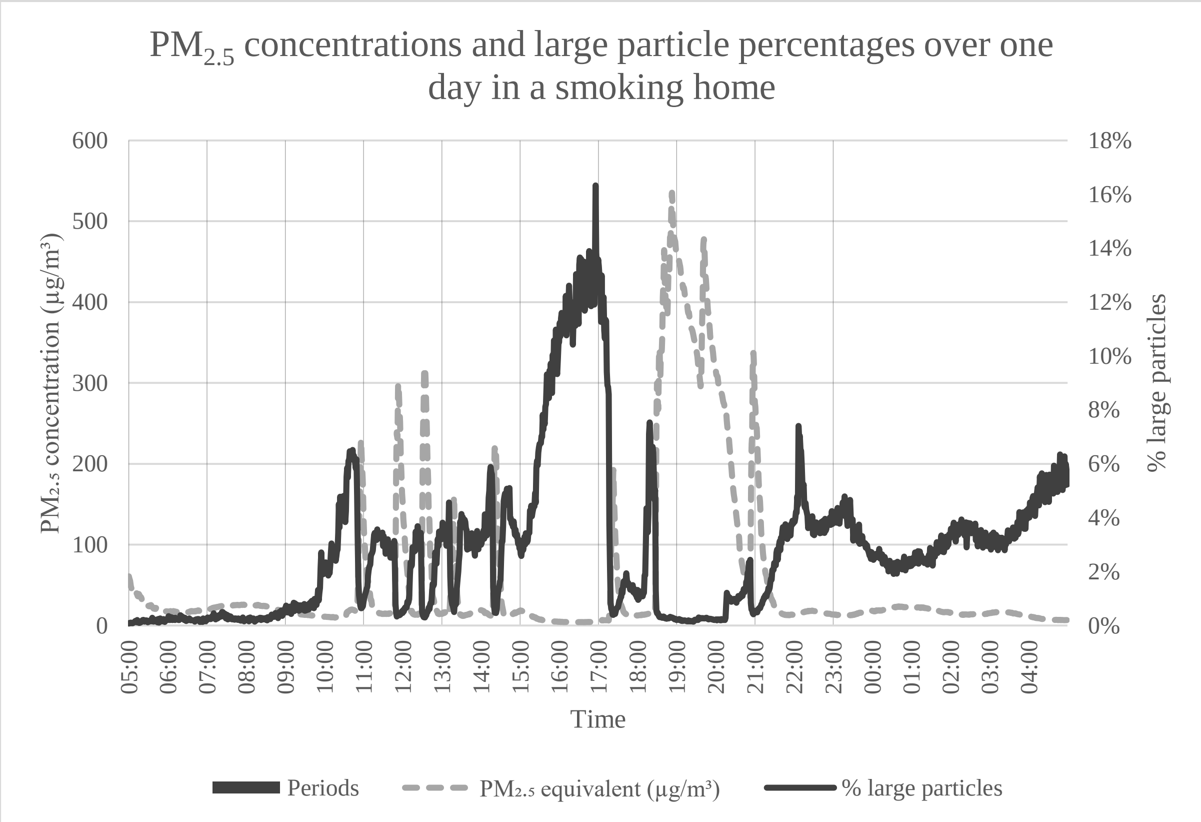


Table 25 - Comparison of algorithm-predicted and actual smoking status on each calendar day.

		Smoking status		Total
		Smoke-free	Smoking	
Predicted smoking status	Smoke-free	49	10	59
	Smoking	5	13	18
Total		54	23	77

Table 26 - Comparison of algorithm-predicted and actual smoking status in each period.

		Self-reported smoking status		**Total**
		Smoke-free	Smoking	
Predicted smoking status	Smoke-free	437	64	501
	Smoking	63	40	103
Total		500	104	604

8.4.4 Discussion

8.4.4.1 Measuring SHS-related $PM_{2.5}$ in Israel

Overall $PM_{2.5}$ concentrations in homes in Israel were very similar to concentrations measured in smoke-free homes in Scotland [189].

Previous research has identified difficulty in using particle monitors to provide air quality feedback in Israel, due to other sources of $PM_{2.5}$ indoors [149]. Although limited in scale, this research suggests that Dylos DC1700 particle counters can be used to measure SHS indoors, and that higher levels of $PM_{2.5}$ in short time periods are clearly associated with smoking inside (rather than with fluctuations in ambient $PM_{2.5}$ caused by weather events or other sources). Therefore, air quality feedback-based smoke-free homes interventions could be used in Israel with similar confidence to previous trials in the UK and other countries.

8.4.4.2 Applying the SHS detection algorithm

In this trial, the SHS detection algorithm performed in line with a larger study in Scotland (where a PPV of 0.974 and an NPV of 0.88 were attained) [189]. This indicates that the algorithm is broadly resilient to environmental differences between those two countries.

It was possible to use the algorithm to classify 24 hour periods as smoking or non-smoking, but this was less accurate than whole log records. The algorithm could not be used to identify two-hour periods as smoking or non-smoking at all. This may be due to the paucity of data available in each period, or could be because SHS persists following a cigarette for a long time at detectable levels [89] – a cigarette smoked towards the end of one period could lead to SHS persisting throughout the next. Errors in diary data, such as participants failing to report smoking times accurately, could also explain the algorithm's inability to classify these periods correctly.

8.4.4.3 Limitations

This was a very small trial relying on data from 16 homes for periods of between 4 and 6 days. As the study took place entirely in mid-summer, weather conditions in the other months of the year (such as increased humidity at winter, for instance) could conceivably affect the results of the detection algorithm.

Homes included in the study may not have been representative of all homes in Israel. As they were recruited opportunistically through university contacts, smoke-free homes may have been wealthier than average. Demographic factors may also have been unrepresentative – for example, no Haredi homes were included in the study.

8.4.4.4 Future research

The principle of using the size bins of the Dylos DC1700 to identify SHS in homes has been established in this and previous work [189]. Further research should attempt to extend the principle behind the algorithm to other particle monitors which provide size bin data. Some new low-cost sensors provide data from multiple size bins (for instance the Plantower PMS5003 sensor, which provides estimated PM concentrations for particles from 0.3µm – 0.5µm in diameter, 0.5µm – 1.0µm, 1.0µm – 2.5µm, 2.5 – 5.0µm and 5.0 – 10.0µm) [213]. This improved resolution, if accurate, could allow for more confident estimates of the source of particles in indoor air, including non-SHS sources.

Further research could be conducted in countries with higher levels of ambient PM pollution.

While the algorithm has been tested in homes, it has not yet been tested in other indoor environments where SHS may be present, such as bars and nightclubs. As these are targets for legislative action to reduce SHS, particularly in developing countries, low-cost SHS-specific monitoring could be a valuable tool to promote smoke-free environments and reduce occupational SHS exposure.

8.5 Using the SHS-classification algorithm as an outcome measure – did detected smoking decline between baseline and follow-up in the Measuring for Change intervention?

8.5.1 Introduction

Air quality measurements have been used in a range of interventions as outcome measures [65]. Where average concentrations of $PM_{2.5}$ are used as an outcome measure the result of a study can be in doubt, as other sources of $PM_{2.5}$ could lead to erroneous results. This has caused practical difficulties delivering feedback in at least one air quality feedback intervention [149].

As the SHS-classification algorithm described previously can classify homes as smoking or non-smoking with a high degree of accuracy, it may be possible to use its results as an outcome measure in an intervention designed to create smoke-free homes. This may be complicated by the fact that most such studies consider reductions in home smoking to be successes, but the algorithm has only been demonstrated to classify homes in a binary fashion. However, it may be possible to use the algorithm-generated SHS score as a measure of the amount of time smoking is occurring in the home.

The air quality feedback intervention described in chapters 6 & 7 (the Measuring for Change trial) resulted in a fall in measured average concentrations of $PM_{2.5}$ in homes during follow-up periods compared to baseline, but it did not result in a significant number of participants achieving entirely smoke-free homes. It can therefore serve to test the usefulness of the algorithm as an outcome measure in circumstances where participants have, on average, made progress towards reducing smoking in the home but have not eliminated the behaviour.

Data from this trial was therefore used to test the algorithm. The overall "SHS score" of each whole period was considered, along with a day-by-day test of the number of "smoking days" in each baseline and follow-up period.

8.5.2 Methods

8.5.2.1 Data for analysis

Dylos data from each intervention, cleaned as described in chapters 6 & 7, was used in this analysis. The algorithm was applied to records from the baseline and follow-up periods of each intervention as described in chapter 6 - the first seven and last seven days of the intervention period during which no information on air quality in the home was delivered to participants.

8.5.2.2 Statistical analysis

Algorithm predictions and SHS score for each day and for each whole outcome measure period were generated using Python 2.7 programmes described earlier in this chapter (section "Identifying smoking in homes using low-cost particulate monitoring – validating an algorithmic approach in a new environment"). Wilcoxon ranked-sign tests were conducted using IBM SPSS Statistics software to compare changes in SHS scores between pairs of baseline and follow-up data.

8.5.3 Results

8.5.3.1 Data used in this analysis

Only the first four days of participant SC_24's follow-up period were included in the analysis. This was due to a fault in data recording – the monitor had failed to send data to the server during the course of the follow-up period, and while $PM_{2.5}$ data was recovered from the associated Raspberry Pi for the primary analysis, full Dylos log data was not.

8.5.3.2 Smoking vs non-smoking classified periods

As the homes in which measurements took place were recruited on the basis that a resident smoked indoors, it can be assumed that all full (seven day) baseline periods should correctly be classified as smoking. While no diary data is available to confirm this, it may also be assumed that smoking occurred in these homes on the majority of individual baseline period days.

8.5.3.3 Whole outcome measure period results

The majority of participants' homes were classified by the algorithm as smoking at both baseline (58) and follow-up (53). Results from periods are given in Table 27.

A binomial test was conducted to compare the number of baseline periods classified as smoking with the number of follow-up periods so classified (using an expected proportion of 85%). No significant difference was detected (p=0.077).

Table 27 - Results of the SHS detection algorithm applied to full baseline and follow-up periods

	Periods in analysis	**Periods classified as smoking**	**Percentage of periods predicted smoking**	**Median SHS score**
Baseline period	68	58	85%	22%
Follow-up period	68	53	78%	21%

SHS scores from baseline and follow-up periods were compared using a paired Wilcoxon signed-rank to test whether participants' SHS scores had declined over the course of the intervention. No significant change was detected in this test (p=0.653).

8.5.3.4 Day-by-day results

A total of 68% of available days of data were classified as smoking at both baseline and follow-up. While there was an absolute decline in the number classified as smoking at follow-up, this was due to the fewer days available in the follow-up analysis (due to exclusion of some follow-up days due to missing data).

Full results are given in Table 28. A Mann-Whitney U test was conducted comparing the number of days classified as smoking and the number classified as non-smoking at baseline and follow-up. The change was not significant (p=0.939).

Table 28 - Results of the SHS detection algorithm applied to each day in baseline and follow-up periods

	Percentage of days classified as smoking	**Days classified as smoking**	**Days in analysis**	**Median SHS score**
Baseline period	68%	314	462	13%
Follow-up period	68%	298	440	17%

8.5.4 Discussion

The algorithm detected a decline in the number of smoking-classified periods between baseline and follow-up, although this was not statistically significant. Further analysis with a larger sample size may be warranted to determine whether an effect can be detected.

The algorithm correctly classified a significant majority (68%) of baseline days as smoking, as would be expected in an intervention targeted to individuals who smoke in the home. However, it did not detect a statistically significant increase in smoke-free days, or a decline in median SHS score over this time. This could be explained by small sample size in the Measuring for Change study.

There was little decline in median SHS score when testing full baseline and follow-up periods, and an increase in median SHS score was observed between baseline and follow-up when testing individual days. This suggests that SHS score may not be a useful metric to measure reduction in smoking in this type of study, and that binary algorithm classification may be a more useful outcome measure.

8.6 Overall conclusions

8.6.1 Using the algorithm in air quality feedback interventions

This algorithm shows promise as a means of detecting homes where SHS is present. The high predictive values (an overall PPV of 100% and an NPV of 80%) suggest that it could be suitable for use in future air quality feedback interventions.

The algorithm developed as part of this PhD is specific to the Dylos DC1700, which could hamper future attempts to use other air quality monitoring equipment to conduct these air quality interventions.

The algorithm cannot precisely identify times when smoking occurred, as demonstrated by its failure to correctly identify SHS in two-hour periods. This could reduce its effectiveness, as participants may wish to reduce the number of cigarettes they smoke indoors rather than instantly switching to smoke only outside. However, if used to detect smoking on a day-by-day basis the algorithm could reinforce the important health message that no amount of SHS is safe – any smoking indoors is harmful. This could potentially be used as an outcome measure in intervention studies measuring $PM_{2.5}$.

Air quality feedback interventions could go beyond SHS feedback. Exposure to $PM_{2.5}$ in the home is not limited to SHS-related $PM_{2.5}$, and so similar interventions could encompass other causes of $PM_{2.5}$ as well – for instance, encouraging participants to avoid methods of cooking which elevate particle pollution (such as frying foods).

As a longer-term tool for behaviour reinforcement, a monitor which detects whether smoking has occurred on each day could be useful. However, it may be necessary to adjust the SHS score at which smoking is detected – a false positive could reduce trust in the conclusions of such a monitor. Further research on the best way to present this information would be necessary, including the potential inclusion of the SHS score as a confidence measure.

8.6.2 The algorithm for other uses

In principle, the algorithm could be used in other environments where SHS is present. It could therefore be used in other indoor public places - potentially for the enforcement of existing smoke-free places legislation or for lobbying to introduce comprehensive smoke-free laws. Further testing would be required to facilitate this.

9 Discussion and conclusions

9.1 Aims of this research

Children's exposure to SHS in the home is a serious cause of ill health [23], and it has been a priority for governments and other policymakers to reduce this exposure [62], which has been estimated to affect as many as 40% of children worldwide [34]. Many behaviour change interventions have been developed and tested with the aim of reducing smoking in the home [65,101–103]. These interventions use a wide range of strategies to promote change, including counselling, remote support, pharmaceutical support, stop-smoking advice and personalised feedback of markers of exposure to SHS.

A number of interventions have used personalised data from air quality monitoring in smoke-free homes, which has shown promise in a number of feasibility studies [72,120,121,126,179] and randomised controlled trials [110,114,117,125,127], resulting in reductions in measured SHS of up to 36%.

Air quality feedback is therefore a promising strategy to promote smoke-free homes. The primary aim of this research was to explore how air quality information is perceived by those likely to be targeted by these interventions, and to design and test an air quality intervention using those principles. Further research was conducted on the possibility of using low-cost sensors to discriminate between SHS and non-SHS related sources of $PM_{2.5}$, in order to provide additional reliable information on the impact of smoking in the home.

9.2 Research questions

This section answers each research question directly, giving a summary of relevant research conducted within the scope of this thesis and considering comparable data or publications from the international scientific literature.

9.2.1 RQ 1 - How do smokers, ex-smokers and those living with smokers understand the relative impact on health of SHS and indoor air pollution compared to outdoor air pollution, as it applies to national policy and their own behaviour?

The research described in chapter 4 was the first study to explore this research area qualitatively. Results from chapter 4 show that SHS may be regarded as the most serious pollutant of indoor air with the exception of carbon monoxide, but that it can be categorised separately rather than considered "air pollution" per se.

Outdoor air pollution is frequently considered a separate issue to SHS exposure. Most commonly, outdoor air pollution was described by participants as associated with vehicles, particularly those fuelled by diesel, although industrial pollution and coal or wood fires indoors were mentioned in focus group discussions as potential sources of air pollution.

Air pollution was frequently described as connected to smell, a concern under some circumstances when the smell of SHS may have dissipated or may not be detectable by an individual despite the presence of harmful pollution. Unpleasant smells which may not themselves be harmful (such as nearby stagnant water) could be thought of as health risks.

While most focus group participants were well aware of the harmful effects of SHS, some participants suggested that SHS was less harmful to health than outdoor air pollution, a possible source of future concern for public health advocates with the rising prominence of outdoor air pollution in the UK media. Some participants and commenters took the view that individual actions were not likely to be effective in reducing air pollution overall (describing it as a societal issue), but in general among focus group participants it was held to be possible to improve air quality inside the home.

Some participants in focus groups, as well as some online comments, expressed cynicism about efforts to prevent SHS (particularly when smoking was seen as government-endorsed through the tax system). This mixed message – that smoking was known to be bad, and yet the government "profited" from it – was common among commenters, and may hamper efforts to reduce the harmful effects of smoking (both active and passive).

9.2.2 RQ 2 - Can giving people in socioeconomic groups associated with high exposure to SHS accurate, personalised information about the effects of SHS on air quality influence their decisions to keep their homes smoke-free?

Results described in chapter 7 suggest that giving air quality feedback on SHS levels in homes can lead to reductions in SHS concentrations indoors. A median decline of 17% in mean $PM_{2.5}$ concentrations following the intervention is broadly in line with several other studies conducted before and during the course of this research (as described in chapter 2, Table 2).

However, only eight participants in the study reduced $PM_{2.5}$ concentrations in their homes from above the World Health Organisation's guideline limit for $PM_{2.5}$ over 24 hours (25µg/m^3) to below this level between baseline and follow-up. 34 participants (50%) ended the study with $PM_{2.5}$ concentrations below the WHO limit, but 26 of these had concentrations below 25µg/m^3 at baseline. This reflects the small median decline observed (-4µg/m^3) compared to the median mean concentration of $PM_{2.5}$ detected at baseline (31µg/m^3).

The clinical significance of relatively small reductions in SHS exposure has not been well studied, with little information available on concentration-response curves available. However, a number of studies have suggested that cardiovascular health is disproportionately affected by the relatively low concentrations of SHS created by the smoke of few cigarettes [33], in line with recent research into cardiovascular response to $PM_{2.5}$ exposure [214]. With this in mind, it may be more effective to target SHS-reduction interventions at homes where lower concentrations of SHS are present, as a 5µg/m^3 reduction in SHS-related $PM_{2.5}$ may have a much greater effect on health when achieved in a home with a mean concentration of 25µg/m^3 than one where the mean concentration is 250µg/m^3. The ethical implications of this strategy may be disturbing, however – if lower-SES smokers live in smaller homes than high-SES smokers, for instance, those homes may have higher concentrations of $PM_{2.5}$ from smoking equal numbers of cigarettes, making it more clinically effective to intervene with smokers in high-SES groups.

Participants' ability to achieve change may be linked to their capability, opportunity and motivation to achieve change (as described by the COM-B model of behaviour change [180]). Due to a lack of fidelity at some centres conducting the intervention, it was not possible to test this across the whole sample (and therefore with numbers powered to detect differences).

While the information given to participants was an accurate reflection of concentrations of $PM_{2.5}$ in their homes, it may not have accurately represented SHS levels under all circumstances. Other sources of $PM_{2.5}$ exist in the home, such as cooking, open flames (such as candles or incense) and potentially the smoking of other substances (such as cannabis) [88]. Electronic cigarettes may also have been used in some homes, and these have been shown to produce $PM_{2.5}$ at high concentrations in some conditions [215] (although other studies have not demonstrated persistent high concentrations following peaks associated with “puffs” on an e-cigarette [216]). Similarly, $PM_{2.5}$ ingress from outdoor sources may have affected results indoors (although, as discussed in chapter 7, this is unlikely to have had a substantial effect on results).

There was no control used in this study beyond each participant acting as their own control by providing pre-intervention baseline data. This is a weakness in the study which limits its validity, as the lack of a control means that the effect detected cannot be ascribed with confidence either to the measuring for change intervention or (more specifically) to the air quality feedback elements of the intervention – it is possible that simply receiving SMS messages with advice on SHS reduction, for instance, could have led to the observed effect. This limitation may also have resulted in an effect being detected erroneously if participants changed their behaviour for non-intervention reasons, or if another effect (such as changes in ambient air pollution or other seasonal effects such as changes in behaviour in warmer summer weather) confounded the result.

However, recent controlled trials in this area of research have not shown a significant Hawthorne or placebo effect in control groups. For instance, in 2018 a trial by Hughes et al [117] showed a 6.5% decline in measured PM in control group homes, whereas the First Steps to Smoke-free study by Semple et al in 2018 [127] showed no change in either control or intervention group homes.

9.2.3 RQ 3 - Does giving that information in different forms influence views of SHS and air quality?

Results given in chapter 5 demonstrate that individuals can have a range of views about the form air quality information takes. Participants in focus groups described different experiences of visualisations of air quality information – some preferring graphs of concentration over time, others preferring simpler air quality index-based explanations of the health risk associated with different concentrations. It is therefore important to consider the needs of people with different levels of numeracy and literacy when developing an air quality feedback intervention, in order to provide information in formats useful to as many participants as possible.

Immediate and delayed feedback strategies have been employed in past air quality feedback interventions. While a delayed feedback approach was used in the development of the AFRESH intervention described in chapter 5, the Measuring for Change study (in chapters 6 & 7) used a semi-immediate model.

The semi-immediate feedback delivery strategy used in the Measuring for Change study (chapters 6 & 7) was not directly tested against other strategies. While no study has directly compared the effectiveness of delayed and more immediate feedback, controlled trials have been conducted using both methods, and their results may elucidate this question. A trial from San Diego State University published in 2018 [117] using immediate auditory and visual feedback resulted in a 19% decline in measured particle number concentrations in intervention-group homes, while a 2013 trial by Harutyunyan et al [114] involving immediate feedback on the impact of smoking a cigarette on indoor air showed a 17% decline compared to the control group.

By way of comparison, three full trials of delayed feedback interventions have been conducted. The most effective, a 2017 study by Ratschen et al at the University of Nottingham [125], resulted in a 36% decline in measured SHS in intervention group homes. However, the protocol for this intervention included the delivery of nicotine replacement therapy to the intervention group, a confounding factor it is impossible to disaggregate from the overall result. In comparison, the purely delayed air quality feedback-based First Steps to Smoke-free study [127] demonstrated no change either in the control group or in the intervention group. The KISS study [110], a 2001 trial using delayed air nicotine feedback delivered by post, showed a significant effect in the intervention group, although with a substantially different protocol from other interventions (using air nicotine monitoring rather than $PM_{2.5}$ as a marker for SHS).

The Measuring for Change intervention resulted in a significant reduction of 17% in measured $PM_{2.5}$ in participants' homes, in line with other successful interventions. Thus, three trials of immediate feedback interventions have shown significant effects, while two of three trials of delayed feedback interventions have been effective (with one of those confounded by other intervention elements and the other using a substantially different methodology from the others to measure SHS in the home). It is not possible to state conclusively that immediate feedback is therefore more effective, but it does not appear from the available evidence that there is a disadvantage to this method. This may be significant in the delivery of future interventions, as the methods used in Measuring for Change and the San Diego study [117] are less time-intensive than those used in the delayed feedback interventions described.

