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ORIGINAL PAPER

Wood burning stoves, participatory sensing, and 'cold, stark data'

James Heydon[1] · Rohit Chakraborty[2]

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Abstract
Wood burning stoves triple levels of particulate matter pollution inside the home. Using an exploratory research design informed by coping theory, this study illustrates how sensors revealing this reality fail to influence the perceptions and behaviours of stove users. After four weeks of participatory sensing, where laypersons used sensors to identify indoor air quality during stove use, the results show how monitoring technology pulls wider preconceptions into the data interpretation process. When faced with numerical data perceived as ambiguous, users draw on preconceptions that frame stoves in a positive light and make comparisons with other indoor emission sources believed to be harmless. This influences the data interpretation process and minimises the threat indicated by sensor technology. It is recommended that participatory sensing research give greater consideration to the role of data presentation in influencing user behaviour, while being more attentive to how socio-cultural knowledges enter the process of interpretation.

Keywords Air pollution · Wood burning stoves · Particulate matter · Indoor air quality · Participatory sensing · Citizen science

Introduction

One of the most harmful components of air pollution is particulate matter (PM). Particles with an aerodynamic diameter equal to 2.5 µm or less (PM2.5) can move into every organ in the body, heightening the risk of developing illnesses ranging from respiratory infections through to dementia, strokes, and Parkinson's disease (Fu et al. 2019). Globally, the World Health Organisation (WHO) (2018) links PM pollution with seven million deaths worldwide per year. In the United

✉ James Heydon
James.Heydon@Nottingham.ac.uk

1 School of Sociology and Social Policy, University of Nottingham, Nottingham NG7 2RD, UK

2 Department of Civil and Structural Engineering, University of Sheffield, Sheffield S1 3JD, UK

Kingdom (UK), the primary source for PM2.5 is the domestic burning of wood and coal for heating. Accounting for 17% of PM2.5 emissions nationally, PM from domestic burning increased by 35% between 2010 and 2020 (Department for Environment, Food and Rural Affairs 2022).

Attempts at making levels of air pollution visible have been ongoing for over fifty years. Focusing on outdoor emissions, much of the early work focused on public understandings of government regulations (see Wall 1974; Kirkby 1972; Blacksell 1972; McBoyle 1972). This was based overwhelmingly on a ‘deficit model’ of public understandings of scientific information (Bickerstaff and Walker 2003). Here, the divergence between scientifically defined and publicly understood environmental risk was explained by reference to a largely ignorant and irrational public (Irwin et al. 1999; Bickerstaff and Walker 1999).

This changed at the turn of the century, where a more sociological literature emerged to draw attention to the ways in which people actively negotiate scientific information. This emphasised social processes of reflexive interpretation and critical evaluation, marking a split with the deficit model and its focus on the passive assimilation of scientific information by isolated individuals (see Bush et al. 2001, 2002; Bickerstaff and Walker 2001, 2003; Howel et al. 2003). As Cupples et al. (2007, pp. 2894–2895) explain, compared to professional scientists,

> the public, which is the target of this information, processes it in a more random and imprecise way, drawing also on lay knowledges and embodied experiences…cultural circumstances are not external to scientific knowledges but are, in fact, the sites on which scientific knowledges circulate…

This sociological literature draws attention to a range of psychological, social, geographic, and cultural influences on public perceptions of and reactions to air quality information. Direct experience provides much of the basis for these understandings (Bickerstaff and Walker 2001), emphasizing the primary role undertaken by the senses in risk perception (Xu et al. 2017; Johnson 2002). This is mediated by social constructions of place, where sense perception is tied up with socio-cultural commitments to location and community memory (Brody et al. 2004; Irwin et al. 1999; Moffatt et al. 1999). Indeed, a ‘halo effect’ has been found to exist in relation to homes (Hofflinger et al. 2019), neighbourhoods (Bush et al. 2001) and public parks (Heydon and Chakraborty 2020). This is where certain spaces are seen to provide ‘sanctuary’ from emissions compared to others, regardless of the actual levels of air pollution in these areas. Other influences on the interpretation of air pollution data include gender, where women with children have been found to be more aware of air pollution than men (Oltra and Sala 2016), trust in government and regulatory institutions (Bickerstaff 2004), and the cultural acceptability of the polluting behaviour in question (Cupples 2009). By drawing attention to the social mediation underpinning public understandings of air pollution, the sociological literature encourages researchers to develop a more holistic understanding of how scientific data is presented and interpreted.