Feedback for behaviour change has been used in many settings, including learning [217] and improving medical practice [218]. Driving behaviour has been a particular target, with a number of studies conducted to compare the effects of delayed and immediate feedback on speed and acceleration.

Pay-as-you-drive insurance programmes allow participants to receive driving insurance based on their own characteristics while driving by remotely monitoring factors such as speed and acceleration [219]. To improve driving standards (and therefore reduce the price of insurance) it can be desirable to give participants feedback as they drive. Several studies have tested a range of different kinds of feedback in these scenarios, including comparing immediate and delayed feedback. One study used a comparison of a web portal to a dashboard-mounted mobile phone to provide this information in a simulation [219], finding no significant difference in results between the two forms. The use of a mobile phone with immediate visualisations was unique, however, and suggests the possibility of a mobile app to provide immediate visual feedback for air quality feedback interventions more immediately (and with more detail) than through SMS messaging.

The role of negativity and positivity in messaging ("feedback sign") should also be more fully explored. Theoretical models of behaviour change have been observed to contradict one another in their predictions about positive and negative messaging [220], so it may be worth testing more positive and more negative messages in the context or air quality. Feedback sign may or may not have a noticeable effect, and care should be taken that negative messages (if used) do not unnecessarily increase participant stress as part of the intervention, as has been observed in other studies [221].

9.2.4 RQ 4 - Can low-cost $PM_{2.5}$ monitors be used to differentiate SHS from other sources of PM, and thus provide more accurate information on the source of poor air quality?

This was the first study to attempt to identify the presence of SHS using only a low-cost PM monitor (others having used low-cost PM monitors in combination with other monitors [222]). Results from chapter 8 show that low cost monitors can indeed be used to detect the presence of SHS in the home with a high degree of accuracy when monitoring was conducted over a period of a day or longer. However, it was not possible to detect the presence of SHS over shorter periods, limiting the ability of this approach to identify the time smoking is taking place or the number of cigarettes smoked.

The research conducted on this method of SHS detection occurred in two developed countries, Scotland and Israel, and did not take into account the effects of sources of indoor air pollution common outside of these countries, such as the combustion of solid fuel indoors. Other potential confounding factors could include the smoking of substances such as cannabis (particularly when combined with tobacco) or extremely high levels of outdoor air pollution (such as those experienced in large industrialised cities like Tehran and Shanghai [193]).

This study did not test the impact of giving participants this information. Future interventions could indicate to participants whether smoking was detected on particular days during an intervention, giving additional context to information and potentially increasing its salience. Further research could also use this information as an additional outcome measure to determine whether SHS reductions had occurred over the course of a study.

9.3 Implications and practical applications

Air quality feedback interventions could be used with the expectation that, if properly designed, they would be able to reduce average concentrations of $PM_{2.5}$ in participants' homes. These interventions should be carefully targeted to those who are able to make change, taking into account participants' levels of capability, opportunity and motivation in order to design interventions which work.

Designers of future air quality feedback interventions should consider the advantages of immediate or semi-immediate feedback models over delayed feedback. There appears to be no disadvantage to the use of immediate and automated feedback compared to manually delivered delayed feedback, and considerable advantages in terms of contact time with participants. The format of messages should be carefully designed, with a combination of graphs of $PM_{2.5}$ over time and simpler visualisations incorporating coloured air quality indices providing a wide reach.

Intervention designers should consider participants' capability to change their behaviour as an important factor. Participants who are heavily addicted to smoking (and so find it difficult to quit or cut down) but who do not have the means to smoke outdoors may find the warnings and messages given during the course of an intervention to be alarming or frightening. This could raise ethical concerns if the overall effect of the intervention is only to cause the participant anxiety.

Recruitment was a source of difficulty in both the AFRESH study and the Measuring for Change study. Neither study recruited the number of participants targeted, with the AFRESH study falling short by 16 (80% of target) and the Measuring for Change study short by 52 (43% of target, excluding Barcelona). This may indicate a lack of demand for the intervention among the targeted group, or that potential participants in that group are particularly hard to reach. In "real world" settings this may result in difficulties rolling the intervention out, potentially affecting the cost-effectiveness of delivering it.

No full cost-benefit analysis has been conducted on the Measuring for Change study. An analysis conducted on a similar intervention (at the University of Nottingham [125]) determined that a reduction of 10µg/m^3 in $PM_{2.5}$ was achieved for every £131 spent on the intervention [223]. With the median baseline $PM_{2.5}$ concentration in a smoker's home in Scotland measured at 68µg/m^3 (in Measuring for Change), achieving a reduction to below the WHO guideline limit for $PM_{2.5}$ over 24 hours would cost around £564. It is not possible to demonstrate definitively whether this is cost-effective without applying some kind of political (rather than scientific) judgement, but by way of comparison, a recent intervention designed to provide a financial incentive to quit smoking in pregnancy cost around £1,127 per quit [224].

It is possible to use a low-cost PM monitor to detect SHS based on detected particle size. Future research on SHS in homes, whether developing behaviour change interventions or observational, could use these techniques to determine the presence of SHS in homes or other environments – for instance to add force to calls for new regulations in jurisdictions without comprehensive restrictions on smoking in public places.

Understanding of the relative health harms caused by indoor air pollution (including SHS) and outdoor air pollution was not high in the groups we studied in this work. Outdoor air pollution, particularly related to vehicles, was often overstated as a health risk while the risks from indoor air pollution were not fully recognised. Future efforts to promote behaviour change indoors could use techniques designed to address these perceptions, such as educational tools which directly compare common causes of indoor and outdoor air pollution [99].

9.4 Directions for future research

This research has demonstrated that air quality feedback has promise as a strategy for promoting smoke-free homes. Future research into these interventions is warranted to develop programmes which can help those who smoke to keep their homes smoke-free.

The automation of elements of the Measuring for Change could allow for a lower resource and higher throughput intervention. The Measuring for Change intervention involved automatically computer-generated feedback, but this was sent manually through a computer programme. Automating this could reduce the person-hours required to deliver the intervention, making it more attractive in different settings.

This study could be combined with a longer trial period with further follow-up measurements (at three months and six months-post intervention, for instance) and a control arm (receiving only generic SHS-avoidance advice) in order to determine the longer term impact of this intervention.

Chapters 6 & 7 describe the first study of internet-connected air quality monitors for behaviour change. However, the monitors used (though highly successful during initial testing as described in chapter 6) were flawed – data was repeated or omitted rather than sent to the server, and the nature of the monitors (which involved a number of components joined by cables) could lead to failures as cables were unplugged accidentally. New low-cost $PM_{2.5}$ monitors which have on-board WiFi connections are now available (such as the Purple Air PA-SD-II [225] and the IQAir AirVisual [226]). Although these devices must be validated before being used to detect SHS, they may be able to monitor air quality remotely without the complexity of the RAPID monitors developed in the course of this research. However, the RAPID monitors may remain suitable for those research organisations which already own a number of Dylos DC1700 monitors.

While both strategies have been used in effective interventions, it may be desirable to conduct a direct comparison of immediate and delayed feedback to determine which strategy is more likely to succeed.

Presentation of information on SHS presence in the home as part of an intervention could increase trust and provide further motivation for behaviour change. As confidence in this method of detection increases, interventions could use this data to provide rewards to those who reduce SHS in the home or keep their homes smoke-free, in a similar fashion to interventions with pregnant people who receive rewards when they succeed in quitting smoking (as verified by a carbon monoxide breath test) [224].

The Measuring for Change intervention was targeted primarily at individuals, though it incorporated messaging for participants who lived with smokers rather than who smoked themselves. Future interventions could take a “whole-house” approach, engaging everyone within the home in the effort to reduce smoking indoors. Furthermore, future interventions may usefully target fathers who smoke specifically, particularly if taking place in the developing world (where the tobacco epidemic is at an early stage and smoking rates are often much higher among men than women [15]).

Future research into detection of SHS using particle monitors could take into account peak shape and duration. Low cost sensors able to detect smaller particles (particularly those with diameters smaller than 0.2µm, in which range SHS peaks) and those which are able to differentiate more particle sizes within $PM_{2.5}$ (for instance, particles between 0.5 and 1.0μm in diameter) may result in improved detection as this information is taken into account.

The continuing fall in cost of laser particle counting sensors has allowed the incorporation of these sensors into a wide variety of equipment designed to be installed permanently or semi-permanently within a home [183]. Behaviour modification techniques could be incorporated into the software and hardware of these devices to promote smoke-free homes. As this technology develops and is standardised, such devices could be installed as standard in new-build housing encouraging a "nudge" [227] approach to smoke-free homes. Given that many household fires in the UK are started by cigarettes left unattended [228], behaviour changing and recording devices may be required by landlords, or may be used to offer reductions in life or building insurance premiums (just as activity trackers have been used to vary the cost of health insurance in the United States [229]).

Air quality feedback interventions could also be used in other highly polluted settings not related to the presence of SHS. This could be used indoors where solid fuel is burned for heat or light (such as using a wood burning stove, or if financially feasible in developing countries where household air pollution related to indoor solid fuel burning for cooking is common [230]). Changing heating or lighting method may not always be feasible in these settings, particularly in the developing world, so care should be taken to apply any such intervention only where useful.

Further applications could be considered outdoors in highly polluted settings – participants could be encouraged to use less polluted routes to travel, or to travel by a different method (as method of transport can affect air pollution does [231]). As outdoor air in developed countries typically has far lower levels of $PM_{2.5}$ than present in a smoking home visualisations and information given to participants would need to be adapted substantially for any such intervention to be successful.

Many jurisdictions now have laws against smoking in indoor public places, including Scotland [232], and in some cases these laws have been expanded to some outdoor spaces [233] and private spaces such as cars [58]. Legislation against smoking at home, however, has not yet been implemented in any jurisdiction despite widespread knowledge of the health harm of SHS indoors. One objection to this type of legislation is on enforceability grounds – how could it be known whether smoking had taken place within a home?

With widespread air quality monitoring and the use of specific SHS detection mechanisms (including a detection algorithm as described in this thesis and, potentially, nicotine monitoring equipment [90]) it would be possible to detect smoking in the home and, therefore, effectively legislate to prevent it. To counteract the inherent uncertainty of air quality monitoring in homes, a "multiple strike" system could be developed. This could be similar to the "Copyright Alert System", a voluntary scheme of the music, TV and film industries in the United States to combat internet piracy [234]. Under this scheme, individuals suspected of piracy received a certain number of warnings before any punishment was applied, and had the opportunity to appeal against each strike if they believed that it had been issued erroneously.

Monitoring equipment packages could be issued only to smokers, perhaps in conjunction with a "smoker's licence" scheme [235] as part of an overall "endgame" approach to tobacco control, designed to effectively eliminate smoking without outright banning tobacco (as in the case of the Scottish Government's stated 2034 target for a "tobacco-free Scotland" [62]).

The few settings in which smoking is banned in homes have tended to affect only people in less well-off settings (such as in the case of proposed bans in social housing in the United States [236]). Those bans can be accused of being inequitable by providing restrictions to behaviour only for those in lower socioeconomic groups. This proposal would instead affect all smokers, rich or poor, avoiding inequitable effects such as fining poorer people more than richer people.

Monitoring SHS in homes to enforce this measure would raise ethical concerns. Data from these monitors may be provided (either deliberately for enforcement purposes or accidentally through hacking) to third parties, presenting privacy concerns (particularly important as increased concentrations in $PM_{2.5}$ can be associated with the movement of people within a home [201]). A conflict could also develop between the social good embodied in the monitor (the desire to stop children's exposure to SHS) and the autonomy of the individual in the home. This imbalance has been explored in the case of devices intended to improve the welfare of older individuals with increasing care needs [237] – is it ethical to mandate the installation of a device which is not useful for its owner?

However, it is important to consider the right of the child to good health as well as the right of the adult to quiet enjoyment of their home. Severe SHS exposure can cause serious potentially debilitating health problems for children, such as asthma exacerbations, meningococcal meningitis or otitis media. Monitoring of this kind could be reserved for homes where children have previously suffered serious exposure to SHS, potentially providing parents or caregivers the opportunity to prove that they can improve a child's care.

9.5 Summary

Air quality feedback can be used as a tool to promote the reduction of SHS in homes where children are present, but are unlikely to be a solution for all smoking households or family groups. In an intervention study, only eight of 68 homes undergoing the intervention successfully reduced their mean $PM_{2.5}$ concentrations to below the WHO guidance level. However, two thirds of participating homes did see reductions, suggesting that air quality feedback, properly used, can promote reduced smoking in the home.

Different forms of feedback may have different effects, and some forms may be more effective with certain individuals than with others. Delayed and immediate feedback models have been used in various interventions, with both showing promise. It was feasible and effective to use internet-connected monitors to deliver daily SMS messages on air quality in the home, incorporating comparisons to previous behaviour and tips on keeping homes smoke-free.

It is possible to use low cost particle monitors to detect SHS in the home with a high degree of accuracy, which could have implications for future air quality feedback interventions and for other studies which rely on the accurate detection of SHS.

In a qualitative study, internet commenters and focus group participants expressed the view that SHS and outdoor air pollution issues are not closely related, and may not have a full understanding of the relative harms of each form of air pollution. This may have implications for designing interventions and methods of communication promoting smoke-free homes, as comparing the health effects of the high salience issue of outdoor air pollution and those of SHS may clearly demonstrate the serious nature of SHS exposure.

The work described in this thesis provides new methods of recognising and quantifying SHS exposure in home settings, and novel insights into how these data can be best presented to encourage smokers to make their home smoke-free.

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Appendix I - Qualitative research topic guide

v1.0 17 November 2017

Topic Guide

Welcome

Thank you for taking the time to talk to me today, I realise that you're busy. This session should last for about an hour. If you need to leave at any time that's no problem at all.

As mentioned in the information sheet, I'm recording this session so it can be transcribed later. As I mentioned before, we might use some of what we've discussed today in scientific reports and publications. If we do, your comments will be anonymised.

Introduction

This discussion is designed to get your thoughts and views about air pollution at home. I'm interested in what you know about these issues and what you think about how important they are in a few different ways. I'll ask a few questions now and then, but I'd really like to get the discussion going to hear what you think.

You've probably heard quite a lot about second-hand smoke and the effects it has on people's health, and the various measures that exist to protect people – smoke-free pubs, for instance, or the recent law banning people smoking in cars carrying children.

You might also have heard in the news about the health risks of air pollution outdoors, often linked to vehicles (like the Volkswagen diesel scandal) or to industrial pollution (like in many places abroad, such as Delhi and Shanghai). There are lots of things that could cause air pollution, and some of them might be more serious than others.

Warm up

- Can we go around the room and introduce ourselves?
- So, when I say "air pollution", what's the first thing that comes into your head?

Guiding questions

- What sort of things do you think cause air pollution? I mentioned a few things earlier, but can you think of any other examples?
- What do you think is the most serious of these causes of pollution? Are any really dangerous, are some of them really not that much of a problem?
- I know you all look after or help look after kids. Do you think the quality of the air has much of an impact on children's health, or is it only a minor factor?
- In general, how clean do you think the air is where you live? That could include in your home, on your street, where you work, where your kids go to school or anywhere else you think.
- How important do you think it is in general to have clean air? And why?
- What do you think should be the overall priorities when trying to have cleaner air? What's most important to do, and what's less important?
- Can individuals take action to protect themselves and their families from poor air quality, or is it more of a society-wide issue that you can't do much about?

Conclusion

Thank you for taking part today. This has been a really useful discussion for me, and I hope you've found it interesting as well. My contact details, as well as the contact details of my supervisors, are on your information sheets, so feel free to contact me if you have any other thoughts or them if you have any concerns about today's focus group.

Appendix II - AFRESH sample report & example visualisations

This appendix comprises a sample air quality feedback report and a comparison report as used in the AFRESH research project (chapter 5) and test visualisations used in focus groups during that project.

Final report used in AFRESH intervention

UNIVERSITY OF ABERDEEN MRC Medical Research Council

AFRESH report v1.0 produced: 16:52 20/07/16

Second-hand smoke in your home

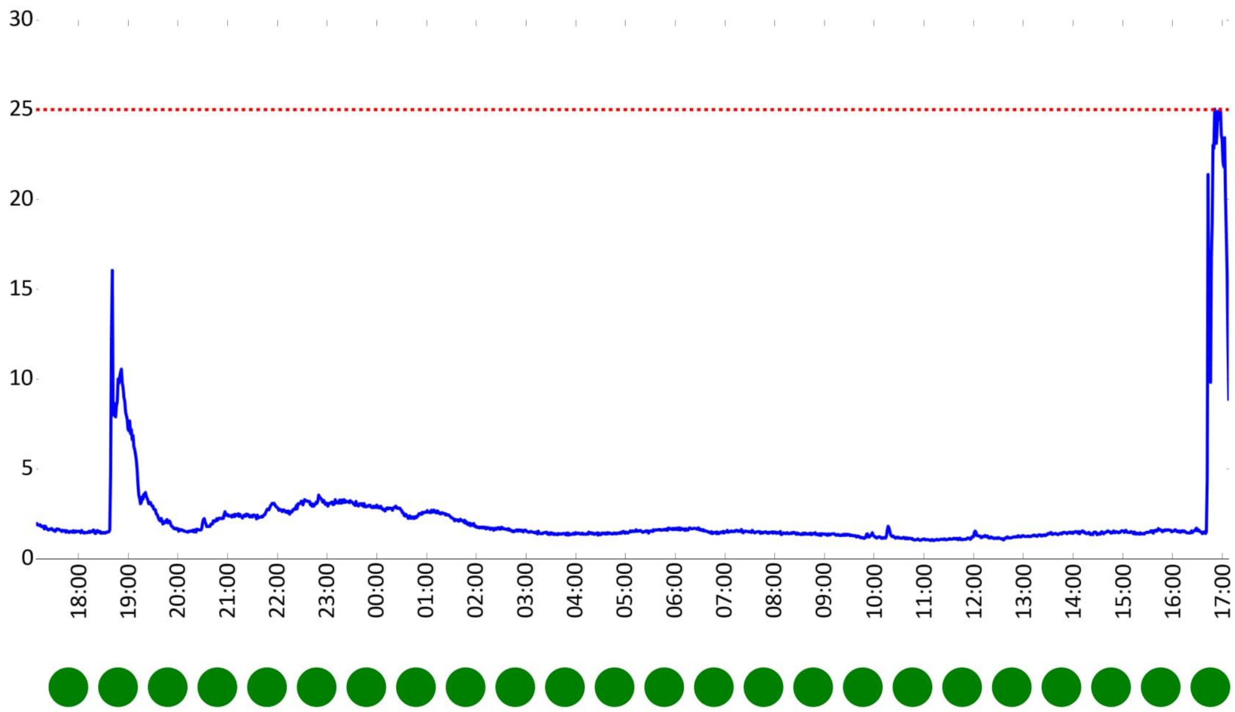
The Dylos DC1700 instrument was used to measure second-hand smoke in your home from 01/04/16 to 07/04/16

This package gives your personalised results.

Report: EXAMPLE_1

Measurement time: 6 days, 1.0 hours and 39.0 minutes

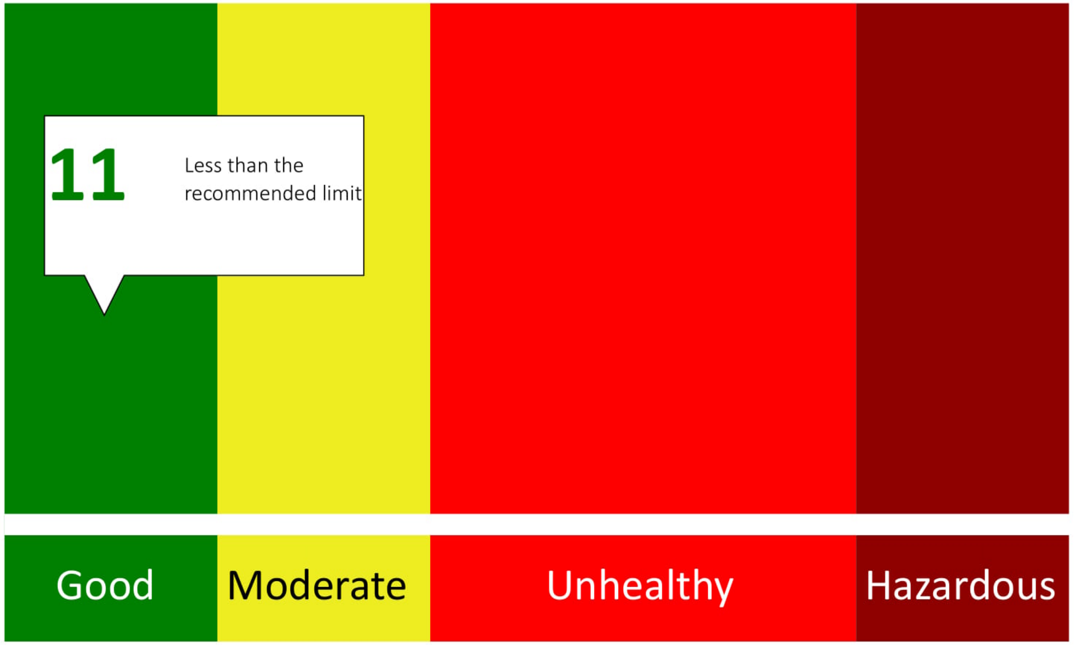
Second-hand smoke in your home over the last day



Dotted red line shows WHO guidance limit for PM2.5

Numerical values given show equivalent PM2.5 concentration in µg/m³ as measured using a Dylos DC1700 Air Quality Monitor.

Your home's average second-hand smoke level



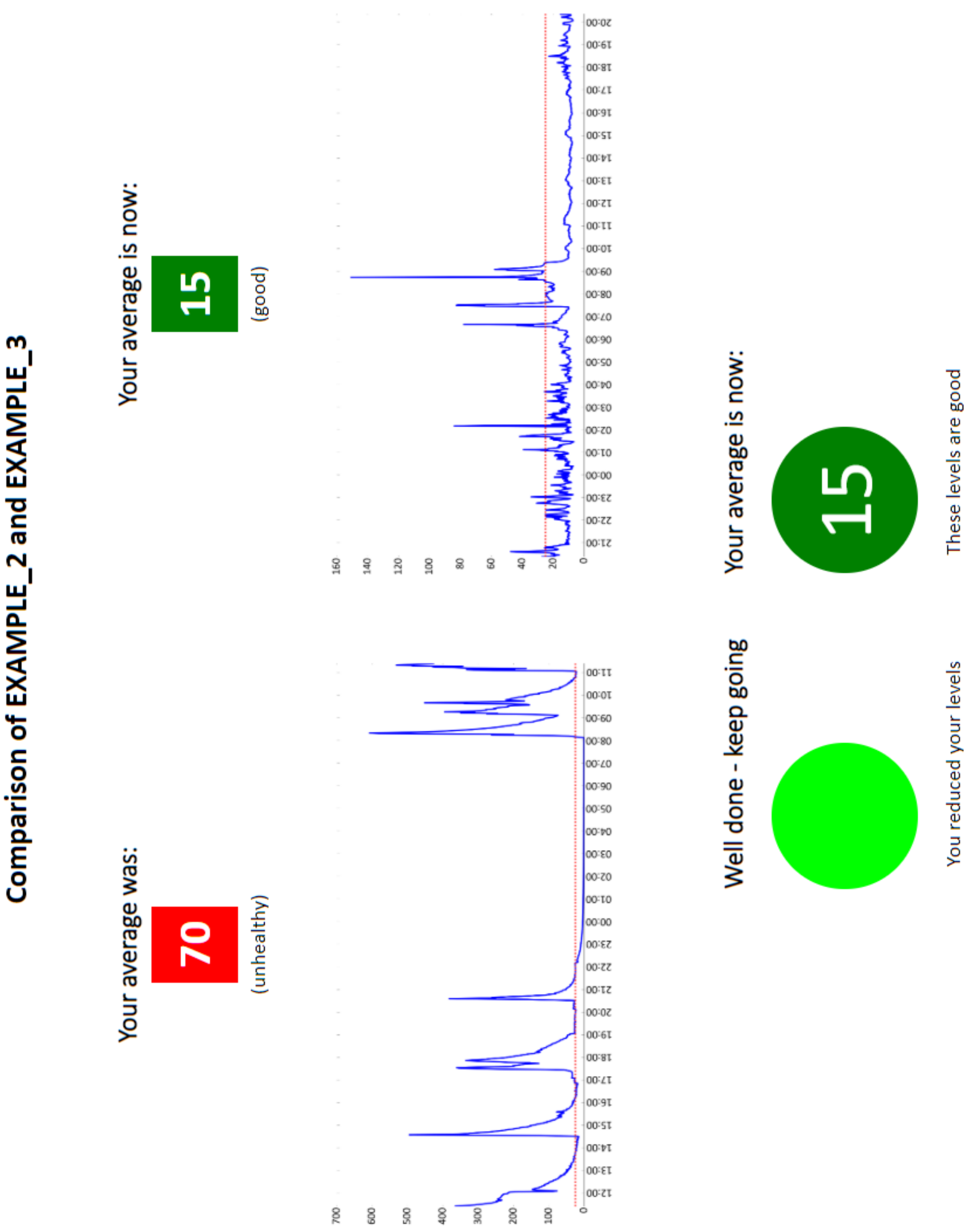
More information

Numerical values given show equivalent PM2.5 concentration in $\mu g/m^3$ as measured using a Dylos DC1700 Air Quality Monitor. Categories are derived from WHO and US Environmental Protection Agency guidance levels. "Good" represents values below $25 \mu g/m^3$, "Moderate" values from 25 to $55.4 \mu g/m^3$, "Unhealthy" values between 55.5 and $250.4 \mu g/m^3$ and "Hazardous" values above $250.4 \mu g/m^3$.

Highest value: **$25 \mu g/m^3$**

Total time that your home's smoke level is above the WHO guidance value: **0%**

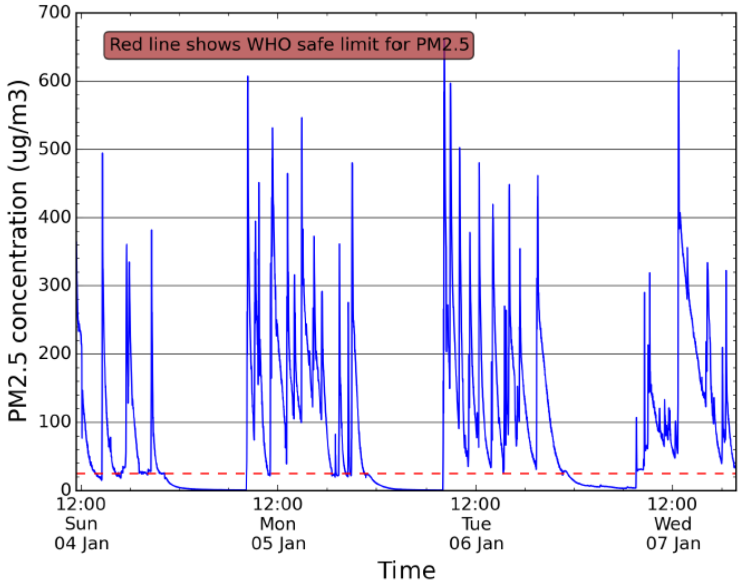
Total time in your house when smoke levels were above those in Scottish bars before they went smoke-free: **0%**

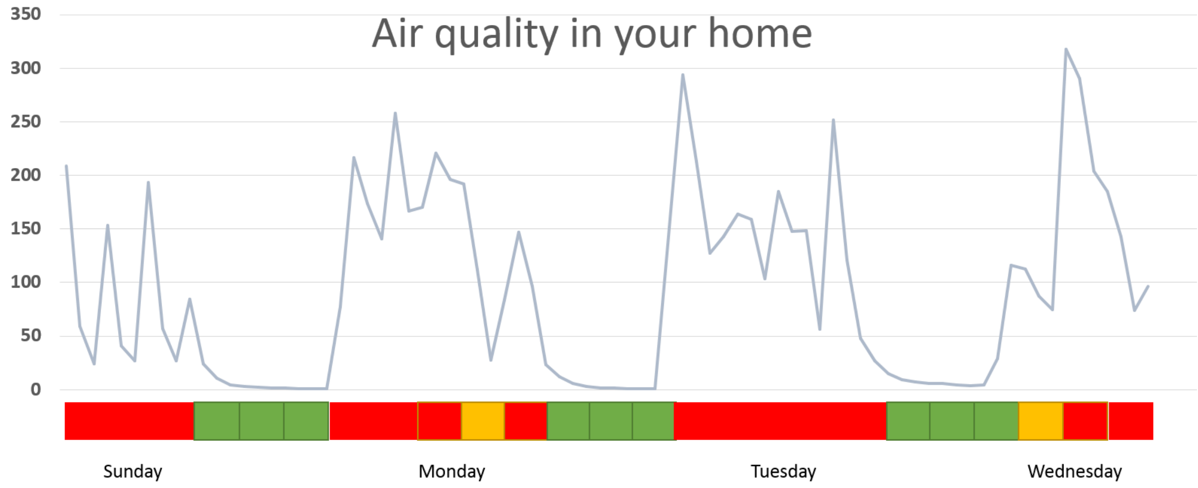


Comparison report used in AFRESH intervention

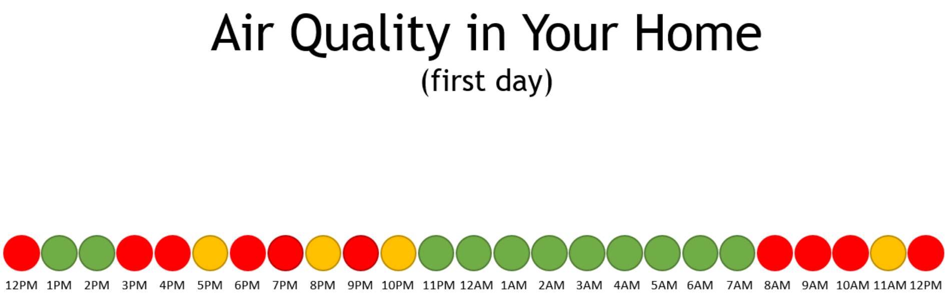
Example visualisations used in AFRESH focus groups

Air quality in your home - whole time

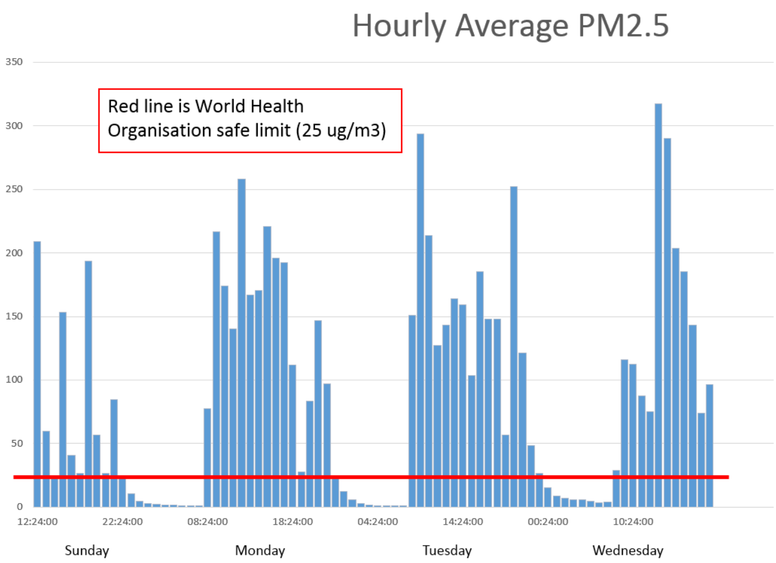




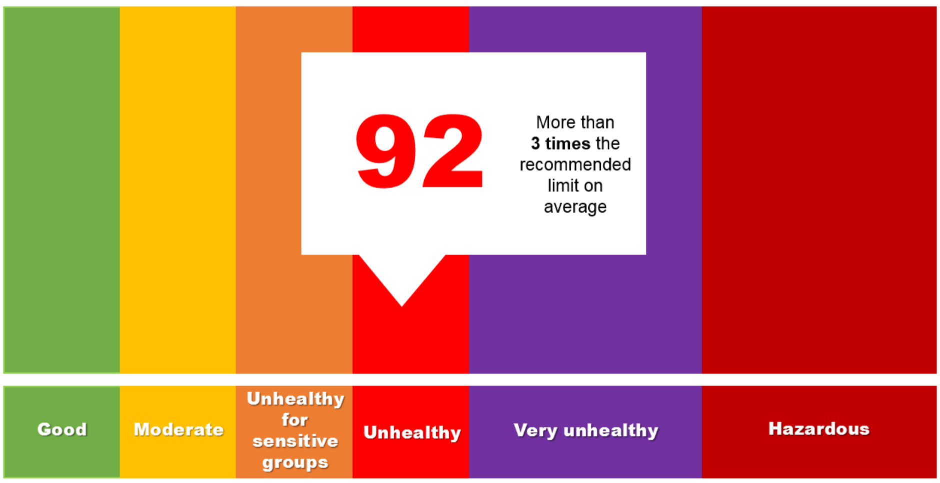
Air quality in your home
350
300
250
200
150
100
50
0
Sunday
Monday
Tuesday
Wednesday



Air Quality in Your Home
(first day)
12PM 1PM 2PM 3PM 4PM 5PM 6PM 7PM 8PM 9PM 10PM 11PM 12AM 1AM 2AM 3AM 4AM 5AM 6AM 7AM 8AM 9AM 10AM 11AM 12PM



Your Home's Average Air Pollution



Comparison of Jane Smith first log January and Jane Smith second log February

Well done!

You reduced your levels

Your average is now:

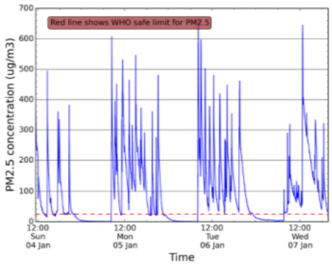
61

These levels are unhealthy

Your average was:

92

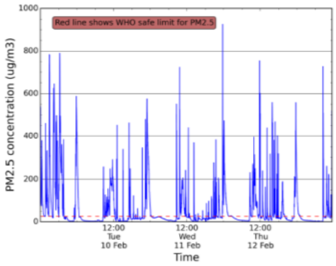
(unhealthy)



Your average is now:

61

(unhealthy)



Comparison of Jane Smith first log January and Good example log

Well done!	Your average is now:
✔	12
You reduced your levels	These levels are good

Appendix III - The AFRESH Programme

Summary

The AFRESH programme, which consists of 6 modules, has been developed to assist parents change their smoking behaviour and create a smoke-free home. The programme is designed to be delivered by care professionals, using a combination of face to face discussion techniques, alongside baseline and follow up measures of second hand smoke levels in the home, as illustrated on pages 5 & 6.

The AFRESH programme flowchart

Contact 1 - Day 1 (takes 20 mins)

Module 1: KBA (Knowledge, beliefs and attitudes)	Materials required:
• Establish context • SHS and Child Health • The nature of SHS • Ineffective strategies • Barriers and solutions • Summary • Invitation to take part in the study	• AFRESH Fact Sheets 1 and 2 • AFRESH Handouts 1 and 2

Contact 2 – Day 3 (takes 10 minutes)

	Materials required:
• Confirm the parent has read the information sheet • Answer any questions • Obtain consent to take part • Provide parent with Dylos machine to take home and install for 5 days	• Study information sheet • Consent form • Dylos machine and extension • AFRESH Handout 3

Contact 3 – Approx. day 9 (takes 60 minutes, can also be split into 2 separate sessions)

Module 2 - Feedback	Materials required:
• Mother returns Dylos machine (OR staff member collects it from mother's home) • Staff member downloads feedback (OR downloads within the next 3 days) • Staff member provides indoor air quality feedback (OR visits mother in home to provide feedback)	• AFRESH Handout 3 • Personalised feedback data
Module 3: Solutions	**Materials required:**
• Facilitators, barriers and solutions	• AFRESH Handout 1
Module 4: Planning	**Materials required:**
• 'If-then' plans • Getting support • Personal plan	• AFRESH Handouts 4 and 5 • AFRESH Handout 1 (optional)
Module 5: Dealing with others (optional)	**Materials required:**
• Why involve others • How to raise the issue • Skills for dealing with barriers	• AFRESH Handouts 1 and 6

Module 1: Parent knowledge, attitudes and beliefs regarding second- hand smoke (SHS) in the home

Materials required to deliver Module 1:
AFRESH Fact Sheets 1 and 2:
What you need to know about second-hand smoke
Second-hand smoke and effects on children's health
AFRESH Handout 1: Parent barriers, facilitators and solutions for creating a smoke-free home
AFRESH Handout 2: Colour print out of example of personalised feedback from a home where smoking takes place

a. Establishing context

The care professional begins by establishing with the parent:

- Who currently smokes in the house and where
- How many cigarettes are smoked per day by each smoker in the home
- How many children live in the house, and their ages
- Any other household members
- Current rules for smokers who visit the house – where are they allowed to smoke?
- Are there any times when the existing smoke-free rules don't apply (i.e. when children not present, when children are asleep, when the weather is bad etc.)
- Has the parent ever considered making the home smoke-free before, and why (not)?

During the course of these discussions, or as a result of previous interactions with the parent, the care professional may have concerns about potential domestic abuse that could arise as a result of the parent initiating steps to make her home smoke-free. The top priority is the safety of participants and families.

In such instances the care professional should make a case-by-case judgement about the parents' participation in the study. For example, any of the following scenarios could be applied:

a. The care professional may consider that the domestic situation is too volatile for the parent to participate in the study

b. The care professional and the parent may agree that the parent will focus on changing her smoking behaviour in the home, without asking others in the household to do the same (so omit delivering Module 5). In this scenario, the care professional should emphasise that reducing SHS levels in the home will be beneficial to her child/children. In addition, the care professional and the parent may agree *not* to place the air quality monitor in the home to record personalised SHS levels (so omit delivering Module 2).

If b, the care professional should use their own judgement to tailor the discussions that follow so that they are more of a 'light touch' approach. For example, spend less time focusing on the health impacts of second hand smoke in the home, which may cause additional feelings of guilt for the parent given she may feel unable to control creating a smoke-free home at this time. Focus more on the steps that she can

b. SHS and child health

The health/social care professional uses a **tailored** approach to first identify what the parent already knows about SHS in the home; reinforces/confirms existing correct knowledge; addresses any misconceptions and provides new information where knowledge is missing. The care professional **discusses** health harms of SHS exposure with the parent and how this may apply to their children (to personalise risk), listening to the parent to establish whether she comprehends the information, and addressing any misconceptions.

- Discussion should cover key areas 1 and 2 below
- Remember throughout to *reinforce* existing knowledge, *address* any misconceptions, and *provide* new information where knowledge is missing
- Refer to the **AFRESH factsheets 1 and 2** if you need to, to help deliver this information

Key

Discussion Area 1: The effects of second-hand smoke

Ask the parent what she knows about second hand smoke and its effects in general
Explain why second-hand smoke is dangerous
Ask the parent how common she thinks it is for other parents keep a smoke-free home
Explain that children whose parents smoke around them are three times more likely to take up smoking as a teenager
Explain that children have smaller lungs, and breathe faster, and so are particularly susceptible to the effects of SHS (this is similar for pets too).
Outline the effects of SHS exposure on child health

Using elaboration techniques may make it more likely that parents remember new information on second-hand smoke. The care professional should try providing some of the information from Factsheet 1, and ask the parent to **elaborate** with any additional information she knows of. For example, they might say:

- Did you know there is no safe level of SHS exposure in the home?

And then ask parents to elaborate with other information they (are more likely to) know, such as:

Key Discussion Area 2: How the effects of second-hand smoke apply to your own child/children

Ask if their child/children have/have ever had had any of the health conditions: coughs, ear infections, chest infections (for example bronchitis, bronchiolitis, pneumonia), wheezing, asthma
If yes: explain that these conditions can be caused by exposure to second-hand smoke

If no: explain there is a higher likelihood that their children will develop such conditions compared to children who live in a smoke-free home

c. Ineffective strategies for eliminating SHS in the home

The Scottish Government's 'Take it Right Outside' video demonstrates how it's never safe to smoke indoors, and could be used as a visual aid during this section:

http://www.rightoutside.org/

The care professional **discusses** ineffective strategies with the parent, listening to ensure the parent understands the information, and addressing any misconceptions she may have. Ineffective strategies include:

Opening a window/smoking out of a window
Smoking in the kitchen or other designated room
Smoking inside, by the front/back door *(page 9 of the REFRESH How to Guide could be used to demonstrate this point)*
Using a fan
Burning candles
Smoking when children aren't present

d. Barriers and solutions to creating and maintaining a smoke-free home

Use the AFRESH handout 1 to aid discussion in this section: *'Parent barriers, facilitators and solutions for creating a smoke-free home'*

The care professional **discusses** with the parent some of the general barriers that other parents have found in trying to create a smoke-free home. This should include barriers relating to the parent themselves, barriers relating to other household members, and barriers relating to the housing environment if applicable.

To illustrate the impact that barriers have on creating a smoke-free home, the care professional should show the parent Handout 2, the personalised feedback graph from a home similar to theirs, where one or more parent is smoking in the home.

This is partly for illustration purposes, and also to show them what the feedback graph looks like if they choose to have measurements made in their own home. The care professional should also comment that by learning from previous difficulties in making the home smoke-free, people are more successful in their next attempt.

The care professional then discusses facilitators with parents, encouraging them to come up with effective strategies for exploring solutions.

e. Summary

The care professional takes time to summarise (a) what parents already know about SHS exposure in the home and (b) what steps are already being taken in the home to reduce SHS levels. The professional checks that their summary matches with the parents' perspective of current knowledge/steps being taken and any discrepancies are discussed and resolved.

Module 2: Delivering personalised feedback on air quality in the home

Materials required to deliver Module 2:

- ***AFRESH Handout 3: Your guide to the air quality intervention***
- ***Colour print outs of personalised feedback data***
- ***Colour print out of personalised comparison data, for follow up sessions only***

a. Deciding whether to have air quality measured in the home

Handout 3: *'AFRESH: Your guide to the air quality intervention'* includes more information on the Dylos air quality monitor, and the procedures involved in having air quality measured. This leaflet should be used to aid discussion in this section, **UNLESS** the intervention is being delivered as part of a research project, in which case refer to the research information sheet that will have been designed for the project, and follow informed consent procedures.

The care professional should ask parents if they would like to see what the air quality is like in their own home. Be clear that this is the parent's choice. They should in no way feel pressured to have an air quality monitor placed in their home. Using the AFRESH intervention guide, the care professional should:

- Explain what will happen during the intervention
- Explain what the air quality monitor does
- Show the parent what an air quality monitor looks like, either using a picture, or using a real-life example.
- Answer any questions that parents may have using the AFRESH intervention guide.

If the parent decides not to have the air quality monitor installed in her home, reassure her that that's ok. If the parent agrees to have her air quality monitored, let her know that you support her decision and continue with the next section of this module.

b. Reinforcing positive steps already being taken

The health and social professional first uses **self-affirmation** techniques to reinforce and encourage parents to elaborate on the positive steps they have already taken to reduce SHS levels in the home (i.e. restricting smoking to particular rooms etc.). This should increase parents' self-image and lower resistance to the personalised feedback if SHS levels are higher than the parent is expecting.

c. Establishing context

Before the machine is installed in the home, the care professional should establish the following:

who currently smokes in the house and where

approximately how many cigarettes are smoked per day by each smoker in the home

how many children currently live in the home, and their ages

The care professional then explains that, by building on what the parent already knows, and what they are already doing, they will be able to better protect their child/children from SHS in the home.

d. Installing the air quality monitor

The care professional should give the parent the air quality monitor to install at home, explaining that:

The air quality monitor should be placed in the living room, out of the reach of children (for example, on a shelf, on top of the television, or on a window sill)

To install, simply plug in and switch on.

The monitor should not be switched off overnight. It is safe to leave it running continuously, and this is required for the purposes of the intervention.

The monitor uses minimal electricity – approximately 10p per day.

The care professional should then agree with the parent a convenient day for her to return the air quality monitor. The duration can be tailored to suit the needs of the parent taking part. The device will log the latest 6 days of measurements so generally return should take place within a week. Ideally measurements should span 5 days with some data from weekends included if possible.

e. Providing feedback on personalised air quality levels

Once Dylos data has been downloaded (refer to '*Using the AFRESH software*', provided separately, for step-by step instructions on downloading), the care professional uses **individualisation** and **personalised risk** techniques in providing personalised air quality feedback, giving parents opportunities to have questions answered according to their individual feedback and progress.