The purpose of this article is to explore how people interpret and act upon air quality data from sensors showing exposure to indoor wood stove emissions. In doing so, it is sensitive to the myriad of situational and contextual influences that come to bear on individual understandings of scientific information. The impetus for this is threefold. First, existing analyses of layperson interpretations of sensor data are largely atheoretical. Research tends to focus on the outcome of data engagement—behaviour change or not—as opposed to the personal, situational and contextual factors acting upon the encounter to produce said outcome (Heydon and Chakraborty 2020). By contrast, this research draws upon Lazarus and Folkman's (1984) coping theory to draw out the decision-making processes underpinning these responses, and identify the factors influencing interpretations along the way. In doing so, the article draws together the literature on public understandings of air pollution and that on participatory sensing, to further develop a fruitful dialogue that has only just started (see Boso et al. 2020).

Second, existing research prioritises technologies used to communicate more general messages about outdoor emissions, such as teletext services, weather information and documentaries (Bickerstaff and Walker 1999; Bush et al. 2001Oltra et al. 2017). Only recently has attention turned to the more personal technologies associated with participatory research, where lay people use sensors to 'objectively record, analyze, and discover a variety of patterns concerning important issues in their lives, such as health, environmental quality, and traffic' (Boso et al. 2020, p. 104). Much of this literature focuses on sensor accuracy, or what the technology can reveal about hitherto unseen aspects of the environment, with relatively few evaluating its cognitive and behavioural implications (Hubbell et al. 2018). By contrast, this study builds on an emerging body of work concerned with how engagement with personal air pollutions sensors in more intimate settings can elicit various psychological and behavioural responses (Boso et al. 2020; Heydon and Chakraborty 2020; Bales et al. 2019).

Finally, exposure to indoor stove emissions is a mounting concern. Although outdoor stove emissions are public knowledge, less well-known is that these appliances triple levels of particulate matter pollution inside the home (Chakraborty et al. 2021). PM originates from older stoves (Semmens et al. 2015; Piccardo et al. 2014), which are without emissions control features and lack approval by national environment regulators. They are also produced by newer stoves, which are equipped with such features or carry a marker of regulatory approval (Vicente et al. 2020; Wang et al. 2020; Noonan et al. 2012; Allen et al. 2009). Such pollutants have been found to result from leakages (Castro et al. 2018), but most of the evidence associates indoor PM with the opening of the stove door during lighting or periodic refuelling (see Chakraborty et al. 2021). Fuel type and moisture content also influence the quantity and content of pollutants released (Price-Allison et al. 2019). Considering the growing market for personal environment monitors, participatory sensing technologies may be well-placed to reveal the reality of indoor stove emissions to otherwise unaware users and subsequently alter behaviour to reduce exposure. As such, this study has implications for the role of participatory sensing in developing solutions to the problem of air pollution.

This article proceeds in four sections. The first outlines coping theory as a model for understanding responses to stressful environmental stimuli, which here refers to data revealing exposure to harmful levels of indoor air pollution. The second section explains the methods used, including research design, sampling procedure and analysis of survey, research diary and interview data. The third section presents an analysis of the findings using coping theory, maintaining a focus on the situation- and person-specific factors working to influence interpretations. The article finishes by discussing the consequences of these findings for the participatory sensing literature, and what they may mean for efforts aimed at raising public awareness of air pollution problems from residential stoves.