Have a colour print out of the personalised air quality feedback to hand!

At this point, the care professional shares the graphs of personalised Dylos feedback with the parent. This includes discussion of:

- average particle ($PM_{2.5}$) levels
- Lowest and highest $PM_{2.5}$ level
- the percentage of time when the $PM_{2.5}$ levels exceed World Health Organisation guidance
- the percentage of time when the household $PM_{2.5}$ levels were higher than those measured in a typical bar before smoke-free legislation came into force in Scotland
- how the average level compares to other homes in Scotland where similar measurements have been carried out.

Visual information is then given on whether their current $PM_{2.5}$ level is satisfactory in terms of risks to child health, and, if applicable, what more they need to do to reach satisfactory levels.

*At this point, **at further follow up sessions only,** any smoking behaviour change should also be discussed since $PM_{2.5}$ was last measured, with a view to ascertaining whether changes have arisen as a result of the air quality monitoring, or whether there are other factors involved. If other factors are involved, the professional should find out more about them and their impact. Use the personalised comparison feedback graph as a starting point for discussion.*

The care professional then discusses air quality findings with the parent, to include:

- Parent reactions to feedback – how do they feel about the $PM_{2.5}$ levels recorded?
- To what extent did they think their child was at risk from SHS exposure in the home, and has their view changed now having seen the feedback?
- What changes would they like to make to their smoking behaviour in the home? Are these changes realistic?

By this point, the care professional should be beginning to identify with the parent a realistic, but potentially challenging goal that they can set to achieve a smoke-free home.

Module 3: Barriers, solutions and facilitators to creating a smoke-free home

Materials required to deliver Module 3:

AFRESH handout 1: Parent barriers, facilitators and solutions for creating a smoke-free home OR *www.rightoutside.org/yoursmoke-freetips*

a. Things that make it easier to create a smoke-free home

The care professional should discuss with the parent the reasons why they want to change their smoking behaviour to establish a smoke-free home.

Encourage the parent to identify these 'facilitators' themselves, by asking them to complete the following sentence: 'I would like to have a smoke-free home because…' This question establishes reasons or motives for taking part.

The care professional should then confirm the parent's beliefs, and add new suggestions for facilitators. Encourage parents to elaborate on additional suggestions that apply to them as well. At this point, the care professional should also correct any existing beliefs about facilitators that the parent has that are incorrect, if applicable.

b. Barriers to creating a smoke-free home

The care professional then encourages the parent to identify barriers to creating their smoke-free home. This can be done in conjunction with planning coping responses, by involving the parent in making a personalised list identifying high-risk situations/barriers and a plan for coping with them. The care professional should then encourage the parent to identify practical steps that need to be taken in order for her to reach the goal of creating a smoke-free home.

At this point, the care professional can share *Handout 1: Parent barriers, facilitators and solutions for creating a smoke-free home*, so that parents can see how other parents have overcome challenges in creating a smoke-free home.

Module 4: Planning for creating a smoke-free home

Materials required to deliver Module 4:

AFRESH Handout 4: Personal smoke-free home action plan
AFRESH Handout 5: Difficult situations and 'if-then' plan
AFRESH Handout 1: Parent barriers, facilitators and solutions for creating a smoke-free home (optional)

Developing a personal smoke-free home action plan

The care professional opens the discussion by explaining that behaviour change is helped by a detailed plan of how parents are going to change their behaviour:

> Creating a smoke-free home will have a positive impact on how you feel about yourself, and improve the health of your child/children. But creating a smoke-free home can be easier said than done. Even if you are strongly motivated, breaking old habits can be a challenge.
> Goals are easier to reach if they're specific ("I'll ask my friend to watch my child while I nip outside for a cigarette", rather than "I'll smoke outside")
> It's not enough to have a goal of creating a smoke-free home. You also need a plan which outlines practical ways to reach your goal.

At this point, the care professional should work through Section 1 of *Handout 4: Personal smoke-free home action plan,* with the parent, confirming her general goal to create a smoke-free home, and identifying associated specific goals.

b. Difficult situations and 'if-then' plans

Handout 5: Difficult situations and 'if-then' plans' should be used at this point to encourage the parent to plan ways of overcoming her own challenges in establishing a smoke-free home. associated specific goals.

The care professional should encourage the parent to make a list of 'if-then' plans using the template provided in Handout 5, i.e. '*if situation Y arises, then I will perform behaviour X'*. The situation itself then becomes a trigger for performing the desired behaviour, for example: *"If it is a weekday morning, then I will go outside and have a cigarette before my partner goes to work."*

The care professional may also want to refer back *to Handout 1: Parent barriers, facilitators and solutions for creating a smoke-free home* to aid discussions with the parent at this stage.

c. Getting support

Planning where the parent can get support for creating a smoke-free home is also important. Ask the parent to think of people who are likely to be supportive and encourage them in changing their smoking behaviour. Together think of ways that the parent can get the most benefit from these people, for example, spending more time with them, having a specific person to phone when they need encouragement. Help the parent to identify any useful sources of support and encourage them to use them.

d. Personal action plan

At the end of the meeting, the parent completes her Personal Action Plan and both the parent and the care professional sign it. This is effectively a behaviour change 'contract' – making contracts has been shown to help people stick to their action plans and achieve their goals.

e. Mini-goals

Once the parent has filled in their Personal Action Plan, the care professional should help them to work out what their mini-goals could be. It is important to remember that the action plan should be reviewed regularly and revised in the light of experience. Parents should be told that they won't necessarily stick to their first plan, but their experience of trying to do this will give very helpful information that can be used to revise the plan to make it work better for them.

f. Reviewing the action plan

Reviewing the action plan involves finding answers to the following questions:

- What was tried?
- With what effects (and did the parent achieve any success)?
- What benefits were there?
- What difficulties were there?
- How did the parent manage any difficulties?
- Were there any problems recording behaviour? How could these be solved?
- How confident is the parent that they can achieve their goal?
- Is the parent getting enough support?
- Does the action plan need changing? (The mini goal (s))

g. Praising any success

Make sure you praise something that the parent has done, however small, to boost their motivation and level of self-confidence. This could include any progress made towards creating a smoke-free home, attending the meeting, recording behaviour or learning more about what they find difficult. Praising the parent may also improve your relationship with them and make communicating easier. Remind the parent that successfully creating a smoke-free home may be a long process in some households, and emphasise the need to build on each small success, learning from any setbacks.

h. Things you could do if the parent has had a setback:

Review the goal – look at the goal that was set. Was it realistic? If not, try setting another goal that the parent will find easier to achieve. Agree that you set the goal too high before.

Barriers and facilitators – were there barriers that the parent hadn't thought about? If so, the barrier, and possible solutions, need to be discussed

Self-monitoring – is the parent still recording their behaviour? If they've stopped, it's easy for them not to realise why the setback has happened. Talk about what is making it difficult for them to record their behaviour, and together come up with ideas that could help.

Difficult situations – review or fill in the 'if-then' table.

Support – check that the parent is receiving enough support from friends and family. Talk about ways of getting more support, and provide information on the types of support available from the community.

i. Building habits

Once a parent has successfully changed her smoking behaviour, the next stage is to maintain this behaviour and continue it into the foreseeable future. Having a smoke-free home needs to become part of their lifestyle, an automatic habit that doesn't require effort or thinking.

Support

Check that the parent is continuing to use the support they can get from friends and family.

Repetition

Simply by repeatedly taking their smoking outside, it is more likely to become a habit. The more frequently a parent performs the behaviour, the less time they spend deciding whether or not to do it and thinking about why they are doing it. As the parent repeats the behaviour many times, it takes less conscious effort and attention, and then becomes a habit.

Reviewing progress, benefits and outcomes

Encourage the client to look back at what they have already achieved. Reinforce the benefits that smoking outside has had or will have. Remind the parent of the skills they have acquired. The fact that they have smoked outside before should increase their confidence that they can do it again. The skills they have acquired may also give them the confidence to think about changing other health behaviours in the longer term.

Module 5: Equipping parents to help persuade other household members to create a smoke-free home (optional module)

Materials required to deliver Module 5:

AFRESH Handout 6: Encouraging other household member to assist with creating a smoke-free home

AFRESH Handout 1: Parent barriers, facilitators and solutions for creating a smoke-free home

Handout 6 contains guidance for parents on helping to persuade other household members to assist with creating their smoke-free home. The contents of Handout 6 should form the basis of the discussion between the care professional and the parent. In addition, the parent can refer to Handouts 1, 2, and 4-5 and 7 in her own discussions with other household members.

a. **Why involve family members in creating a smoke-free home?**

The care professional should emphasise that children will only fully benefit if others in the household smoke outside too. Reiterate that parents are not asking family members to quit smoking altogether, but to smoke outside.

b. How to raise the issue of creating a smoke-free home with other household members

The care professional should discuss with the parent her responsibility to protect her child/children from the SHS of others, and ways of initiating a discussion with other household members about their role in assisting with this. There are many ways of doing this, including:

- Sharing and discussing facts that are most relevant to household members from Module 1
- Sharing personalised feedback graphs regarding actual $PM_{2.5}$ levels in the home
- Explaining an advantage of other household members trying to smoke outside and asking them for any additional advantages they can think of.
- Asking family members what they think/feel about their smoking in the home
- Encouraging other household members to reflect on the impact of their smoking behaviour on the wellbeing of others in the household.

The parent should be encouraged to select the strategies that are most appropriate for them, including sharing the personalised feedback graphs regarding measured $PM_{2.5}$ levels in the home.

c. Skills for dealing with family barriers to creating a smoke-free home

This section outlines ways in which the care professional can equip the parent with skills for dealing with family barriers to having a smoke-free home.

> *Handout 1: Parent barriers, facilitators and solutions for creating a smoke-free home* can be used here, to help the care professional and parent explore together barriers with family members, and solutions to overcome them.

During this section, it is key to explore together potential barriers with family members. The care professional should ask the parent to list any potential barriers with family members that they can think of, and then identify solutions to overcome them.

The parent should also be encouraged to rehearse methods of dealing with barriers with family members, partly to increase her own confidence and partly to practice coping responses associated with raising problems with family members if discrepancies occur.

The care professional should also discuss with the parent strategies for asking visitors for their support in making the home smoke-free. Similarly, the care professional should ask the parent to list any potential barriers with visitors that they can think of, and then together identify solutions to overcome them.

The parent should then be encouraged to rehearse methods of dealing with barriers with visitors, partly to increase her own confidence and partly to practice coping responses associated with raising problems with family/friends if discrepancies occur.

The care professional should remind the parent that most barriers can be overcome, especially when possible solutions are discussed together. However, if it becomes clear that other household members are unable or unwilling to assist the parent in creating a smoke-free home, suggest that the parent does the best she can to reduce second-hand smoke levels in her home by taking her own smoking outside.

d. Planning for a smoke-free home together

If other household members are able to assist in creating a smoke-free home, suggest that the parent talk with them about how they will achieve this. They may want to complete their own personal action plan, and/or develop their own ‘if-then’ plans. Emphasise the importance of monitoring progress together, discussing any setbacks as they arise, and praising successes.

e. Asking visitors for their support

Encourage the parent to think about strategies for asking visitors for their support in making the home smoke-free, just as they have done with family members.

Module 6: Quitting smoking (optional module)

Materials required to deliver Module 6:
AFRESH Handout 7: Quitting smoking

At any stage of this programme, if a parent decides she wants to quit smoking completely, *Handout 7: Quitting smoking* should be used as a basis for discussing quit options and actions.

a. Why quit?

The care professional should discuss with the parent her reasons for wanting to quit, and encourage her by pointing out that:

- Stopping smoking is the single most important thing a smoker can do to improve their health
- Stopping smoking immediately reduces the risk of heart disease, cancer, stroke, diabetes, rheumatoid arthritis and dementia
- A 20-a-day smoker paying £7.50 a packet will save over £2700 a year.

b. What tools can help with quitting?

The care professional should discuss the different tools that are available to help with quitting smoking. Emphasise that different things work for different people. If the parent has tried to stop smoking before using one of the products listed, suggest that she could try something else:

- Nicotine therapies, such as chewing gum, patches, lozenges and inhalers can be provided free by NHS stop smoking services
- GPs may be able to prescribe stop smoking medicines
- Some people have used e-cigarettes to help them quit. We don't know how effective they are, but some users have found them helpful. If this is the route they choose, explain that:
    - The vapours produced by e-cigarettes contain nicotine, but they are likely to be less harmful to children than second-hand smoke.
    - Parents may want to consider using e-cigarettes out of the sight of children. The hand to mouth action mimics that of smoking, which children may go on to imitate. Children may also find brightly coloured lights and flavoured smells associated with some e-cigarettes attractive.

c. What else can help?

Be clear that stop smoking services offer the best chance of quitting smoking. Encourage the parent to either:

- Contact Smokeline on **0800 84 84 84** (8am – 10pm 7 days a week) to speak with an advisor
- Visit www.canstopsmoking.com for help, information or to web chat with an advisor
- Make an appointment with their GP who can refer them to their local stop smoking service
- Visit their local pharmacy to talk to their pharmacist about quitting

AFRESH: FACT SHEET 1

WHAT YOU NEED TO KNOW ABOUT SECOND-HAND SMOKE[2][3][4]

What is second-hand smoke?

Second-hand smoke is all the particles and vapours that go into the air when a tobacco product is burned. That means both smoke coming off the lit end of a cigarette, as well as smoke breathed out after taking a drag.

More than 85% of tobacco smoke is invisible and has no smell.

Why is second-hand smoke dangerous?

Around seventy chemicals in second-hand smoke are thought to cause cancer, while others cause diseases like glue ear, meningitis and cot death. These chemicals can quickly build to dangerous levels in a home or car, even after just one cigarette.

In a home, second-hand smoke can remain at dangerous levels for more than five hours. Levels can still be high everywhere in the home even if you open the windows or you only smoke in one room.

There is no safe level of second-hand smoke in the home.

Why are children particularly vulnerable to second-hand smoke?

Children have small, growing lungs, and breathe more deeply and more quickly than adults. Because of this, they can suffer more from the effects of second-hand smoke. For that reason, it's important to keep children safe from second-hand smoke by never smoking inside the home or car.

Is smoking in the home something that lots of other parents do?

Approximately 90% of children living in Scotland under the age of 16 live in smoke-free households.

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[2] US Department of Health and Human Services. The health consequences of involuntary exposure to tobacco smoke: a report of the Surgeon General. US Department of Health and Human Services, 2006.
[3] Semple, S and Latif, N. (2014) How long does second-hand smoke remain in household air: Analysis of $PM_{2.5}$ data from smokers' homes. Nicotine and Tobacco Research, 16 (10):1365-1370.
[4] Campbell-Jack, D., Hinchliffe, S. & Bromley, C. (eds). Scottish Health Survey 2014: Volume 1: Main Report. Available from: www.gov.scot/Topics/Statistics/Browse/Health/scottish-health-survey

AFRESH: FACT SHEET 2

KEY FACTS[1] ON SECOND-HAND SMOKE AND EFFECTS ON CHILDRENS' HEALTH

Second-hand smoke exposure has been shown to have a number of harmful effects on children's health:

Children and infants are more vulnerable to tobacco smoke than adults. Children have smaller airways, breathe faster and their immune systems are still developing.

A woman who smokes one to nine cigarettes a day during pregnancy is more than four times as likely to have a baby die as a cot death than a woman who doesn't smoke at all during pregnancy

Tobacco smoke can cause low birth weight in babies which has been associated with coronary heart disease, type 2 adult onset diabetes, and being overweight in adulthood

Middle ear infection in a child is 50% more likely to occur if one parent smokes

Children whose parents smoke at home are twice as likely to have asthma symptoms all year round

Exposure to second-hand smoke is associated with an increased risk of respiratory tract infections such as coughing, wheezing and croup

Approximately 9,500 children are admitted into hospital in the UK every year because of tobacco smoke

Children are three times more likely to smoke when they get older if they grow up around smokers.

[1] Royal College of Physicians (2010) Passive smoking and children: A report by the Tobacco Advisory Group. London: RCP

AFRESH HANDOUT 1: PARENT BARRIERS, FACILITATORS AND SOLUTIONS FOR CREATING A SMOKE-FREE HOME

How do I handle the situation when my partner/visitors smoke? I'm concerned it may upset relationships in the home.	Remember that you're protecting both your child/children and others from the effects of second-hand smoke. Ask friends/partners for their support in helping make the home smoke-free. Most people respond well to requests for help so don't be afraid to ask for their support. Remind your partner/family/friends that you are not asking them to stop smoking altogether but to smoke outside if they want to have a smoke. You could have a no-smoking sticker in the home or by the door, or ask your child to draw a smoke-free home poster, to remind visitors.
I live in a high-rise flat and don't have access to a balcony where I could smoke OR I can't leave my children alone whilst I go outside to smoke.	The safety of your children is essential. We know it can seem like you don't have a choice, but there are other ways that might work for you and your kids: Do you live with someone who could look after the children while you go outside for a smoke? Or do you have a friend that could come over and mind your child whilst you nip outside for a cigarette? You could always offer to do the same for your friend if they smoke too. Is there a safe area outside where your child/children could play while you have a cigarette? Could you wait and have a cigarette when you are outside (e.g. on the way to the shops, during the nursery/school run, or whilst you walk the dog if you have one)? You could consider using NRT products such as an inhalator or gum while in the flat. If you decide to use NRT, we recommend you take advice from a pharmacist or GP as to the product that would best suit your needs.

What do I do about the cravings that I get when I get stressed in the house?	Most cravings will subside within a few minutes and doing something different will take your mind off cigarettes. Sipping water, chewing gum, or brushing your teeth can help with cravings. Some parents find it helpful to take up a hobby that uses their hands to help take their mind off the cravings (and help keep their hands off the cigarettes). Maybe drawing, or colouring in with your child might help? Some parents find that phoning a friend or family member takes their mind off the cravings. Try and speak with someone who will be a source of support and encouragement for you. Maybe you could go for a walk with your child/children, or play a game with them. You could consider using NRT products such as an inhalator or gum while in the flat. If you decide to use NRT, we recommend you take advice from a pharmacist or GP as to the product that would best suit your needs.
I think that the effects of second-hand smoke are exaggerated as my parents smoked when I was a kid and I'm fine.	There is a lot more information available these days on the health effects of second-hand smoke exposure in the home, compared to 20 years ago, when we knew very little about the impacts on children. A lot of the research that has been conducted comes from right here in Scotland! Have a look at the facts section of the 'Right Outside' website. Here you'll find more information on harmful effects of second-hand smoke exposure in the home, including some of the key impacts on child health such as ear infections, chest infections and asthma: http://www.rightoutside.org/facts You could also take a look at the 'Right Outside' video here, to learn about how second-hand smoke lingers in your home after smoking: https://youtu.be/OJaNZcgcvVc
Can I smoke in one room with the window open/back door open?	Sometimes parents think that smoking in the kitchen with the window open, for example, is enough to protect their children from second hand smoke in the home: Smoking in a room with a window open, with an extractor fan on, or by the back door will lessen some of the smoke in the home, but it doesn't remove the health risks because many of the harmful

	toxins in second-hand smoke remain in the room for many hours (see the 'Right Outside' video here: https://youtu.be/OJaNZcgcvVc). Smoking outside of the home/car is the only way to adequately protect children from the health risks of second-hand smoke. Perhaps you could put an ashtray and umbrella by the back door. If it's possible, try to create a small area of the garden or communal area where you can smoke well away from the back door.
If I reduce the amount I smoke I might put on weight.	You don't have to give up smoking completely to protect your child/children from second-hand smoke. People don't always put on weight when they stop or reduce smoking. Don't let the fear of weight gain keep you from making a positive change to a smoke-free home which will be beneficial for all of the family. Tackle one thing at a time, and remember it's a great achievement to create a smoke-free home. If you do end up gaining a few pounds during the process, you can lose them later on with the same determination you are using to create a smoke-free home. Regular moderate exercise and avoiding high calorie snacks should help you avoid putting on any extra pounds.

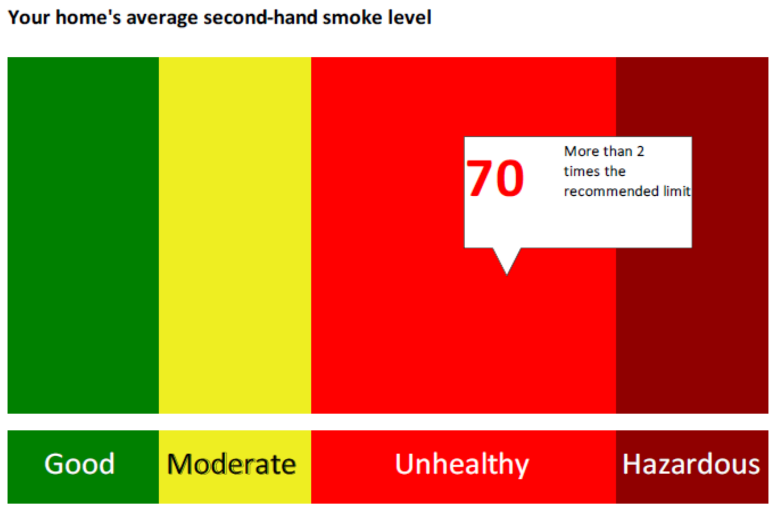
Adapted from the REFRESH How to Guide (2012): http://www.ashscotland.org.uk/media/458831/refresh_howtoguidecreate-a-smokefree-homejan12.pdf

AFRESH HANDOUT 2: EXAMPLE OF PERSONALISED FEEDBACK FROM A HOME WHERE SMOKING TAKES PLACE

The linked image cannot be displayed. The file may have been moved, renamed, or deleted. Verify that the link points to the correct file and location.

(Numerical values given show equivalent $PM_{2.5}$ concentrations in $\mu g/m^3$ as measured using a Dylos DC1700 Air Quality Monitor)

AFRESH HANDOUT 2: EXAMPLE OF PERSONALISED FEEDBACK FROM A HOME WHERE SMOKING TAKES PLACE (cont.)



Numerical values given show equivalent PM2.5 concentration in µg/m³ as measured using a Dylos DC1700 Air Quality Monitor. Categories are derived from WHO and US Environmental Protection Agency guidance levels. "Good" represents values below 25µg/m³, "Moderate" values from 25 to 55.4µg/m³, "Unhealthy" values between 55.5 and 250.4µg/m³ and "Hazardous" values above 250.4µg/m³.

(Numerical values given show equivalent $PM_{2.5}$ concentrations in µg/m^{3}as measured using a Dylos DC1700 Air Quality Monitor. Categories are derived from WHO and US Environmental Protection Agency guidance levels. 'Good' represents values below 25µg/m^3, 'Moderate' represents values from 25 to 55.4µg/m^3, 'Unhealthy' represents levels between 55.5-250.4µg/m^3 and 'Hazardous' represents values above 250.4µg/m^3)

AFRESH HANDOUT 2: EXAMPLE OF PERSONALISED FEEDBACK FROM A HOME WHERE SMOKING TAKES PLACE (cont.)

The linked image cannot be displayed. The file may have been moved, renamed, or deleted. Verify that the link points to the correct file and location.

AFRESH HANDOUT 3: YOUR GUIDE TO THE AIR QUALITY INTERVENTION

What is the air quality intervention?

Most parents know that second-hand smoke is dangerous and take steps to keep their children safe. But many people don't realise that smoke can hang around in the air for many hours, even though you can't see it or smell it.

If you use an air quality monitoring machine, you can count the invisible particles of smoke that are in someone's home and turn the information into a graph. That lets you see if there are sometimes dangerous levels of smoke in the air.

It also shows you when there aren't particles in the air. That means that if the air is mostly OK but sometimes has high levels of particles, you can focus on doing things to get the levels down when you need to.

What will happen during the intervention?

It's really easy to take part. You'll need to give a couple of answers to a short survey, and then someone from a local organisation will give you simple instructions on installing an air quality monitor in your house. The monitor is a small black box that you plug into the electricity, and just leave in the living room for five days. After that, you'll be able to unplug the monitor and bring it back to the centre staff.

An air quality monitor

A few days later, a worker from the organisation will talk to you about your results. They might let you know that there aren't high levels of particles in the air. If they show that there are high levels, the worker will talk with you about a few simple ways you can get the levels down. They'll also ask you a few more questions for a survey.

A few weeks later, the same worker will give you the monitor again, and you'll be asked to install it in your home for another five days. Once you've brought the monitor back to the centre again, the worker will be able to give you some information about how your readings have changed.

What is second-hand smoke?

Second-hand smoke is all the particles that go into the air when a tobacco product is burned. That means both smoke coming off the lit end of a cigarette, as well as smoke breathed out after taking a drag. Despite the name, it doesn't just mean the smoke you can see and smell – more than 85% of tobacco smoke is invisible and has no smell.

Why is second-hand smoke dangerous?

There are lots of dangerous chemicals in second-hand smoke. Around seventy are thought to cause cancer, while some cause diseases like glue ear, meningitis and cot death. These chemicals can quickly build to dangerous levels in a home or car, even after just one cigarette. And in a home, second-hand smoke can remain at dangerous levels for more than five hours. Levels can still be high everywhere in the home even if you open the windows or you only smoke in one room.

Why are children particularly vulnerable to second-hand smoke?

Children have small, growing lungs, and breathe more deeply and more quickly than adults. Because of this, they can suffer more from the effects of poisonous second-hand smoke. For that reason, it's important to keep children safe from second-hand smoke by never smoking inside the home or car.

What does the air quality monitor do?

The monitor counts tiny particles of second-hand smoke in the air. This "particulate matter" is known as $PM_{2.5}$. If there are news stories about high levels of air pollution in cities such as London or Beijing, $PM_{2.5}$ will often be the focus of the problem. It is only one of the many harmful components of second-hand smoke, but is fairly simple to test for in the air.

By using the monitor to measure the levels of $PM_{2.5}$ in a home, we can visualise these invisible particles into a graph over time. That lets us demonstrate the existence of dangerous second-hand smoke levels even when people might think a room is clear.

Why am I being asked to take part?

One of the workers at a local organisation thought you might be interested in trying the intervention out and seeing results in your home. There's no pressure, so don't worry if you wouldn't like to try the intervention at the minute.

AFRESH HANDOUT 4: PERSONAL SMOKE-FREE HOME ACTION PLAN

XXX's [insert name here] smoke-free home action plan

SECTION 1:

My general goal is to create a smoke-free home

My specific goal

- What am I going to do?

....
....
....

- How am I going to do it?

....
....
....

- With whom am I going to do it?

....
....
....

SECTION 2:

How will I know how I'm doing? It is important to measure and record your progress, as it motivates you when you are succeeding, and helps you work out what you can change if your plan isn't working.

- How will I record my progress?

....
....

- When will I record my progress?

....
....

We will chat about how you get on at our next meeting on [insert date/time here]

Parent signature .... Date ....

AFRESH HANDOUT 5: DIFFICULT SITUATIONS AND 'IF-THEN' PLANS

Difficult situations

- Are there any situations that you can think of that could make it especially difficult for you to create or maintain your smoke-free home? A time or a place or a feeling that might tempt you to go back to your old behaviour? For example: on a Saturday night when my friends are over, we just want to smoke indoors. Make a list of your difficult situations:
  ……………………………………………………………………………………………………
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Now make some **plans** for how to avoid these situations or make them more manageable. For each difficult situation, think of something you could do that would lower the chance of it interfering with your planned behaviour. For example, 'on a Saturday night when my friends are over, if they want to smoke in the kitchen, I'll remind myself that most people smoke outdoors now, rather than in the home. I'm putting my child's health first by asking them to smoke outside when they are here.' Fill in the table below with your difficult situations, and for each one, make an 'if-then' plan for coping with it.

Difficult situations	How I will avoid or cope with them
If...	**Then**…
• ………………………………………	………………………………………………
• ………………………………………	………………………………………………
• ………………………………………	………………………………………………
• ………………………………………	………………………………………………
• ………………………………………	………………………………………………
• ………………………………………	………………………………………………
• ………………………………………	………………………………………………

AFRESH HANDOUT 6: ENCOURAGING OTHER HOUSEHOLD MEMBERS TO ASSIST WITH CREATING A SMOKE-FREE HOME

Raising the issue

Most people respond well to requests for help, so don't be afraid to ask for support in helping to make the home smoke-free. These general tips may help you to raise the issue of making your home smoke-free:

Firstly, you should consider whether other household members are likely to be receptive to the conversation. Don't go ahead with the discussion if you feel very uncomfortable about raising the issue with others in your home.

Think about whether it's the right time and place to hold the conversation.

Listen carefully to other people's responses, and respond to their statements calmly, openly and without judgement.

Remind them that you are not asking them to stop smoking altogether, but to smoke outside rather than in the home.

Emphasise that children will only fully benefit if others in the household smoke outside too.

Sharing information

Parents often find it helpful to show other household members their personalised feedback graph, so that they too can see $PM_{2.5}$ levels in the home. Discussing the graph with other household members may be enough to persuade them to assist you with creating a smoke-free home.

You may also find it helpful to:

Share and discuss facts that are most relevant to household members from Handouts 1 and 2

Explain an advantage of other household members trying to smoke outside and ask them for any additional advantages they can think of

Ask family members what they think/feel about their smoking in the home

Encourage other household members to reflect on the impact of their smoking behaviour on the well-being of others in the household.

Overcoming family barriers to creating a smoke-free home

Some household members may talk about barriers that they have to assisting with creating a smoke-free home. In some families, for example, not everyone understands or believes the health risks to children from second-hand smoke in the home. In other families, smoking in the home is something that parents or grandparents may have done for years, and breaking a habit like this can be hard to contemplate.

You will have already discussed potential family barriers, and identified possible solutions to overcome them, with your care professional. If you have thought of any new barriers since this discussion, try and identify some possible solutions yourself.

Rehearse methods of dealing with family barriers. This will increase your confidence about having the discussion with other household members. It also gives you the opportunity to practice your responses to questions that family members may have.

Ask family members if there is anything preventing them from making changes, and help them to come up with their own solutions to assist with creating your smoke-free home.

Most barriers can be overcome, especially when possible solutions are discussed together. However, if it becomes clear that other household members are unable or unwilling to assist you in creating a smoke-free home, then do the best **you** can to reduce second-hand smoke levels, by continuing to take your own smoking outside. If family members see you sticking to your goal, they may change their mind.

Planning for a smoke-free home together

If other household members are able to assist you in creating a smoke-free home, talk with them about how they will achieve this. They may want to complete their own personal action plan, and you may want to encourage them to develop their own 'if-then' plans. Monitor your progress together, discuss any setbacks as they arise, and praise successes.

Asking visitors for their support

Have a think about strategies for asking visitors for their support in making the home smoke-free in just the same way as you have done with family members. Reinforce your decision to create a smoke-free home by having a no-smoking sticker in the home, or by the door to remind visitors.

AFRESH HANDOUT 7: QUITTING SMOKING

Why quit?

Stopping smoking is the single most important thing a smoker can do to improve their health and will immediately reduce risk of heart disease, cancer, stroke, diabetes, rheumatoid arthritis and dementia. In addition, a 20-a-day smoker paying £7.50 a packet will save over £2700 a year.

What tools can help me quit?

You can use lots of different tools to help you quit smoking. Different things work for different people, so if you've already tried one or more of the products listed below, why not try something you've not used before:

Nicotine therapies, such as chewing gum, patches, lozenges and inhalers can be provided free by NHS stop smoking services

Your GP may be able to prescribe stop smoking medicines

Some people have used e-cigarettes to help them quit. We don't know how effective they are, but some users have found them helpful.

What else can I do?

Stop smoking services offer your best chance of quitting smoking. Get the best help:

Phone Smokeline on **0800 84 84 84** 8am – 10pm 7 days a week

Visit www.canstopsmoking.com for help, information or to web chat with an advisor

Make an appointment with your GP who can refer you to your local stop smoking service

Visit your local pharmacy to talk to your pharmacist about quitting

Appendix IV - Using air quality monitoring to reduce second-hand smoke exposure in homes: the AFRESH feasibility study

This appendix comprises the text of a paper on the AFRESH intervention (chapter 5) as published in Tobacco Prevention & Cessation. This paper can be cited as:

> *Dobson R, O'Donnell R, de Bruin M, et al. Using air quality monitoring to reduce second-hand smoke exposure in homes: the AFRESH feasibility study. Tob Prev Cessat 2017;**3**. doi:10.18332/tpc/74645*

Abstract

Background

Few interventions to reduce second-hand smoke in homes where children are present have been successful. A novel intervention was developed which included personal air quality feedback. This study aimed to evaluate the feasibility and acceptability of delivering this theory-based intervention through small third sector organisations in deprived areas within Scotland.

Methods

The setting was third sector organisations in Scotland. Support workers used air quality monitors to give information on smoke-free homes to parents. This advice was structured around computer generated reports, co-developed with workers and target group members. Participants received a monitor then received a report, which was discussed with a support worker. Two weeks later, the monitor was reinstalled and another report produced to evaluate success. Three participants and one support worker were interviewed afterwards to explore their experiences.

Results

One centre out of six approached agreed to deliver the intervention. Four participants took part. All participants saw a decline in average concentrations of $PM_{2.5}$ in their homes. In

interviews, the participants and the support worker indicated that the intervention was acceptable and useful. The centres which declined to participate in the study cited a range of reasons including a lack of staff time and perceived difficulties in recruiting members of the target population.

Conclusions

This intervention was acceptable for the target population tested, and may help participants to create smoke-free homes, although it is not possible to generalise the results of this small study. However, the resources required for the delivery of AFRESH do not match with the resources available in third sector organisations, despite smoke-free homes being a policy priority.

Introduction

Second-hand smoke (SHS) exposure is a serious cause of ill health for children, contributing to illnesses such as meningitis, respiratory infections and sudden infant death syndrome. Worldwide, it is estimated that more than 40% of children are regularly exposed to second-hand smoke in the home.[1] Second-hand smoke can persist indoors at potentially harmful levels for long periods following even one cigarette.[2] Reducing this exposure is a public health challenge which has been embraced by policymakers and regulators.[3,4] However, there are few interventions that are effective in reducing SHS in deprived households with children.[5]

Fine particulate matter ($PM_{2.5}$) is a significant component of indoor air pollution, and has been widely used in tobacco control research as a marker for the presence of SHS. [6] Indoor air quality monitoring and feedback has therefore been explored as a potential motivator in interventions to encourage parents to keep smoke-free homes.[7–9] However, there is currently little evidence of interventions which have solid theoretical foundations in behaviour change theory.

AFRESH (Finding Ways to Reduce Second-hand Smoke Exposure in Homes), a novel intervention to promote smoke-free homes, was developed using intervention mapping [10] to systematically develop a theory- and evidence-based behavioural intervention to reduce second hand smoke in deprived households with children, with air quality feedback as a central component of the behavioural strategy. The full description of the intervention and its development process will be published separately.

The aim of this study was to evaluate the feasibility and acceptability of delivering this theory-based intervention through small third sector organisations in deprived areas within Scotland. While previous research in this area has relied on researchers providing air quality information to participants [7], this study gave full responsibility to non-technical staff, thus testing the feasibility of the intervention in a real-world setting.

Methods

AFRESH Intervention

The AFRESH intervention is designed around the delivery of personalised air quality information to parents from deprived settings who do not live in smoke-free homes. The intervention is designed to be delivered by support workers employed by third-sector organisations, therefore widening the potential group of people who can deliver it from researchers and healthcare workers as used in previous research.[7] The intervention is designed to be simple to deliver, to use a low-cost monitor and is structured around a series of modules and contacts between the worker and the parent: full details are available in the supplementary material.[11]

For this feasibility study, third sector community centres were invited to take part, with their support workers receiving training on the intervention from the research team. Parents with a child under the age of six living in a smoking home were invited to participate in the intervention by a support worker. Following informed consent, the participant was given information about SHS by the third party worker and provided with an air quality monitor to place in their home for approximately five days. Following the measurement period, the monitor was returned to the worker who prepared an air quality report. Custom software [12] developed for AFRESH was used to facilitate the support worker in download and processing data and the preparation of air quality reports.

This report was given to the participant, and used as a focus to discuss planning for a smoke-free home with the worker. These discussions included techniques to talk about the issue of SHS with other smokers and support to quit smoking entirely.

Two weeks later, the monitor was returned to the participant's home for another five day period. A second report was produced including a comparison sheet (Figure 1). The worker and participant then discussed successes and challenges in keeping a smoke-free home.

Ethics

Ethical approval was provided by the College Ethics Review Board of the College of Medicine and Life Sciences of the University of Aberdeen.

Recruitment

A target of 20 intervention participants between two third sector centres was set at the beginning of the study, which was believed to be attainable based on previous work in this setting and in line with the literature on good practice for feasibility studies testing intervention efficacy[13].

Community centres were approached to take part through pre-existing relationships with research staff. These third sector organisations employed workers in direct contact with members of the target population.

Training

Support workers taking part in the intervention were trained over two to three hour sessions. The first gave information about SHS and its effects on health and air quality, while the second gave information about the intervention. Following this session, an online course was developed to allow others to use the intervention.[14]

Analysis

The primary outcome measure for intervention efficacy was change in average $PM_{2.5}$ measured in each home following the intervention. Secondary outcome measures included self-reported changes in smoke-free home rules and both participant and staff experiences of using the intervention.

Qualitative interviews

Up to 10 parents were to be invited to take part in an individual telephone interview at the end of the intervention to explore their experiences of taking part, and the impacts of the feedback they received on their smoking behaviour in the home. Support workers were also invited to take part in interviews at the end of the intervention, to explore their experiences of intervention delivery. These interviews used a semi-structured format.

Results

Recruitment

One of the six centres invited to take part agreed to participate. In this centre, four participants were recruited and three of these participated in qualitative interviews. Five centres declined to take part for several reasons: staff turnover (n=1), lack of staff time (n=2), inability to recruit sufficient members of the target population (n=2), and the perceived intrusiveness of the intervention (n=1) were cited (with one centre giving multiple reasons for declining to participate).

Quantitative results

Average household $PM_{2.5}$ levels were lower in all four homes following the intervention, but the small sample size precluded statistical significance.

Baseline measurements took place for between 5 days, 26 minutes and 6 days, 6 hours & 22 minutes, while follow-up data was measured for between 3 days, 23 hours & 53 minutes and 5 days, 7 hours & 15 minutes. While the programme materials suggested carrying out follow-up measurements two weeks after the end of the baseline measurement, in practice follow-up measurements began 18-39 days later (mean 28 days).

Mean measured $PM_{2.5}$ was 80.5µg/m^3 (range 11-239µg/m^3) at baseline and 66 µg/m^3 (range 6-201µg/m^3) at follow-up. Reductions of average $PM_{2.5}$ over this period ranged from 2-38µg/m^3, but no home which had average $PM_{2.5}$ measured above the WHO guidance level at baseline had an average concentration below this value at follow-up.

Qualitative results

Parent perceptions of the intervention

Three of the four participants consented to take part in a semi-structured telephone interview, conducted by a member of the research team, to discuss their experience of the intervention.

Changes to smoking behaviour were noted by two participants as a result of their personalised feedback; one had started smoking outside instead of indoors; a second was smoking inside, but now with the window open. The third had moved home between measurements, and was now smoking outside as smoking inside her new flat was prohibited as part of the rental agreement.

Parents stated that the intervention was acceptable, and found the air quality feedback reports understandable and meaningful:

> "*The graphs were quite understandable. It showed me the peak times [when SHS was highest]. It was very accurate too – I could see when I was smoking in the home and it was right"*

When asked about benefits of taking part, all three commented on knowledge they had acquired through participating, for example:

> *"I've noticed that it [SHS] does linger longer than I thought it did. So when I come down in the morning, it's all clear [the air], but the machine says not."*

> *"Now I know that it can make a difference to your kids if you don't smoke in the home. It's basically not normal to smoke around your children."*

> *"I've learnt that second-hand smoke is more harmful to kids than it is to adults. And that second hand smoke can cause asthma in children – I thought you were just born with it."*

Worker perceptions of the intervention

The support worker was also interviewed about their experience of delivering the intervention. They valued the training received prior to conducting the intervention, and highlighted the importance of existing relationships with parents to aid recruitment. They spoke of capacity issues limiting recruitment given they became the sole worker on the project within their organisation:

“*we could have managed more[participants] if we had someone else doing* it.”

However, the staff member felt the intervention itself was feasible and that feedback reports had the potential to change smoking behavior in the home, *“especially with those that were high levels, because you could see that they were quite shocked with it, and it was interesting, just that graph and all the different colours and stuff. The colours really helped actually.”*

They considered that the intervention would be

“*easy to integrate into our practice…I think the only thing would be the staff capacity.”*

Discussion

Recruitment of centres

The main finding from this study was that recruiting centres to take part was problematic. The multi-step nature of the intervention was perceived to be excessive for reasons which include having too great an impact on staff time. Carrying out one intervention requires between five and seven contacts between a worker and a participant. This can involve travel to the participant’s home or another location, potentially taking more time. Even centres which initially expressed eagerness to take part were sometimes unable to do so, reflecting the high workload, limited resources and short-term funding cycles of the third-sector organisations approached. Expense could be another factor constraining the use of the intervention. The cost of purchasing the relatively inexpensive Dylos DC1700 can exceed £400 GBP (500 USD), a substantial sum for a small organisation. Staff time would represent an additional cost - assuming an hour per contact paid at the median UK hourly wage (£11.78 in 2015),[15] this would range from £58.90 - £82.46 per intervention. These costs would not apply where air quality monitoring equipment was already available, or in countries where labour costs are substantially lower than in Scotland.

The perceived inability to recruit smoking parents was unexpected since our previous experience is that many clients attending centres such as those invited to take part are regular smokers. Better-funded statutory bodies or recruiting participants directly may ameliorate these issues. The challenge in recruiting community “champions” is an important message for future studies and suggests that specific staff dedicated to smoke-free homes interventions are required rather than seeing this as an ‘add-on’ to the already high workload of support staff or support workers dealing with parents in deprived settings. Contacting potential partner organisations further in advance than the timeline of this study permitted, or providing them with financial compensation for engaging in the intervention programme, may improve participation rates.

Feasibility of the intervention

This feasibility study demonstrated that while the AFRESH intervention could be delivered by third-sector organisations working with individuals in low socioeconomic groups the difficulties in doing so are substantial. Participants could understand, interpret and accept the results of air quality monitoring and, as with previous studies,[7] this may assist in encouraging changes to smoking behaviours.

All participants experienced reductions in average household $PM_{2.5}$ concentrations at follow-up measurements though some changes were small. Carrying out the follow-up stage of the intervention repeatedly over a longer period may motivate participants to continue making changes, and provide evidence of the effectiveness of the different elements within the AFRESH programme.

Conclusions

Overall, those participants and workers who took part found the AFRESH programme acceptable and useful, but difficulties recruiting centres to take part would make the programme impossible to use widely in its current form. SHS levels fell modestly in all four homes, although the small sample size made statistical analysis of this decline impossible. Working with small community-based third sector organisations presents practical and logistical challenges and these would be a significant barrier to using this model widely to promote smoke-free homes. Future research should focus on efforts to reduce the time and number of home visits or face-to-face contacts required to deliver the programme to those who express interest.

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Appendix V - Monitoring second-hand tobacco smoke remotely in real-time: a simple, low-cost approach

This appendix comprises the text of a paper on the development of the RAPID monitoring system (chapter 6) in Tobacco Induced Diseases. This paper can be cited as:

> *Dobson R, Rosen L, Semple S. Monitoring secondhand tobacco smoke remotely in real-time: A simple low-cost approach. Tob Induc Dis 2019;**17**. doi:10.18332/tid/104577*

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Abstract

Introduction

Second-hand smoke (SHS) in the home is a serious cause of ill-health for children. SHS indoors can be indirectly measured using particulate matter monitors, and interventions have been developed using feedback from these monitors to encourage parents to keep their homes smoke-free. These interventions often use data which is several days out of date, as it must be downloaded manually from monitors. It would be advantageous to access this information remotely in real-time to provide faster feedback to intervention participants.

Methods

Using off-the-shelf computer components and the Dylos DC1700 air quality monitor, a portable internet-connected monitor was developed which could send data to a server remotely. Four of these monitors were tested in homes in Israel to test the reliability of the connection. Data was downloaded from the monitor's onboard memory and compared to the data sent to the server.

Results

Eight homes were monitored for between four and six days, with a combined total count of 44 days. Less than 1% of data was lost, with no outage lasting longer than one hour 45 minutes. There was no significant difference in the mean concentrations measured in homes between mobile-transmitted data and data downloaded directly.

Discussion

This system appears to be a reliable way to monitor home air quality remotely for use in intervention studies, and could potentially have applications in other research. Labs which own Dylos DC1700s may wish to consider converting them to such a system a cost-effective way of overcoming limitations in the Dylos design.

Introduction

Second-hand smoke (SHS) in the home is a cause of indoor air pollution and a serious health risk for children [1]. Interventions have been designed and trialled using air quality feedback to encourage parents not to smoke indoors [2–6].