Coping theory

The process-based model of coping explains how a person evaluates and responds to potentially stressful encounters. Developed by Lazarus and Folkman (1984), it is 'process-based' because instead of coping being conceived as a personality trait it is understood to result from a recursive relationship between person and environment. Under this approach, 'coping' refers to the 'thoughts and behaviours used to manage the internal and external demands of situations that are appraised as stressful' (Folkman and Moskowitz 2004, p. 745). The model defines 'internal' demands as stemming from beliefs and commitments, and 'external' demands as relating to the features of the circumstances in question. Following this, the extent to which a given event is defined as 'stressful' is determined by a combination of factors relating to the person and the situation (Lazarus and Folkman 1984).

This study uses coping theory to understand how adults respond to sensor data on indoor emissions from residential stoves. Almost four decades since its publication, coping theory remains key to understanding responses to environmental stimuli across multiple disciplines (Biggs et al. 2017, p. 361). Taking cue from literature on the 'infusion' of wearable healthcare devices into a person's life (see Marakhimov and Joo 2017; Casselman et al. 2017), this study follows the emerging use of coping theory in other participatory sensing studies (Heydon and Chakraborty 2020). By drawing attention to the cognitive process triggered by an environmental encounter, coping theory sensitises analyses to internal and external influences on the way to a given behavioural outcome. In doing so, the study provides a more nuanced account of those engaged in participatory sensing when compared to the largely atheoretical approach adopted by existing scholarship.

According to the theory, coping behaviour results from an initial two-part appraisal of a person's encounter with environmental stimuli. A 'primary appraisal' occurs when a situation is first evaluated as exerting an influence on someone's wellbeing (Biggs et al. 2017). Stress may result from the interpretation of the situation as 'harmful', where some damage or loss to the person has already occurred, or as a 'threat', which involves anticipated harms or losses (Lazarus and Folkman 1984, pp. 32–33). Also implicated at this point is a 'secondary appraisal', which entails a person's evaluation of their control over the stressor to determine their ability to manage or alleviate its consequences. Despite the labels 'primary' and 'secondary', these forms of appraisal are not necessarily sequential. As Folkman (1982, p. 97) clarifies:

> When that which is at stake is meaningful and coping resources are judged less than adequate for managing the demands of the situation, psychological stress is experienced. The greater the imbalance, the greater the stress.

This initial stage of 'cognitive appraisal', where an individual encounters a given stimuli, interprets it as stressful or not and decides whether it can be managed, acts as the precursor to subsequent mental and behavioural adaptations to the situation (Biggs et al. 2017). The coping efforts subsequently triggered take many forms, but they are here categorised as either problem-focused or emotion-focused coping efforts. The former refers to proactive attempts at managing or mitigating the source of stress, including attempts at removing or reducing obstacles, attaining new skills, seeking assistance or planning for action towards these efforts (Lazarus and Folkman 1984). By contrast, emotion-focused coping refers to internal attempts at mitigating the mental and emotional distress elicited by a stressful encounter. This may include attempts at redefining the situation, denying it, or accepting it as inevitable (ibid). Although different, these categories are not wholly independent from one another and to 'set them up as competitive is to distort the way coping actually works' (Lazarus 2006, p. 22).

Following this, people may then 'reappraise' the situation to determine whether their problem- or emotion- focused coping responses worked to mitigate the stress experienced. This third stage refers to a new process of appraisal following earlier iterations, converting what first appears to be a linear process into a circular one (Lazarus and Folkman 1984). In essence, this acknowledges that an initial coping effort may work to alter the outcome of a subsequent appraisal. Taking this as the point of departure, the article now applies this model to those using air pollution sensors to detect indoor emissions from residential stoves.