These interventions have generally involved the use of feedback generated after monitors have been retrieved from homes, leaving a gap between the smoking behaviour and the resulting feedback [4,7]. It may be valuable to deliver this feedback more quickly to demonstrate the positive effect on household air quality on the reduction of smoking.

Previous research by our group [5,8] and others [9,10] has used the Dylos DC1700 (Dylos Inc, CA, USA) successfully to monitor fine particulate matter ($PM_{2.5}$) as a surrogate for SHS. The Dylos is a relatively inexpensive and widely used optical particle counter, considered to be well-suited for monitoring in homes. However, it has no internet capability and has numerous other limitations, including a small internal memory with a maximum data capacity of just over six days.

Now with the advent of the “internet of things” [11] networked monitors can provide a similar function, reporting data over the internet and allowing analysis and feedback in real-time, even when a monitor is still on site. However, these monitors are of variable quality and are generally dependent on a local WiFi connection rather than sending data over a mobile network [12]. A device that can use a local mobile phone signal instead can be installed more quickly, avoids the security implications of connecting to a study participant’s home network and does not rely on the presence of a fixed internet connection (important in lower socioeconomic status households in the developed world and in the global south).

It was decided to develop a prototype networked monitor based on the Dylos DC1700, using commercially available components. This monitor would send Dylos data to a website via mobile internet access, allowing real-time access and feedback on air quality in the home.

Materials and methods

System design

The Raspberry Pi computing board [13] is a small (87.1mm × 58.5mm) inexpensive computer (currently retailing for approximately 33 GBP), useful for embedded computing, particularly where manufacturing a new device would be unnecessary, undesirable or unaffordable. While small, the computer can run sophisticated, modern software in a manner similar to a PC. To allow connections to the internet, the latest model, the Raspberry Pi 3 B, comes equipped with both an Ethernet port and a WiFi chip.

As it clearly suited our needs, the Raspberry Pi was selected to form the computing portion of our monitor. For identification purposes, the combined monitoring system has been named “RAPID” (a combination of the terms “Raspberry Pi” and “Dylos”).

Although the Raspberry Pi does not include a method of accessing the internet over the mobile phone network, devices are available off the shelf which allow it to do so. This would allow for a wholly autonomous monitor which would require only electrical power to send data for as long as required. For our purposes Huawei wireless access equipment (Huawei Technologies Co. Ltd.) was selected, as it is widely available and compatible with the Raspberry Pi.

The Dylos DC1700 is a direct-reading low-cost optical particle counter, a class of instruments which detect light scattered by a laser to estimate particle size and number in the air [14]. The Dylos estimates counts of particles larger than 0.5µm in diameter (total particle count) and particles larger than 2.5µm in diameter (large particle count) per 0.01 cubic feet of air taken in [8]. In addition to recording them in its internal memory, the Dylos DC1700 reports these particle counts each minute over a 9-pin RS232 serial port in the following format:

<total particle count/100>,<large particle count/100><end of line>

These data can be converted to an estimated $PM_{2.5}$ concentration through the use of a pre-existing equation [15].

By design, particle count data can be read each minute by a computer using a serial cable. The Raspberry Pi does not have a serial port, so a USB-Serial converter cable was used. Previous experience has determined that those cables containing an FTDI conversion chip are most reliable, so these cables were selected for this project.

Software to record, convert, send, receive and store air quality data was developed using the Python 2.7 programming language [16]. The PythonAnywhere cloud programming service [17] was used to host the website to receive data and store it in a database. Source code and further information on the RAPID system has been made available online by the authors [18]. Source code is available under an open source and free software licence.

Monitor production

Four RAPIDs were produced using four Dylos DC1700 monitors, four Raspberry Pi 3 computers and four 16GB microSD cards. For mobile internet access, three Huawei E5330 MiFi units and one Huawei E3533 wireless dongle were used, along with SIM cards for Israel's Partner mobile network. The total cost of the component parts to 'retrofit' a Dylos DC1700 device to a RAPID was approximately 98GBP each (excluding SIM cards).

RAPIDs were produced as follows. A microSD card loaded with a Raspberry Pi-compatible operating system (Raspbian Linux) was installed in the Raspberry Pi. The custom RAPID software was then installed and set to launch as soon as the Raspberry Pi was powered on. This software was set to send data to a server running custom software designed to store the information in a database, and a unique identifier was given to the RAPID to ensure that data could be downloaded reliably later.

The Raspberry Pi was then connected to a mobile internet device and (if applicable) the WiFi network name and password were saved. The Dylos was powered on and plugged in to the Raspberry Pi using the serial-USB cable, and the Raspberry Pi was restarted to check that the completed device functioned.

Installation in homes

The four RAPID monitors were installed in eight homes during July and August 2017 for periods between four days and 18 hours to six days and six hours (the maximum memory capacity of the Dylos) at a time, depending on participant availability. Installation took place at variable times of the day. Monitors were installed in the main living area of the home (the living room or, in one case, a kitchen used as the main living space). Monitors were placed at least 30cm from walls, at least 30cm above the floor and as far as possible from windows (depending on the placement of electrical sockets in the room). Ethical approval was provided by Tel Aviv University Ethics Committee.

Data analysis

Data from the Dylos's internal memory and the RAPID system were compared to test the reliability of the internet connection system. Following a period of monitoring in each home, data was downloaded conventionally from the memory of each Dylos. These data were cleaned and compared to the data received and stored on the internet using the RAPID system over the same time period.

Outcome variables were the arithmetic mean and median $PM_{2.5}$ concentrations in each home using each method of data retrieval. Wilcoxon signed-rank tests were carried out to compare the mean and median $PM_{2.5}$ concentrations recorded by each method, to determine whether significant data were lost by using the RAPID server-based data retrieval method compared to the onboard memory of the Dylos. Additionally, Spearman correlation coefficients were calculated for mean and median concentrations derived from each retrieval method. IBM SPSS Statistics software was used to conduct statistical tests [19].

Results

$PM_{2.5}$ in smoking and non-smoking homes

Monitoring took place in two homes in Haifa, two in Jerusalem, three in Tel Aviv and one in Be'er Sheva. Four homes were inhabited by smokers who reported that they lived indoors, while four reported no smokers.

Results from homes are available in Table 1. Smoking homes had higher mean and median concentrations of $PM_{2.5}$, but no significant difference was detected in a Mann-Whitney U test ($p=0.686$ in means, $p=0.486$ in medians). This may be due to the small sample of homes in which data was collected.

Table 1 – Mean and median $PM_{2.5}$ concentrations detected using the RAPID system in homes where smoking was and was not permitted, and geometric means of arithmetic mean and median $PM_{2.5}$ concentrations.

Home ID	Smoking status	Mean $PM_{2.5}$ concentration (μg/m^3)	Median $PM_{2.5}$ concentration (μg/m^3)
BE_03	Smoking permitted	82.01	13.92
HA_04	Smoking permitted	30.85	15.32
JE_03	Smoking permitted	7.10	6.05
TA_04	Smoking permitted	7.10	6.33
HA_01	Non-smoking permitted	9.27	7.75
JE_05	Non-smoking permitted	8.08	6.89
TA_01	Non-smoking permitted	6.77	6.21
TA_02	Non-smoking permitted	7.14	5.90
All smoking permitted homes		18.90	9.51
All non-smoking permitted homes		7.76	6.65

RAPID system testing

Averaged over the eight homes, 0.57% of data was lost when using the RAPID system compared to the Dylos onboard memory – equating to six hours and eight minutes of data lost over 44 days of measurement. No more than 2.4% was lost in any monitoring period, while the longest single period of data loss was 1 hour 45 minutes.

The close relationship between mean PM concentrations from the remote server and the Dylos local memory can be seen in Figure 1, a Bland-Altman plot of the differences between each measurement. Using Wilcoxon paired-rank tests no significant difference was detected between the means or medians collected using the RAPID and the onboard memory of the Dylos (p=0.327 and p=0.093

respectively). Spearman correlation coefficients showed near-perfect relationships between RAPID and Dylos data for both mean and median concentrations (ρ = 1.000 and ρ = 0.929 respectively).

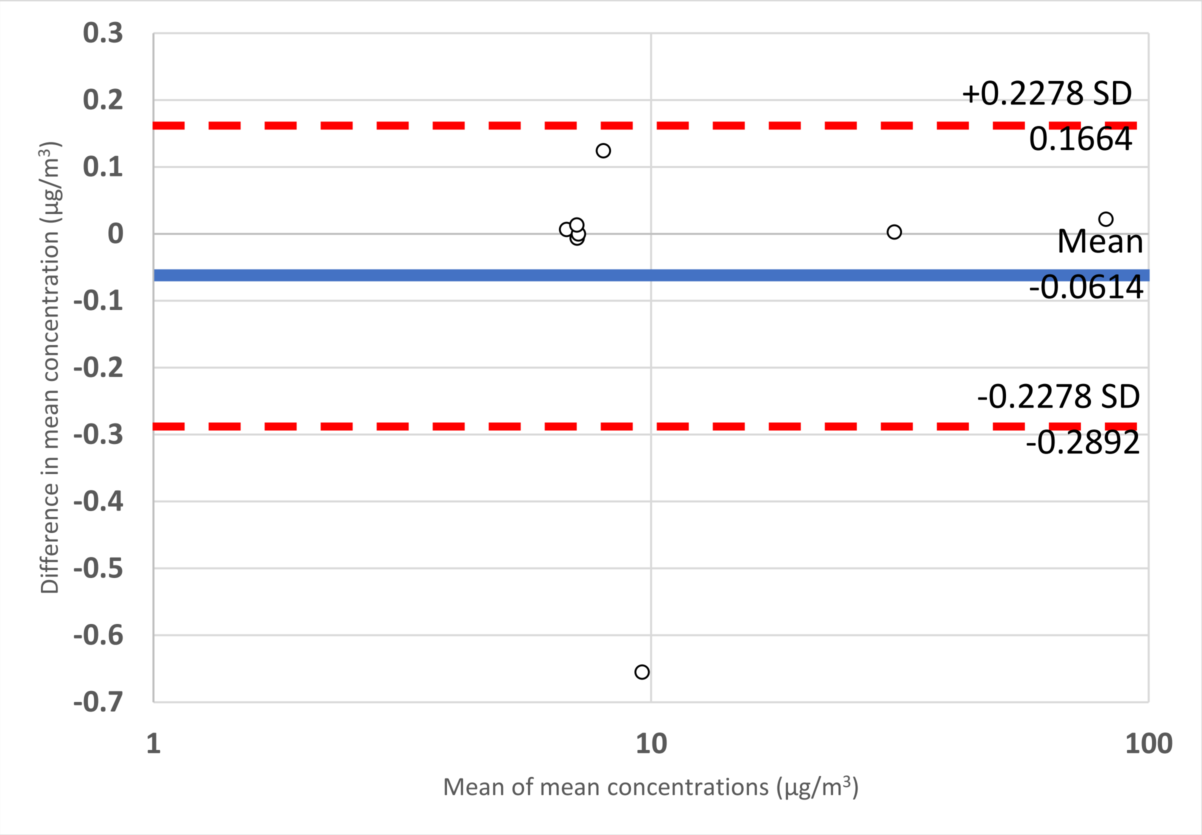

Figure 1 - Bland-Altman plot of mean concentrations from Dylos and RAPID against the differences between each measure (n=8). Note the logarithmic scale used on the x-axis to account for the wide range of measurement values.

Discussion

The results show that it is possible to use low cost monitors combined with inexpensive, off-the-shelf consumer technology to reliably monitor $PM_{2.5}$ in real-time in homes. This technology could be adapted for use in smoker behaviour modification interventions with relative ease.

Advantages

Data obtained from the online server using the RAPID system were highly reliable when compared to conventional Dylos onboard memory records, demonstrating that little information was lost when being sent over the internet.

The components used to make the RAPID are widely available and inexpensive, and could therefore be accessed in many settings. The Dylos DC1700 has been widely used and research groups with existing monitors could 'retrofit' their Dylos devices into RAPIDs for lower cost than purchasing a new monitor with these features.

The core Raspberry Pi software could be customised to incorporate other monitors and sensor technology, such as humidity and temperature sensing.

Disadvantages

Although errors were rare, they did occur, and could be more common in areas with poor mobile network coverage. This could be remedied by the option of connecting the RAPID to a conventional home WiFi connection.

Due to the short design period, the software used in this version of the RAPID suffered from a number of bugs which could have contributed to data loss. More recent unpublished research using these devises have resulted in substantially improved reliability.

Data loss may have occurred due to temporary failure of the mobile connection equipment or a slow internet connection (causing the RAPID software to "time out" the connection with the remote server rather than remain connected indefinitely, pausing data recording). Updates made to the RAPID software following the study period allow the system to store and re-send data which did not reach the server due to a failed internet connection.

The present form of the RAPID has used 'off-the-shelf' components and a number of connecting cables. The RAPID can therefore be disabled if a component is accidentally disconnected. This may not be obvious to the participant in a study due to the complexity of the device. Future work could easily remedy these problems by designing an enclosure for the Raspberry Pi and wireless access components of the device.

It should be noted that the Dylos DC1700, like all similar monitors, cannot specifically identify the source of $PM_{2.5}$ it detects. Even with the addition of RAPID components and functionality the monitor can only be used to detect $PM_{2.5}$ as a proxy for SHS. This could be advantageous if the equipment is to be used in other settings – for instance, for monitoring household air pollution or biomass smoke – but should be considered in the design of studies monitoring exposure to SHS. Other methods of recording information about indoor air pollution (such as diaries and data from monitoring stations on outdoor air) should be considered when using the RAPID to mitigate against this disadvantage. Additionally, it may be possible to use features of the particle size distribution of SHS (which predominantly consists of particles of 0.2-0.25μm in diameter [20]) to detect SHS with better specificity [21].

Summary

Monitoring SHS remotely in real time is feasible without a large financial investment. This holds potential for intervening to reduce exposure to tobacco smoke and for research.

Declaration of interests

None.

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Appendix VI - Measuring for Change data collection instruments

This appendix collects data collection instruments used in TackSHS Measuring for Change (chapters 6 & 7):

- initial recruitment questionnaire & stage of change assessment
- baseline questionnaire
- day 9 stage of change assessment
- day 23 stage of change assessment
- follow-up questionnaire

Initial recruitment questionnaire and stage of change assessment

Assessing eligibility to take part in 'Measuring for Change' (WP4) *(Use during initial contact call to confirm suitabilty to participate)*

Participant initials: **Date:**

Postcode: **SIMD quintile:**

Email:

Address:

Mobile:

Voucher:

Please circle one response for each of the following questions:

	Eligible to take part	Not able to take part
1. Are you 18 years of age or over?	**YES**	
2. Are you taking care of one or more children (16 years or under) in your home at least once per week?	**YES**	
3. Are you planning to move house within the next 1-2 months?	**NO**	
4. Do you have a mobile phone, email address and regular access to the internet?	**YES**	

Assessment of stage of change and potential opportunity to create a smoke-free home

5. Do you think that your smoking behaviour in the home is a problem for you, or anyone else at the moment?

☐ Yes (*contemplation, preparation, or action stage*; **go to Question 2**)

☐ No (*maintenance or precontemplation stage, which does not fit with the inclusion criteria for taking part in the study*)

6. When do you think you might change your smoking behaviour in the home?

☐ Some day *(contemplation stage)*

☐ Not soon *(contemplation stage)*

☐ In the next few months *(preparation stage)*

☐ I'd like to do something about it now *(action stage)*

7. Thinking about some of the potential barriers to making your home smoke-free such as other people you live with who smoke, or having an outside space to go to if you wish to smoke, on a scale of 0-10, how realistic do you think it would be to:

a. Make your home smoke-free in the next 2 months? (where 0=not realistic at all, and 10=extremely realistic)

Write value here: _

b. Reduce the amount of second-hand smoke in your home in the next 2 months? (where 0=not realistic at all, and 10=extremely realistic)

Write value here: __

8. *Tell us more about the scores you've just given us. Why have you chosen these numbers?* (find out about barriers and decide whether they can be overcome within the timescales of the study)

____

Partcipant number (if all inclusion criteria are met): ______

Baseline questionnaire

Measuring for change: air quality feedback to reduce SHS exposure in the home

Baseline questionnaire

Personal information

Name: ____

Address: ____

________________________ Postcode: ____________

Phone number: ____

Email address: ____

Do you have home internet access? ☐ Yes ☐ No ☐ Only through a mobile phone

CHOICE OF SHOPPING VOUCHER:

General information

Is your home

- a detached house ☐
- a semi-detached house ☐
- a terraced house ☐
- a flat ☐
- If your home is a flat what floor do you live on? __________

Does your home have

- a private garden ☐
- a shared garden ☐
- no garden space ☐
- a balcony ☐

Is smoking allowed inside your home (tick all that apply)?

- Smoking is not allowed ☐
- Smoking is allowed in certain places only ☐
- Smoking is only allowed when no children are present ☐
- Smoking is only allowed on special occasions ☐
- Smoking is only allowed when children are in bed ☐
- Smoking is only allowed when the weather is bad ☐

Smoking is allowed anywhere in the home ☐
Other (please specify) ☐ ______________________________

Do you currently own a car? (Y/N)

Can you tell us about the people you share your home with and if they smoke please estimate how many cigarettes, *on average*, they might smoke in the home each day?

Person Number	**Relationship to You**	**Average number of cigarettes they smoke in the home each day** (Tick appropriate box)
1		Non-smoker ☐ < 5 ☐ 5 - 10 ☐ 10 – 20 ☐ > 20 ☐ Don't know ☐
2		Non-smoker ☐ < 5 ☐ 5 - 10 ☐ 10 – 20 ☐ > 20 ☐ Don't know ☐
3		Non-smoker ☐ < 5 ☐ 5 - 10 ☐ 10 – 20 ☐ > 20 ☐ Don't know ☐
4		Non-smoker ☐ < 5 ☐ 5 - 10 ☐ 10 – 20 ☐ > 20 ☐ Don't know ☐
5		Non-smoker ☐ < 5 ☐ 5 - 10 ☐ 10 – 20 ☐ > 20 ☐ Don't know ☐

How many children aged 16 or under live in your home? ___________

If smoking is allowed in certain places only, could you tell us where (tick all that apply)?

Kitchen/utility room	☐	Living room/lounge	☐
Dining room	☐	Your bedroom	☐
Attached garage	☐		
Other (please specify)	☐ ____________________________		

8. Have you ever considered making your home smoke-free before? (Y/N) [If no, why is that, if yes, how did it go/what led to smoking being allowed in the home again?)

9. To what extent do you agree or disagree with each of the following statement about smoking? Please tick one box for each statement.

	Strongly agree	**Agree**	**No strong opinion**	**Disagree**	**Strongly Disagree**
Inhaling other people's tobacco smoke poses a high risk to health					
I would challenge someone smoking in a non-smoking area					
The dangers of inhaling other people's tobacco smoke are greatly exaggerated					
I would ask someone who smokes to smoke outside of my house					
Children are more at risk from other people's tobacco smoke than adults					
Exposure to other people's tobacco smoke can increase the severity of asthma in children					
Other people's tobacco smoke can cause significant problems for children					

10. When we telephone you to see how you're doing (days 9 and 23), would you prefer us to call in the morning, afternoon, or evening? Is there any day of the week that doesn't suit you for taking these phone calls?

11. Finally, can I just check, what would be the best number to ring you on? (make a note of the telephone number here).

Thanks very much for your help today.

Date Completed: ____________________________

Name of Researcher: ____________________________

*** For researcher use only ***

Participant ID: ____________________________

Day 9 call stage of change assessment

NOTES: TELEPHONE CALL 1 – DAY 9

Materials required:

Completed baseline questionnaire from first home visit
Participant's air quality data
(You may also want to have the AFRESH 'Handout 7: Quitting smoking' handy, and the other AFRESH handouts/factsheets if required)

Participant number: Date of phone call:

1. Introduction

This telephone call will last no longer than 15 minutes. You can ask any questions, at any time during this conversation, and you can finish the interview, without having to give a reason why, at any point. We are going to talk more about your air quality feedback, but first:

Can I check, have there been any problems with having the air quality monitor in the home since the air quality machine was installed?

☐ YES (if yes, make a note of the problems and try and resolve them)

☐ NO

Have there been any changes to who is living in your house since the air quality machine was installed?

☐ YES (if yes, make a note about these changes)
☐ NO

Have you received the text (and email graph) feedback and have had a chance to look at these?

☐ YES
☐ NO (if they haven't received them, check you have the correct email and

mobile telephone number for them, and resend the feedback. If neccessary, run the telephone call and explain their findings to them without them seeing the graph, but ensure that they receive it after the call has ended).

2. Air quality levels in your home over the last week:

Your daily average from the last text message was: ____

Your overall average measured over the past 7 days (as given in the email on day 8) was: ___

The average level in a smoke-free home in your area is ___. (*Compare this with the participants' levels. Are they better, worse, or about the same?*)

Mention variation between days.

If SHS exposure is clear then pick out 1 or 2 specific times to highlight as being particularly smoky. Also pick out specific times where levels are low.

If SHS exposure is not obvious:

Are there times you can remember when smoking has taken place in their home? ***Look to see if this matches with the graph.***

3. Discuss current strategies in place for reducing SHS exposure in the home *(Have to hand the information about current strategies obtained from the baseline survey)*

Can I just double check the steps that you're currently taking to protect their child/children from SHS. When XX visited you to install the air quality monitor, you mentioned that you're (insert strategies here)...........Is this information still correct?

☐ YES

☐ NO (If no, establish what changes have been made, and why)

If the parent uses ineffective strategies:

> ***Ensure the parent understands why these are ineffective, and address any misconceptions they may have.***

Have you taken any additional steps to reduce SHS in your home since the monitor was installed?

☐ YES *(Make a note of the additional steps have been taken)*

☐ NO

If they have taken additional steps:

> ***Ask whethere these changes have been made successully, and make a note of the changes***
> ***Ask whether they are seeing any benefits in making the changes identified, and make a note any outcomes.***

4. Assess stage of change and opportunity for change:

Do you think that your smoking behaviour in the home is a problem for you, or anyone else at the moment?

☐ YES (*contemplation, preparation, or action stage*; **go to Qs 4b-6**)

☐ NO (*maintenance or precontemplation stage*, **go to question 7**)

FOR CONTEMPLATION, PREPARATION OR ACTION STAGE PARTICIPANTS ONLY

When do you think you might change your smoking behaviour in the home?

☐ Some day *(contempation stage)*

☐ Not soon *(contempation stage)*

☐ In the next few months *(preparation stage)*

☐ I'd like to do something about it now *(action stage)*

Thinking about some of the potential barriers to making your home smoke-free such as other people you live with who smoke, or having an outside space to go to if you wish to smoke:

On a scale of 0-10, how realistic do you think it would be to make your home smoke-free in the next 2 months? (where 0=not realistic at all, and 10=extremely realistic)

Write value here: ____

5. Barriers and solutions to creating a smoke-free home

Tell us more about the score you've just given us. Why have you chosen that number? (make a note of barriers below, and discuss whether they can be overcome within the timescales of the study)

Encourage the parent to identify practical steps that need to be taken in order to overcome the barriers identified.

Explain that goals are easier to reach if they're specific ("I'll ask my friend to watch my child while I nip outside for a cigarette", rather than "I'll smoke outside").

Encourage parents to think about situations that might tempt them back to smoking in the home. For example, 'on a Saturday night when my friends are over, we just want to smoke indoors.' Ask parents to think of ways to avoid these situations or make them more manageable, so that they don't stand in their way.

____

____

____

____

____

____

6. Getting support

Discuss the importance of getting support for creating a smoke-free home. Ask the parent to think of people who are likely to be supportive and encourage them in changing their smoking behaviour.

Mention that further information is available on the 'Right Outside' website, at www.rightoutside.org (or other country specific equivalent)

7. FOR MAINTENANCE OR PRECONTEMPLATION PARTICIPANTS ONLY

Thinking about some of the potential barriers to making your home smoke-free such as other people you live with who smoke, or having an outside space to go to if you wish to smoke:

On a scale of 0-10, how realistic do you think it would be to make your home smoke-free in the next 2 months? (where 0=not realistic at all, and 10=extremely realistic)

Write value here: ____

Tell us more about the score you've just given us. Why have you chosen that number? (find out about barriers and decide whether they can be overcome within the timescales of the study)

____
____
____
____
____
____

Briefly check what parents already know about SHS exposure in the home, and it's effects in general

Ask if they know that SHS impacts on children's health even more than adults

Check to see if they know that the following child health conditions are all caused by SHS exposure: coughs, ear infections, chest infections (for example bronchitis, bronchiolitis, pneumonia), wheezing, asthma

Check to make sure they know that second-hand smoke can remain in household air for many hours after the last cigarette smoked.

Mention that further information is available on the ‘Right Outside’ website, at www.rightoutside.org (or other country specific equivalent)

Bring the telephone call to a close:

Check to see if the participant has any additional questions about the information they have received
Remind the participant that we will be back in touch by phone in two weeks time to discuss second-hand smoke levels in their home between now and then. Check that they are happy with this.
Arrange a suitable time to call them on day 23.
Check that they’re happy for you to text them on day 22 to remind them about the next call.
Thank them for their time today, and for taking part in the study.

Day 23 call stage of change assessment

NOTES: TELEPHONE CALL 2 – DAY 23

Materials required:

Notes from telephone call 1 (Day 9)

Completed baseline questionnaire from first home visit

(You may also want to have the AFRESH 'Handout 7: Quitting smoking' handy, and the other AFRESH handouts/factsheets if required)

Participant number: Date of phone call:

Introductions

This telephone call will last no longer than 15 minutes. You can ask any questions, at any time during this conversation, and you can finish the interview, without having to give a reason why, at any point. We are going to talk more about your air quality feedback, but first:

Have there been any problems with having the air quality monitor in the home since the last telephone call (Day 9):

☐ YES (if yes, make a note of the problems and try and resolve them)

☐ NO

Have there been any changes to who is staying in the house since the last telephone call on Day 9:

☐ YES (if yes, make a note about these changes)

☐ NO

Have you received the email graph and feedback and have had a chance to look at these?

☐ YES
☐ NO (if they haven't received the email, resend the feedback. If neccessary, run the telephone call and explain their findings to them without them seeing the graph, but ensure that they receive it after the call has ended).

2. Air quality levels over the past week:

Your daily average from the last text message was:

Your overall average measured over the past 7 days (as given in the email on day 22) was:

The average level in a smoke-free home in your area is 11. (*Compare this with the participants' levels. Are they better, worse, or about the same?*)

Mention variation between days.

If SHS exposure is clear then pick out 1 or 2 specific times to highlight as being particularly smoky. Also pick out specific times where levels are low.

If SHS exposure is not obvious:

Are there times you can remember when smoking has taken place in their home? ***Look to see if this matches with the graph.***

3. Current strategies in place for reducing second-hand smoke exposure in the home

Have you taken any additional steps to reduce second-hand smoke levels in your hiome since our last phone call?

☐ YES *(Make a note of the additional steps have been taken)*

☐ NO

If they have taken additional steps:

Ask whether these changes have been made successfully, and make a note of the changes

Ask whether they are seeing any benefits in making the changes identified, and make a note any outcomes.

4. Assess stage of change and opportunity for change:

Do you still think that your smoking behaviour in the home is a problem for you, or anyone else at the moment?

☐ YES (*contemplation, preparation, or action stage*; **go to Qs 4b-6**)

☐ NO (*maintenance or precontemplation stage*, **go to question 7**)

FOR CONTEMPLATION, PREPARATION OR ACTION STAGE PARTICIPANTS ONLY

When do you think you might change your smoking behaviour in the home?

☐ Some day *(contempation stage)*

☐ Not soon *(contempation stage)*

☐ In the next few months *(preparation stage)*

☐ I'd like to do something about it now *(action stage)*

Thinking about some of the potential barriers to making your home smoke-free such as other people you live with who smoke, or having an outside space to go to if you wish to smoke:

On a scale of 0-10, how realistic do you think it would be to make your home smoke-free in the next 2 months? (where 0=not realistic at all, and 10=extremely realistic)

Write value here:

Tell us more about the score you've just given us. Why have you chosen that number? (find out about barriers and decide whether they can be overcome within the timescales of the study)

5. Things you could do if the parent has had a setback:

Review the steps they were planning to take to create a smoke-free home. Were the plans realistic? If not, encourage them to find another way of achieving their goal.

Barriers and facilitators – were there barriers that the parent hadn't thought about? If so, the barrier, and possible solutions, need to be discussed

Review any difficult situations and final alternative approaches for dealing with them.

Support – check that the parent is receiving enough support from friends and family. Talk about ways of getting more support, and provide information on the types of support that might be available.

6. When changes have been made successully:

If the parent has successfully changed their smoking behaviour, the next stage is to maintain this behaviour and continue it into the foreseeable future. Having a smoke-free home needs to become part of their lifestyle, an automatic habit that doesn't require effort or thinking.

Check that the parent is continuing to use the support they can get from friends and family.

Explain that simply by repeatedly taking their smoking outside, it is more likely to become a habit. The more frequently a parent performs the behaviour, the less time they spend deciding whether or not to do it and thinking about why they are doing it. As the parent repeats the behaviour many times, it takes less conscious effort and attention, and then becomes a habit.

Encourage the parent to look back at what they have already achieved. Reinforce the benefits that smoking outside has had or will have. Remind the parent of the skills they have acquired. The fact that they have smoked outside before should increase their confidence that they can do it again. The skills they have acquired may also give them the confidence to think about changing other health behaviours in the longer term.

7. FOR MAINTENANCE OR PRECONTEMPLATION PARTICIPANTS ONLY

Thinking about some of the potential barriers to making your home smoke-free such as other people you live with who smoke, or having an outside space to go to if you wish to smoke:

On a scale of 0-10, how realistic do you think it would be to make your home smoke-free in the next 2 months? (where 0=not realistic at all, and 10=extremely realistic)

Write value here: ____

Tell us more about the score you've just given us. Why have you chosen that number? (find out about barriers and decide whether they can be overcome within the timescales of the study)

____
____
____
____

Bring the telephone call to a close:

Check to see if the participant has any additional questions about the information they have received
Arrange a suitable time to visit them in their home to complete the follow up questionnaire and pick up the air quality monitor on day 30. If this is not possible, arrange the visit for as soon after day 30 as you can.
Thank them for their time today, and for taking part in the study.

Follow-up questionnaire

Measuring for change: air quality feedback to reduce SHS exposure in the home

Follow-up questionnaire

General information

Following the feedback you have received on air quality in your home, please tell us about current smoking rules **inside** your home (tick all that apply):

Smoking is allowed anywhere in the home ☐
Smoking is allowed in certain places only ☐
(if ticked, go to question 2)
Smoking is only allowed when no children are present ☐
Smoking is only allowed on special occasions ☐
Smoking is never allowed anywhere inside the home ☐
Other (please specify) ______________________________

If you said smoking is allowed **'in certain places only'** inside your home in question 1, please tell us where (tick all that apply). *(If you did not say smoking is allowed in 'certain places only' in question 1, skip this question)*

Kitchen/utility room ☐
Dining room ☐
Living room/lounge ☐
Your bedroom ☐
Another adult's bedroom ☐
Attached garage ☐
Other (please specify) ______________________________

3. Since you had first indoor air quality measurement and feedback have you changed any aspect of your smoking behaviour or smoking rules in the home?

Yes ☐ No ☐ (if yes, go to question 4, if no go to question 5)

4. Which of the following changes have you made to your smoking behaviour, or smoking rules in the home (please tick all that apply)

Smoking is allowed in fewer rooms indoors ☐
Smoking is not allowed in rooms where children are ☐

Smoking is no longer allowed anywhere indoors ☐
I have reduced the amount I smoke ☐
I have stopped smoking ☐
Other (please specify) ______________________________

5. Thinking about **yourself**, since you had your first indoor air quality measurement and feedback, have you made any of the following changes to your smoking behaviour **in the presence of children**?

I smoke in the presence of children **inside the home...**:

Not at all ☐
Less than before ☐
About the same as before ☐
More than before ☐
Not applicable - I don't smoke ☐

6. Thinking about **other people in your household**, since you had your first indoor air quality measurement and feedback, have they made any changes to their smoking behaviour **in the presence of children**?

No changes have been made ☐
They smoke *less* than before ☐
They smoke *about the same* as before ☐
They smoke *more* than before ☐
Not applicable - nobody else smokes in the home ☐

7. Have you moved home during the study period? Yes ☐ No ☐

*** For researcher use only ***

Participant ID: ____________________________

Appendix VII - Measuring for Change text message components

This appendix contains SMS message components as used in the measuring for change intervention (chapters 6 & 7).

Section	Attribute	Text
Today	goingup	Your second-hand smoke level was {{today_result}} over the last 24 hours.
Today	stable	Your second-hand smoke level was {{today_result}} over the last 24 hours.
Today	goingdown	Your second-hand smoke level was {{today_result}} over the last 24 hours.
Comparison	goingup	This is higher than the average over the previous seven days.
Comparison	stable	This is about the same as the average over the previous seven days.
Comparison	goingdown	This is lower than the average over the previous seven days, well done!
Localarea	higher	This is higher than a smoke-free home in your area.
Localarea	sameorlower	This is about the same as a smoke-free home in your area.
Advice	general	Remember to take smoking right outside.
Advice	general	Consider using nicotine gum or lozenges when you know you'll be indoors for a long time.
Advice	general	Second-hand smoke can stay at harmful levels over five hours after just one cigarette.
Advice	general	The only way to keep your kids safe is to take smoking right outside every time.
Advice	general	Opening a window or smoking in just one room isn't enough - you need to take smoking right outside.
Advice	general	Could someone else watch the kids while you go out to smoke?

Each text message consists of a selection from each of the four sections as shown in Table 1:

<Today> + <Comparison> + <Localarea> + <Advice>

The text "{{today_result}}" is replaced by the measured concentration over the previous 24 hours.

Appendix VIII - “How do you know those particles are from cigarettes?”: An algorithm to help differentiate second-hand tobacco smoke from background sources of household fine particulate matter

This appendix comprises the text of a paper on the development of an SHS detection algorithm (chapter 8) as published in Environmental Research. This paper can be cited as:

> *Dobson R, Semple S. “How do you know those particles are from cigarettes?”: An algorithm to help differentiate second-hand tobacco smoke from background sources of household fine particulate matter. Environ Res 2018;**166**:344–7. doi:10.1016/j.envres.2018.06.019*

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COMPETING INTERESTS STATEMENT

The authors have no competing interests to declare.

CONTRIBUTORSHIP STATEMENT

Ruaraidh Dobson contributed to experimental design and planning, carried out fieldwork and statistical analysis, drafted this paper and had final approval of the version to be published. Sean Semple contributed to experimental design and planning, redrafting and critical revision, and had final approval of the version to be published. Both authors are accountable for all aspects of the work.

KEYWORDS

Second-hand smoke; tobacco smoke exposure; air quality monitoring; particulate matter

ABSTRACT

Background

Second-hand smoke (SHS) at home is a target for public health interventions, such as air quality feedback interventions using low-cost particle monitors. However, these monitors also detect fine particles generated from non-SHS sources.

The Dylos DC1700 reports particle counts in the coarse and fine size ranges. As tobacco smoke produces far more fine particles than coarse ones, and tobacco is generally the greatest source of particulate pollution in a smoking home, the ratio of coarse to fine particles may provide a useful method to identify the presence of SHS in homes.

Methods

An algorithm was developed to differentiate smoking from smoke-free homes. Particle concentration data from 116 smoking homes and 25 non-smoking homes were used to test this algorithm.

Results

The algorithm correctly classified the smoking status of 135 of the 141 homes (96%), comparing favourably with a test of mean mass concentration.

Conclusions

Applying this algorithm to Dylos particle count measurements may help identify the presence of SHS in homes or other indoor environments. Future research should adapt it to detect individual smoking periods within a 24h or longer measurement period.

INTRODUCTION

Second-hand smoke (SHS) is a serious cause of poor indoor air quality in homes. Around 40% of children are regularly exposed worldwide,(GTSS Collaborative Group, 2006) putting them at risk of serious illness and impaired lung development(US Surgeon General, 2006).

For that reason interventions to promote smoke-free homes are of significant public health interest. Several interventions have been developed using air quality monitoring to inform parents of the impact of smoking on their indoor air quality, and the consequent effects on their children.(Dobson et al., 2017; Klepeis et al., 2013; Rosen et al., 2015; Wilson et al., 2013) A low-cost air quality monitor, the Dylos DC1700, has proved useful for monitoring $PM_{2.5}$ as a proxy for SHS in smokers' homes in these kinds of interventions.(Semple et al., 2015, 2013) The Dylos is a small, portable monitor which provides comparable accuracy at a considerably lower price than other widely used optical particle counters, such as the TSI Sidepak.In addition to being approximately one-tenth of the cost of the Sidepak instrument, the Dylos has several specific advantages in terms of low noise, simplicity of use and the ability to determine particle size distribution in terms of fine and coarse particulate (Semple et al., 2013)

$PM_{2.5}$ has been widely used as a proxy to quantify indoor concentrations of SHS in many settings including bars, homes and vehicles (Apelberg et al., 2013; Gorini et al., 2005) as reliable measurements can be taken easily and affordably over time using optical particle counters, in contrast to the high cost and complexity of more specific methods such as air nicotine measurement. Other activities in these settings can generate $PM_{2.5}$. These can include cooking emissions, combustion such as candle burning or the use of solid fuels for heating, and aerosols such as deodorants and hair sprays.(He et al., 2004) These sources can produce high concentrations of PM within a home which could be confused for SHS in interpretation.

Parents in previous intervention trials have been observed to deny and challenge messages about the risk of SHS, (Passey et al., 2016) and if feedback wrongly identifies non-SHS sources as being smoking activity this is likely to weaken the effectiveness of such approaches and make the participant question the validity of the measurement method. Developing reliable and accurate information on PM concentrations that are specifically linked to SHS is therefore important in the development of effective interventions.

The particle size distribution of tobacco smoke is known to skew towards fine and ultrafine particles. (Klepeis et al., 2003) The mean diameter of particles in tobacco smoke has been measured as 0.27μm (in the case of mainstream smoke) and 0.09μm (for sidestream smoke); smaller mean diameters than those associated with common household activities like frying, cleaning and the movement of people, and other sources (Abt et al., 2000) while still producing a sustained increase in particle mass concentration over time.(Semple and Latif, 2014)

The Dylos DC1700 provides data on both the fine and coarse fractions of particulate matter in the form of particle counts for particles larger than 0.5µm and particles larger than 2.5µm. It may therefore be possible to use this particle size information to distinguish between different sources of PM in a home, and potentially to classify homes as smoking or non-smoking.

This research uses particle concentration data measured in homes to develop and test a rule-based approach to determine whether tobacco was smoked in the home during the monitoring period. This information could be useful in providing air quality data to support behavioural interventions designed to encourage smokers to keep their homes smoke-free.

MATERIALS AND METHODS

Measuring mass concentrations and particle counts in homes

Previously reported methods (Semple et al., 2013) were used to assess $PM_{2.5}$ concentrations in homes. From previous work by our group (Semple, 2016), time resolved $PM_{2.5}$ data were already available from 116 smoking homes. Data from non-smoking homes were collected in the course of this research. Minute-by-minute particle counts reported by the Dylos DC1700 monitor were converted to estimated $PM_{2.5}$ concentrations using a previously developed equation (Equation 1).

$$PM_{2.5} = 0.65 + 4.16 \times 10^{-5}(Dylos\ total\ particle\ count - large\ particle\ count) + 1.57 \times 10^{-11}(Dylos\ total\ particle\ count - large\ particle\ count)^2$$

Equation 2 - Conversion of Dylos particle counts to approximate mass concentration (Semple et al., 2013)

Also, the large particle percentage, consisting of the particles larger than 2.5µm as a percentage of the total particles detected, was calculated for each minute for use in the algorithm.

Algorithm development

A four-step algorithm was developed to classify homes as smoking or non-smoking based on one day or more of Dylos-recorded data by excluding data points which were unlikely to be related to smoking. This algorithm was designed to use the ratio of large to small particles detected by the Dylos as a “signature” for the presence of SHS. Additional steps were intended to reduce noise in the data caused by brief fluctuations in levels of PM.

For each home:

Remove data where $PM_{2.5}$ concentration is below 5μg/m^3. This step is intended to account for low ambient concentrations of $PM_{2.5}$ which are not related to SHS. 5μg/m^3 was chosen as indoor $PM_{2.5}$ has been shown to correlate to 79% of ambient $PM_{2.5}$ in similar conditions (Cyrys et al., 2004), while the average ambient $PM_{2.5}$ concentration in Scotland has been modelled at 6.6μg/m^3.(Sykes, 2016) Previous research on smoke-free homes has shown

For each minute of data, calculate the percentage of the total detected particles which are larger than 2.5μm in diameter. Remove data where the percentage of large particles is greater than a threshold (described throughout as the 'Large Particle Threshold' or LPT).

Remove data where a peak lasts for fewer than three minutes, to account for random fluctuations compared to the sustained impact of SHS on indoor air quality.(Semple and Latif, 2014)

Take the percentage of minutes in the log where data has not been removed in one of the steps above. This can be used as an "SHS score" to classify the home as smoking or non-smoking if the score is above a cut-off (determined experimentally).

Statistical analysis

Use of the algorithm relies on two factors: the LPT which best indicates smoking, and the best-performing cut-off value for the SHS score, over which a log can be classified as smoking. Receiver operating characteristic curves were used to determine these factors.

ROC curves are a common method for determining the efficacy of a diagnostic test. (Bewick et al., 2004) In an ROC curve, a test is carried out on a set of records, and its specificity and selectivity are plotted. This allows comparison between different tests using the area under the curve (AUC) of this plot – a mathematical representation of the overall effectiveness of the test. Tests which classify records more successfully than random have AUC values greater than 0.5, while a hypothetical perfect test would have a value of 1.0.

Variants of the algorithm using LPTs between 0.1% and 4.0% (stepped up in 0.1% increments) were applied to the full dataset of logs and the categorisation results plotted on an ROC curve using IBM SPSS v24.(IBM Corp., 2016) The LPT which resulted in the highest AUC was selected, and the curve analysed to find the SHS score cut-off which maximised selectivity and specificity. An ROC curve was also generated using the mean $PM_{2.5}$measured in each household as a predictor of smoking status. Custom Python 2.7 scripts were developed to apply the algorithm to Dylos data logs.

Smoke-free homes data collection

Participants working at three health charities in Scotland were recruited. Only people living in homes where smoking or e-cigarette use was not permitted were eligible to participate in the study. A target of 30 people was set as achievable with the time and resources available.

Participants were given a Dylos DC1700 monitor and an instruction sheet asking them to install and run the monitor for 48 hours in their main living space, elevated above floor level and away from doors and windows. This mirrored instructions given during previous studies of personal exposure to SHS.(Semple et al., 2012) Participants were also asked to keep a diary of events which could cause elevated PM in the home, including cooking and heating use.

After the monitoring period, the Dylos was returned to the research team and data was downloaded from it. A short report on air quality in the home was prepared for the participant and emailed to them, along with any relevant information on reducing air pollution in their home. The monitor's memory was then cleared prior to use with the next participant.

Smoking homes data

The pre-existing smoking homes dataset comprised minute-by-minute measurements from 116 homes, each spanning approximately 5 days, taken from the First Steps 2 Smoke-free (FS2SF) study(Semple, 2016). Participants in that study self-reported that smoking took place regularly within the home. No data on other events which could affect air quality was available from these homes.

Ethics

Ethical approval for this study was given by the College Ethics Review Board of the College of Life Sciences and Medicine at the University of Aberdeen.

RESULTS

Estimated $PM_{2.5}$ concentrations in smoking and smoke-free homes

For the smoke-free home data collection part of the study 27 participants were recruited, with 25 of those completing the study. Homes were monitored for a mean of two days, eight hours and six minutes (ranging from one day, 20 hours and 45 minutes to three days, 13 hours and 32 minutes). Two participants withdrew or were unable to provide 24h of data.

When compared to the existing data from 116 smoking homes the 25 smoke-free homes had significantly lower concentrations of $PM_{2.5}$, with a geometric mean of 5.2µg/m^3 (geometric standard deviation (GSD) ±2.16), compared to 37.6µg/m^3 (GSD ±3.0) ($p<0.001$, natural logs compared with a one-tailed Student's t-test).

Mean large particle percentages were also significantly different, with a geometric mean in smoke-free homes of 7.49% compared to 3.56% in smoking homes ($p<0.001$, natural logs compared with Student's t-test).

Classifying homes algorithmically

Potential large particle percentages were selected based on previous research on the particle size distribution of SHS.(Klepeis et al., 2003) The algorithm was applied to the whole dataset using LPTs between 0.1% and 4.0%, incremented by 0.1%. The resulting output was plotted as an ROC curve to determine the LPT which maximised AUC. An LPT of 1.8% was most successful, with an AUC of 0.945.