Materials and methods

Research design

The design of this study is exploratory and primarily qualitative. The data were collected from three instruments administered in sequence: surveys, research diaries and interviews. The surveys were administered prior to receipt of the sensor technology. These collected baseline information on participant knowledge of—and concern with—indoor and outdoor air quality, along with their reasons for using a stove and knowledge of its environmental impact. Participants were then asked to complete a research diary entry each time they used the stove over a four-week period. The research diary required users to check the sensors every time their stoves were lit, thereby ensuring engagement. They also collected data on how the stoves were used, duration for which they were lit, amount of fuel added and whether any other emitting activities were undertaken during combustion. The diaries also collecting data on whether engagement with the monitoring data was influencing perceptions or behaviours. Each participant was then interviewed about their experiences, perceptions and behaviours at the conclusion of the four weeks, where more detailed data was gathered on participant experiences by drawing comparisons with their answers in the pre-use survey.

The study was granted ethical approval by the Research Ethics Sub-Committee at the University of Nottingham. The Reference Number evidencing this approval is 1920-059-STAFF. Uncoerced, prior and informed consent was received by all participants prior to conducting the study. The datasets generated and analysed during the current study are not publicly available because this was not part of the ethics agreement signed by participants.

Sample and procedure

The sample consisted of thirty participants recruited from across the city of Sheffield, in the north of England. The majority of these were homeowners ($n=28$) and lived with one other adult ($n=25$). Two thirds of participants lived in the same household ($n=20$). Half of the sample were male ($n=15$) and half female ($n=15$). Participation was limited to adults in households with a stove approved by the Department for Environment, Food and Rural Affairs (DEFRA) ($n=19$) or an open fire that was used according to DEFRA guidelines ($n=1$). Two households used a stove as the primary heat source. Participants were recruited through local community social media pages. Following the initial expression of interest, participants were sent an electronic copy of the survey to complete.

Arrangements were then made to install the indoor and outdoor monitors. There is little guidance on the use of indoor sensors, so decisions were made to ensure consistency across the sample. The PMS5003 optical sensor was used for particle monitoring, being chosen for its accuracy and portability (Bulot et al. 2019). The indoor monitor was placed in the same room as the stove, approximately two metres away and at a height of no more than five feet. This was to ensure the sensor did not get too hot. Participants were asked not to move the sensor, which could have caused an inconsistency between readings. The outdoor monitor was placed in waterproof casing and attached to the outside of the house. All sensors were co-located with the local authority reference station four weeks prior to the study. PM1, PM2.5, and PM10 were sampled every 145 seconds, with the participant dashboard being updated every five minutes. At the point of installation, participants were given a tablet computer and instructed on how to access the sensor data. Information on the thresholds and colour coded data display was also provided. Participants were then asked to check the sensor data and complete the research diary each time the stove was used.

Semi-structured interviews were conducted after 4 weeks, with questions centring on participant experiences over this time. To facilitate reflection on aspects of change, responses to the pre-use survey informed the questions and were recalled during the discussions. Each interview lasted between forty and sixty minutes.

Analysis

The qualitative data gathered from the surveys, research diaries and interviews were thematically analysed according to the approach outlined by Braun and Clark (2006). This was conducted on a rolling basis and justified on the grounds of theoretical saturation, where participant recruitment continues until no new or deviating data were being added to the categories of analysis (see Saunders et al. 2017). The analysis allowed for both inductive and deductive codes to be generated, although those pertaining to the tenets of coping theory formed primary focus. Analysis of the qualitative data was conducted using NVivo and the quantitative data was analysed using Microsoft Excel.

Limitations

The study exhibits several limitations. First, it draws its data from stove users within a relatively narrow geographic area, the majority of which use stoves as a secondary heat source. Consequently, the findings may not relate to those using stoves under different circumstances, such as in rural areas or situations where stoves are relied on as the primary heating source. Second, the study focuses on perspectives relating to indoor emissions, meaning different conclusions may be reached if perspectives on outdoor stove emissions were under investigation. Third, thirty is a relatively small number of participants from which to make generalisations, owed to the exploratory nature of the study.

Findings and analysis

Two appraisal pathways, one outcome: no perceived threat

As illustrated in Fig. 1, two main appraisal pathways were undertaken by participants when engaging with the sensor data. Those in Pathway A, which comprised just under half of the participants ($n=13$), understood the sensor data as indicating a ‘threat’, to use the language of coping theory. They then made conscious behavioural adjustments to try and mitigate the perceived risk. By contrast, those in Pathway B, which comprised just over half of the participants ($n=17$), did not perceive the indoor air quality data as indicating a threat and, as such, made no conscious behavioural adjustments following engagement. Each pathway will be examined in turn.

When an encounter is conceived as stressful, coping actions aimed at managing or mitigating it are enacted (Lazarus and Folkman 1984). Those in Pathway A ($n=13$) altered their behaviour because of the emission peaks witnessed on the monitors at the point of stove lighting (see Chakraborty et al. 2021). A variety of coping efforts were attempted by this group, most of which focused on stove management actions. These included opening the stove door less widely and less frequently ($n=4$), closing stove air vents ($n=4$), minimising refuelling

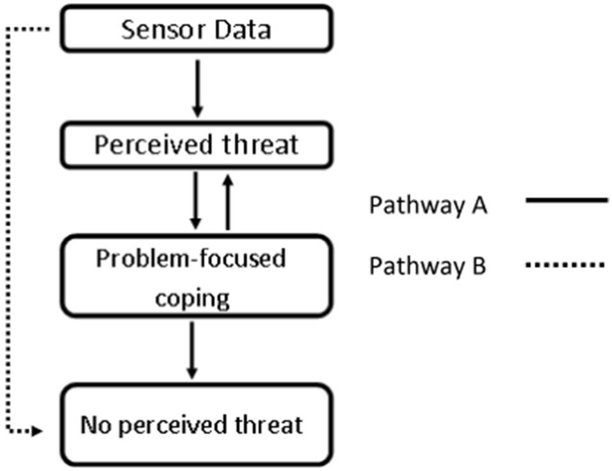

Fig. 1 Two main cognitive appraisal pathways

($n=4$), improving ventilation through opening doors and windows or purchasing an air purifier ($n=3$), avoiding stoking the fire ($n=1$), putting logs on more slowly ($n=1$) and striking the match inside the stove ($n=1$). Some made multiple changes at once in an attempt to reduce their exposure to the peaks. All were low-cost adjustments similar to those reported by sensor users in Boso et al. (2020). Decisions to act in these ways originated from several—and often overlapping—sources, including intuition or existing knowledge ($n=11$), and internet searches ($n=4$).

The coping efforts made by users in Pathway A led to reappraisal and, ultimately, served to assuage their concerns about the PM levels seen on the monitors. Compared to pre-sensor use, all but one saw their levels of concern stay the same or decrease through engagement with the data. Of the thirteen in Pathway A, five finished the study 'not at all concerned', five 'slightly concerned', two 'very concerned' and one 'concerned'. Only one of the 'very concerned' respondents experienced an increase in concern. This is why the cognitive appraisal process for those in Pathway A ends with no threat being perceived; the coping efforts are considered effective at reducing the peaks in indoor PM detailed on the monitors, requiring no reappraisal or further action:

> The more particulates were visible on lighting and then the first, maybe, half hour after that. Then once we were able to get the fire hot, really hot, it started to die down. Once it was started, the levels in particular didn't really concern me. It was just the initial stage.
> (Participant 26, interview)

This absence of concern was more immediate for those following Pathway B ($n=17$), where participants perceived peaks like those in Pathway A but did not interpret them as a stressor. As a result, these sensor users did not pursue coping efforts at all. As Participant 30 noted, 'the readings went high when we first lit the fire but then they were very low. I actually feel much better about using it because of how low they are'. Similarly:

> There was a spike in all particle readings just after lighting. All levels declining since lighting. Results don't seem too severe and enjoyment of the log burner is more important to me.
> (Participant 5, research diary)