Comparison with classification by $PM_{2.5}$ concentration

An ROC curve was plotted using the results of the algorithm along with the mean $PM_{2.5}$ concentrations of each home (Figure 1).

The AUC for selection using mean $PM_{2.5}$ was 0.937, while the algorithm classification attained 0.945. Both methods were highly successful in classifying homes, with the algorithm more successful (although this was not statistically significant).

Determining the SHS score classification cut-off

Coordinates of the curve values were examined to determine the best-performing SHS score. The value 1.455% maximised sensitivity (0.974) and specificity (0.88) and was therefore selected. Using this value, the algorithm classified only 3/116 smoking and 3/25 non-smoking homes incorrectly.

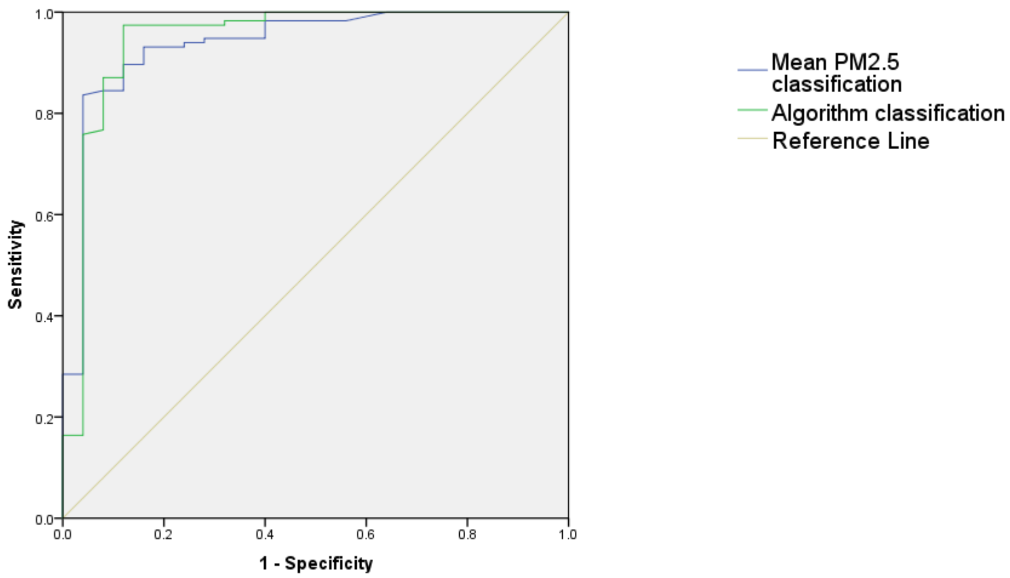

Figure 1 – Receiver operating characteristic curve comparing home classification using the algorithm with home classification using mean PM2.5 in a home. Mean $PM_{2.5}$ classification refers to the use of mean $PM_{2.5}$ concentrations in isolation as a score to classify homes as smoking or smoke-free. Algorithm classification refers to the use of steps 1-3 of the algorithm to produce an SHS score which was used as a classifier. Curves approaching the upper left corner of the chart represent effective classifiers. Sensitivity refers to the number of true positive smoking homes identified, while 1 – specificity refers to the number of false positives identified. Coordinates of the curve were analysed separately to decide on an SHS score cut-off point which would best indicate a smoking home.

DISCUSSION

It is possible to apply a simple algorithm to Dylos DC1700 particle number counts in order to predict with a high degree of certainty whether smoking occurred in a home during a multi-day monitoring period. While mean $PM_{2.5}$ concentration in the homes measured is clearly linked to smoking status, the algorithm was able to characterise homes independently from that factor, suggesting that the additional steps linked to large particle percentage and removing data where low concentrations of $PM_{2.5}$ are present are useful additions to the process of determining the presence of SHS in a home.

Previously, data from a similar monitor has been used to develop a logistic regression model to distinguish SHS from non-SHS sources of PM.(Dacunto et al., 2014) In this study, a large particle threshold of 1% was identified as indicative of SHS, similar to the threshold identified in this paper.

$PM_{2.5}$ is a well-recognised marker for SHS(Gorini et al., 2005) which has been used in a number of behavioural interventions.(Klepeis et al., 2013; Rosen et al., 2015; Wilson et al., 2013) PM sensors are well-developed, easily portable and inexpensive, allowing them to be used in a wide range of settings where it may be useful to measure SHS. This need not be limited to homes – for instance, this technique could be used to promote smoke-free public places laws.

Limitations

The limited number of measurements available from smoke-free homes made it impossible to determine whether the algorithmic approach was statistically superior to an approach based purely on the use of logistic regression analysis on the mean level of $PM_{2.5}$. A follow-up study in further smoke-free homes may determine this.

Although the classification rate established by the algorithmic approach was high, one in eight of the smoke-free homes tested was still mis-classified. These false positives could cause intervention participants who have succeeded in keeping their homes smoke-free to be told that they have not done so, potentially reducing their trust in the intervention.

Scotland has relatively low levels of outdoor particulate air pollution. The large particle threshold and score values developed in these circumstances may not hold true in countries with high levels of coarse particle pollution (including dust storms or other natural particulate pollution).(Ahmed et al., 1987) Further research should be carried out in these conditions.

In step 1 of the algorithm we have assumed that 79% of ambient PM will infiltrate, leading to an ambient $PM_{2.5}$ concentration indoors of around $5\mu g/m^3$. Values below this concentration are therefore excluded from the result. Infiltration of ambient PM varies greatly depending on building ventilation and other factors, and so this assumption is unlikely to hold true generally. Furthermore, measurements in settings where ambient PM is significantly higher than $6.6\mu g/m^3$ may cause few data points to be excluded at step 1, affecting the results of the algorithm. Further research is most likely necessary to test the algorithm in a variety of other settings, and to test the assumptions implicit in step 1. It may be beneficial to generate a specific "ambient $PM_{2.5}$" value for the time periods in which measurement takes place.

The results of this research can only be applied directly to the Dylos DC1700, with its two size bins. It may be possible to adapt the algorithm to other optical particle counters with multiple size bins, but research would be needed to measure their agreement with the size classifications made by the Dylos.

In general, optical particle counters are limited instruments compared to more labour- and time-intensive methods of detecting and quantifying PM, such as gravimetric methods. A wide range of factors can affect their results, including relative humidity, (Ruprecht et al., 2011) aerosol composition and the age of cigarette smoke in the air.(Dacunto et al., 2015) The particle number to mass concentration equation used in this study has been developed with reference to SHS aerosol only, so mass concentrations calculated by this method should be considered as estimates or approximations of exposure.

The effectiveness of the algorithm may be impeded in settings where there are other significant sources of $PM_{2.5}$, such as open flames. Similarly, high concentrations of PM_{10} in outdoor air could impede the effectiveness of the algorithm, raising the percentage of large particles measured by the monitor. This would be a particular concern in countries with high levels of outdoor air pollution.

Implications

Due to the well-known health implications of $PM_{2.5}$ in air and of SHS, particularly for children, interventions to reduce the number of homes in which smoking takes place are of importance in improving public health, with several recent studies describing the use of the Dylos DC1700 monitor.(Klepeis et al., 2013; Rosen et al., 2015; Semple et al., 2013)

While most people are well aware that SHS is harmful, many smokers blame other factors such as outdoor air pollution when presented with evidence of poor air quality in their homes. Researchers developing air quality feedback interventions for smoke-free homes or smoking cessation should consider incorporating this classification method to reinforce the specific danger of SHS.

Although this study took place solely in homes, the algorithm could be used to detect SHS in other indoor environments such as bars, casinos and other workplaces. This could be useful in assessing occupational exposure to SHS, and in providing evidence for advocacy for comprehensive smoke-free legislation.

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Appendix IX - A worked example of the SHS detection algorithm

This appendix presents a brief worked example of the SHS classification algorithm described in Chapter 8. This algorithm can be applied to Dylos DC1700 logs from homes to classify them as smoking permitted or non-smoking permitted, based principally on the ratio of large particles (>2.5µm) to small particles (0.5µm – 2.5µm) detected by the monitor.

Data

Data from a smoking home in Be’er Sheva, Israel (identified as ISSI_BE_03) has been used to demonstrate the application of the algorithm by stage. The Dylos DC1700 logs small and large particle number concentrations once per minute, which have been converted to estimated $PM_{2.5}$ mass concentrations by the use of a previously described equation[5]. Table IX-1 provides descriptive statistics about the data, while Figure IX-1 shows the detected $PM_{2.5}$ concentration over time in the original data.

Table IX-1 - descriptive statistics on log ISSI_BE_03

Log ID	**Location**	**Minutes of data recorded**	**Mean $PM_{2.5}$ concentration (µg/m^3) (SD)**	**Median $PM_{2.5}$ concentration (µg/m^3) (IQR)**
ISSI_BE_03	Be’er Sheva, Israel	8,764	82.0 (150.3)	13.9 (5.9 – 49.4)

[5] *Semple S, Ibrahim AE, Apsley A, et al. Using a new, low-cost air quality sensor to quantify second-hand smoke (SHS) levels in homes. Tob Control 2015;**24**:153–8. doi:10.1136/tobaccocontrol-2013-051188*

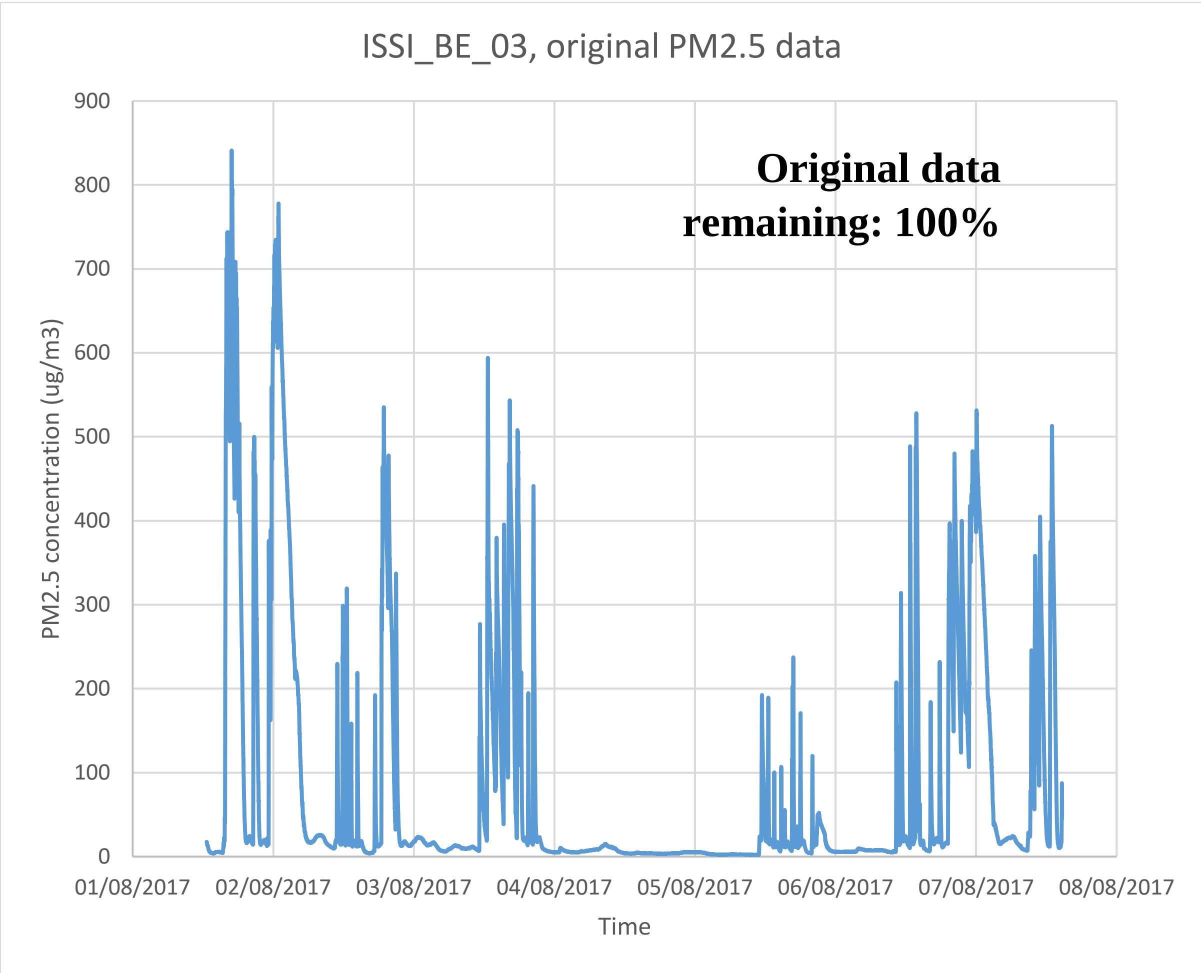

Figure IX-1 - original PM2.5 concentration data over time in this example log (ISSI_BE_03)

The algorithm by stage

Stage one

The first stage of the algorithm involves removing all records with $PM_{2.5}$ concentrations under 5µg/m^3. This removes values so low as to resemble ambient air-related concentrations of $PM_{2.5}$.

At this stage, 16.4% of records in ISSI_BE_03 are removed (leaving 83.6%). Figure IX-2 shows the results of this step on a graph of $PM_{2.5}$ concentrations over time.

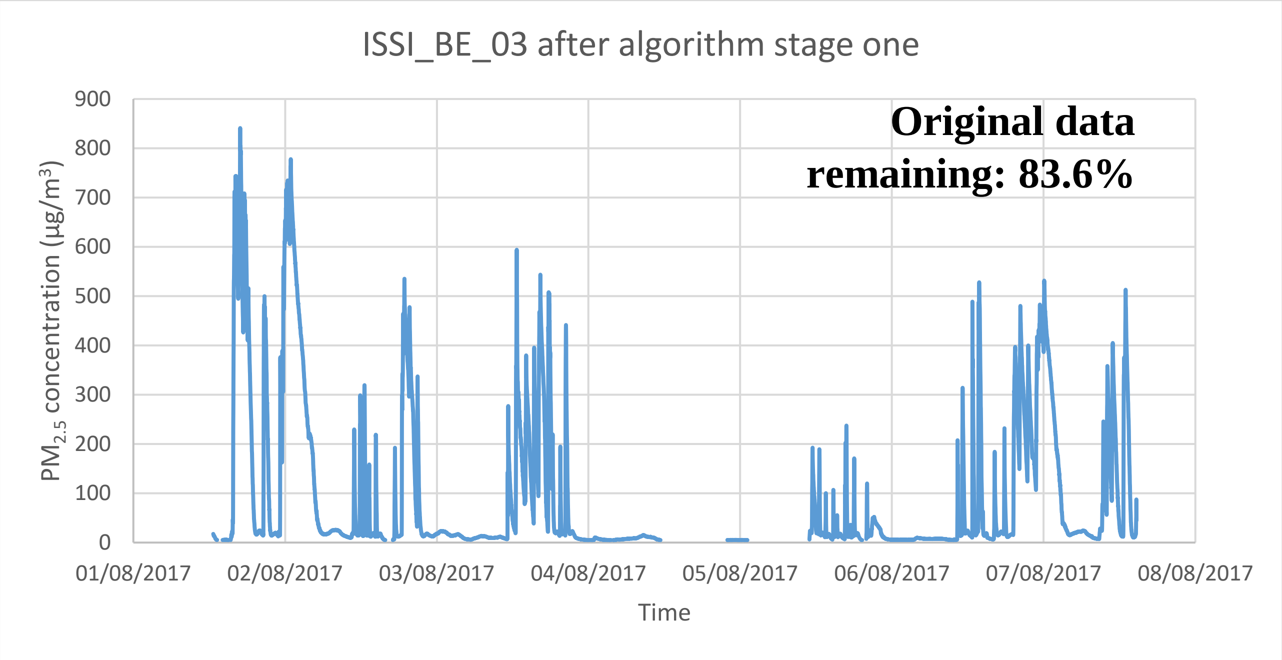

Figure IX-2 - PM2.5 concentrations over time of records remaining after algorithm stage one has been applied

Stage two

In stage two, records where the number of large particles (>2.5µm) detected make up more than 1.8% of the total particle count are removed (Figure IX-3). At this stage in the example record a further 49.6% of records are removed, leaving 34% of records.

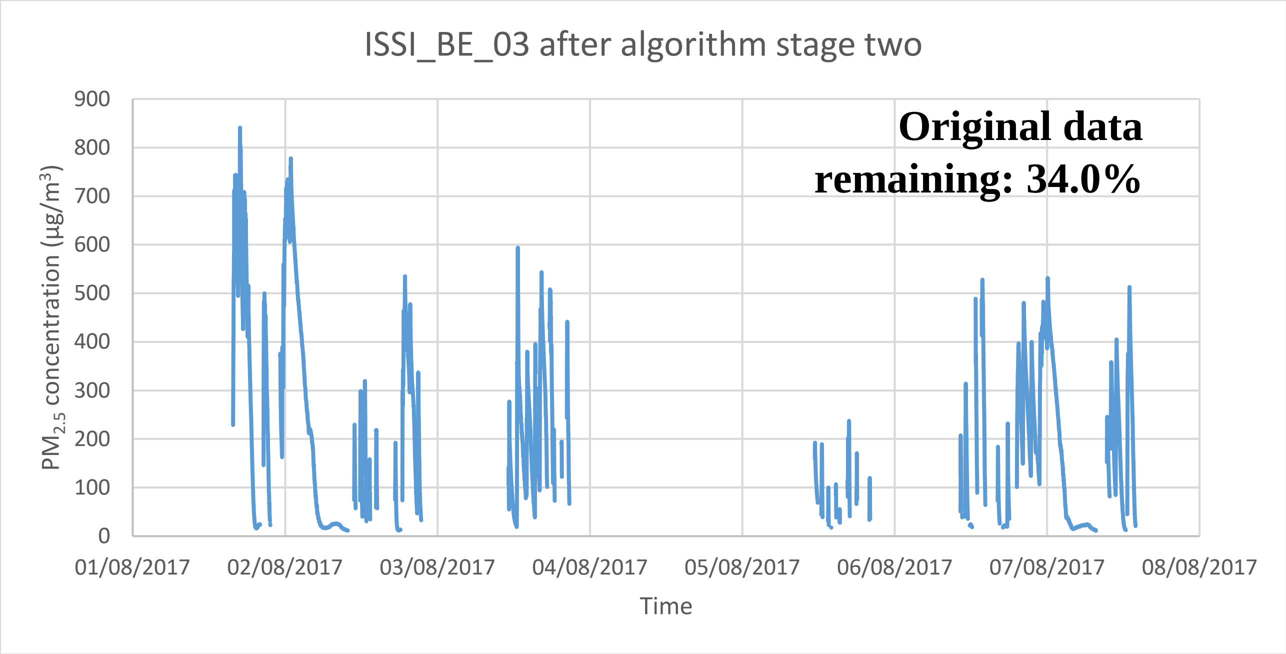

Figure IX-3 - PM2.5 concentrations over time of records remaining after algorithm stage two has been applied

Stage three

In stage three short periods of data (lasting three minutes or less) are removed (Figure IX-4). This represents only a few records (a further 0.2% of the original data) leaving 33.8% of the original data.

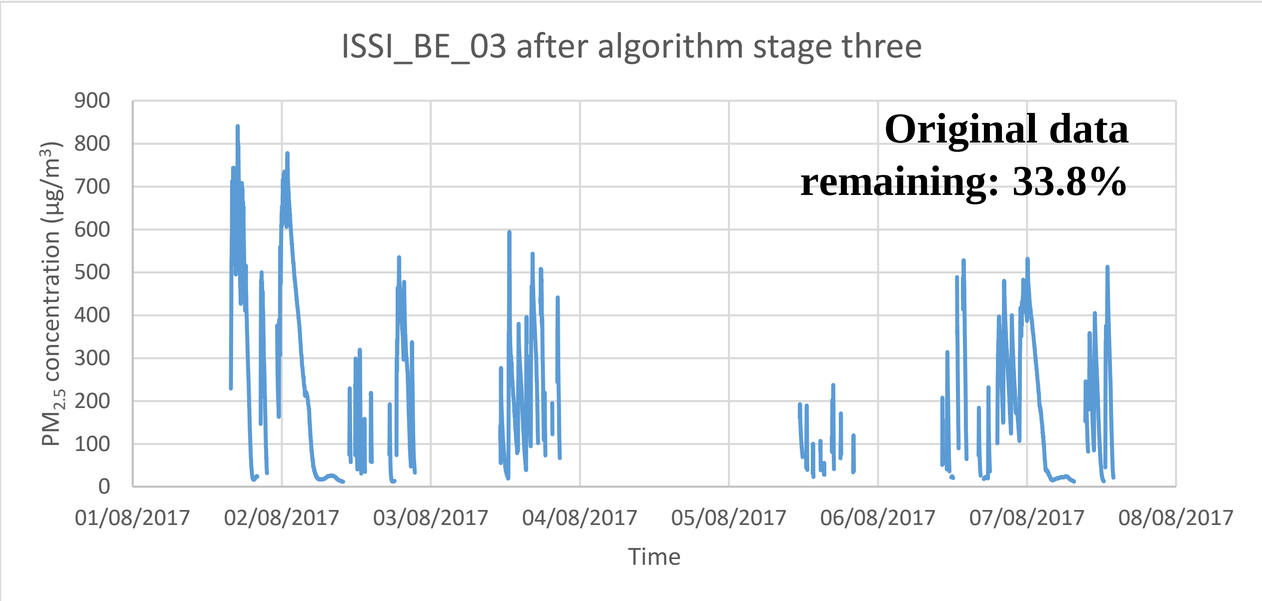

Figure IX-4 - $PM_{2.5}$ concentrations over time of records remaining after algorithm stage three has been applied

Stage four

At this stage, the percentage of data remaining in the log after the previous three stages is used to classify the log as smoking or non-smoking. If the percentage of data remaining after stage three (the "SHS score") is greater than 1.45%, the log is classified as smoking permitted; otherwise, it is classified as non-smoking permitted. The number of records remaining over each stage of the algorithm is summarised in Table IX-2.

Table IX-2 - records over each stage of the algorithm

ISSI_BE_03	Original data	Stage one	Stage two	Stage three
Number of records remaining	8,764	7,330	2,983	2,963
Percentage of original records remaining	100%	83.6%	34.0%	33.8%

In the case of ISSI_BE_03, as 33.8% of the data remains following the application of the first three stages of the algorithm, the log is classified (correctly) as smoking permitted.