Comparing reported levels pre- and post- monitor use, all seventeen in Pathway B experienced the same or decreased feelings of concern about their stove following engagement with the data. Of these, ten finished the four weeks 'not at all concerned' about the effects of their stove on indoor air quality, while the remaining seven were only 'slightly concerned'. Combined with the results from Pathway A, the prevailing effect of sensor use across both pathways was to decrease concern about the indoor emissions from their residential stoves (see Fig. 2). Engagement with sensor data therefore generated a combination of 'irrelevant' and 'benign-positive' appraisals, eliciting either an indifference towards or positive perception of stoves. As Lazarus and Folkman (1984, p. 32) note, such a combination is not unexpected; 'appraisals can be complex and mixed, depending on person factors and situational context'. As can be seen below, the intersection of these two spheres is heavily implicated in the decreasing concern reported.

Situation factors influencing interpretation: the role of data presentation

Exposure to both intense peaks and average increases of PM occurred for the majority but were not perceived as particularly harmful. Even those that perceived the peaks as 'threatening' considered risk to be almost completely negated through minimal behaviour changes. This divergent interpretation arose for those in both coping pathways for reasons relating to data presentation format and preconceptions about

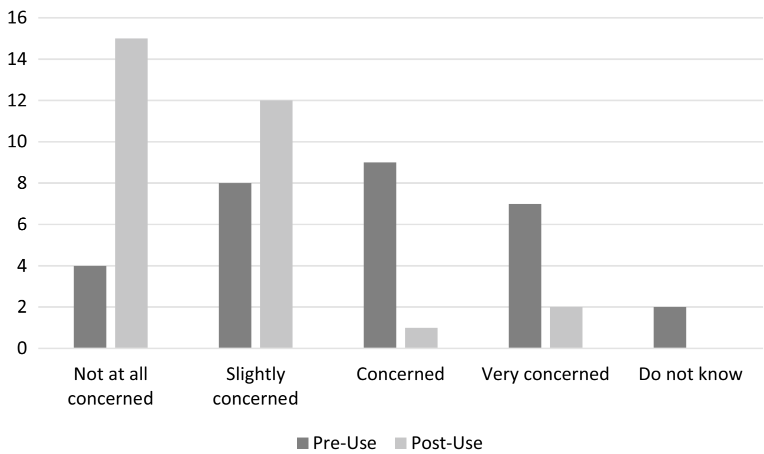

Fig. 2 Reported concern about indoor air pollution from stoves pre- and post- sensor use

stoves, speaking to the confluence of person and situation factors in the process of deeming an event stressful (Lazarus and Folkman 1984). Taking the situation factor of data presentation as the point of departure, while six participants were relatively satisfied with the data presentation format, the remaining twenty-four described it as decontextualised and lacking relatability. As noted by participant twelve, '[a]lthough I've learnt what stuff means, as in I've learnt what PM1 is, I can't actually relate that to anything'. Similarly:

> You can see what the figure is but it's not telling you what the impact is. There's no comparison with anything else. It's not contextualised in any way… it's not bound to anything, is it? It's cold, stark data.
> (Participant 15, interview)
> I think this actually speaks…to the lack of information that the numbers give us. Like, while they do give us lots of information they also don't tell us a lot about the actual [health effects]…that sort of meaning, you know?
> (Participant 18, interview)

The quantification spoken of here is visible in Fig. 3. The data was presented using a set of dials with real-time PM1, PM2.5 and PM10 exposure data displayed at the top of the screen, and with longitudinal graphics illustrating exposure over a 24-h period. There is no known safe limit for PM1, but the 'traffic-light' system used for the other fractions are colour-coded according to the WHO's 24-h exposure thresholds. This approach is common in the air quality sensor industry, where this colour scheme and threshold combination are widely used to inform data displays. However, the only non-quantified meaning being communicated is via the traffic-light system and, even then, each colour only depicts a quantity of PM ug/m^3. A level of risk is communicated by this colour coding, but what that translates to in terms of health effects or equivalent risks is not detailed.

A second feature implicated in the interpretation of data relates to the suitability of the presentation format for the indoor emission pattern produced by stoves. As Chakraborty et al. (2020) demonstrate, indoor exposure takes the form of intense 'peaks' and average increases of PM over the time in which stoves are lit. The real-time dials are effective at displaying this information in the moment, but it is only short-lived. By contrast, the longitudinal graphs display this data over time, allowing

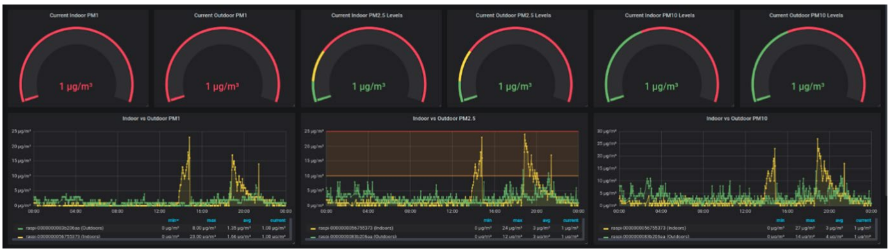

Fig. 3 Data Display for Air Quality Sensor

users to view their exposure over a longer period. However, these graphs actually obscure the significance of such 'peaks' because they are based on the WHO 24-h average threshold. Even when the peaks are of a very high intensity or occur repeatedly before returning to lower levels, their significance is lost in a graphical interface that presents more information on the period in which stoves are not lit than when they are (see Fig. 3).

The absence of meaning inherent to this presentation generated a space in which participants searched for indicators of meaning elsewhere. For many, these 'signs' came in the form of other emissions picked up by the sensors, including those from cooking, lighting candles and cleaning, amongst other things. Comparing stove emissions to these more 'everyday' activities served as a benchmark by which the figures relating to stoves could be better understood. However, as the quantification and 24-h average thresholds remained unchanged, participants drew from their already-existing understandings of these other activities as harmless when reading the data. This is visible in their interpretations, which further diluted the perception of indoor stove emissions as harmful:

> [T]oast gives massive spikes…joss sticks and candles, they give off loads. So that made me think, well, you need to judge pollution against other things that are happening. So, I guess I went from, to begin with, thinking 'oh my god, this stove is leaking, it's giving us spikes', to then thinking, 'actually, in the context of other things that seem quite normal, maybe it's not so bad'.
> (Participant 10, interview)
> After I saw the readings of the first couple of times of having it on I thought 'oh jeez, we're all in there', you know, especially having a child…But I was worried at first and now I'm not particularly, so obviously the effects haven't lasted. We got some really big peaks when we were cooking, which everybody does, and you can't really get away from that so how bad can it be, really?
> (Participant 25, interview)

It is at this point where the data presented by the individual monitors encounter more personal understandings of indoor air pollution. Much like the 'clues' sought by participants in Irwin et al.'s (1999, p. 1319) study, the ambiguity communicated by the sensor data encouraged users to seek a relatable explanation elsewhere. Here, already-existing understandings of air pollution from other indoor activities came to occupy the interpretive space created. At the point of encounter, the sensor data was not exerting influence on a neutral position of understanding, but came to contend with already-existing terrains of knowing and unknowing with which it vied for influence. Ultimately, the ambiguous presentation format generated the space for other influences to enter the appraisal process, minimising the threat perceived and affecting the coping efforts undertaken thereafter.

Person factors influencing interpretation: the role of preconception

While coping theory emphasises the situational encounter in explaining how people respond to environmental circumstances, it acknowledges that such responses do not occur in a vacuum. 'Person factors' also exert an influence. This is particularly so

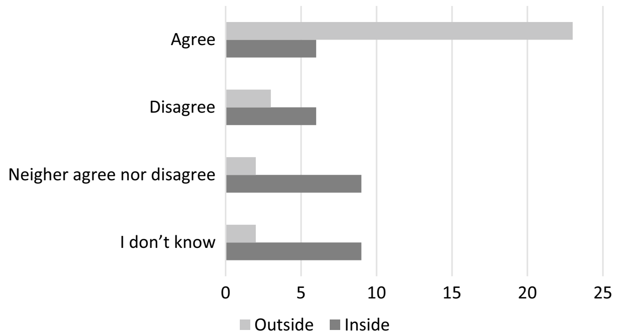

Fig. 4 'My stove reduces the quality of air outside my house' vs. 'My stove reduces the quality of air inside my house' Pre-sensor use

when the situational information required for an appraisal is unclear or insufficient. As Folkman and Lazarus (1984, p. 104) explain, such ambiguity causes people to:

> [i]nfer meanings based on personal dispositions, beliefs or experiences. The greater the ambiguity, the more influence person factors have in determining the meaning of the environmental configuration…whenever there is ambiguity, person factors shape the understanding of the situation, thereby making the interpretation of the situation more a function of the person than of the objective stimulus…

As Sect. "Situation factors influencing interpretation: the role of data presentation" shows, interpretations of sensor data relating to other indoor sources were based on pre-existing understandings of whether emissions from these activities were harmful. However, the pre-use survey and interviews also allowed for some of the wider preconceptions around stove emissions to be viewed. These demonstrate that the sensor data not only fails to convince because of an unrelatable data presentation format, but also because it is entering a cognitive process already coloured by a predisposition to view residential stoves in a positive light.

Compared to knowledge of their detrimental effects on outdoor air quality, pre-use knowledge of indoor stove emissions was far less certain (see Fig. 4). Those answering 'neither agree nor disagree' recognised that indoor emissions resulted from stove use but considered it to be insignificant. This ambiguity about indoor stove emissions may be related to the lack of knowledge about indoor air pollution more generally. For instance, one study found that 46% of adults could not name a source of indoor air pollution and only 36% were aware of its effects on health (Whiffen 2018; see also Niphadkar et al. 2009). This may be associated with the status of indoor air pollution research being historically overshadowed by its outdoor counterpart (Royal College of Paediatrics and Child Health 2018). Indeed, research on indoor emissions from DEFRA-certified stoves is a relatively recent undertaking (see Chakraborty et al. 2021), meaning there is little wider social commentary supported by credible evidence about the indoor air pollution produced by these forms of heating.

The second and third preconceptions were more positive in orientation and built on this ambiguity, with the former concerning the justification for stove use and the latter how 'environmentally friendly' users considered their stoves to be. The dominant reasons given for stove use included warmth ($n=24$) and 'cosiness' ($n=21$), often being presented together ($n=18$). This mirrors a recent DEFRA (2020, p. 86) survey of almost 1000 UK stove users, which found the primary reason for lighting a fire was 'to create a homely feel'. As such, wider visual imaginaries around wood burning are here exerting influence within the cognitive appraisal process to affect interpretations of air quality data.

The third characteristic added to this positive preconception, with the majority of participants ($n=18$) considering their stove to be 'environmentally friendly'. For most, this perception drew its credibility from several sources; the DEFRA stove certification, use of seasoned wood instead of wet wood, and comparisons with the CO2 produced by gas-fired central heating systems. As participant 20 noted, 'I don't know if it's environmentally friendly, but the blurb says DEFRA approved, so…'. Similarly:

> The stove is DEFRA approved for smoke control areas and refers to environmental credentials in sales literature. I burn fully seasoned, waste wood and burn far less gas as a result.
> (Participant 12, pre-use survey)
> Yes, it is environmentally friendly. It's DEFRA-exempt, we burn only well-seasoned dry logs, is CO2 neutral and we use locally sourced fuel.
> (Participant 19, pre-use survey)
> It's DEFRA-rated, we burn a waste wood-based briquette product and seasoned logs, carefully monitoring burning conditions. It's likely better in terms of carbon neutrality than the gas central heating.
> (Participant 28, pre-use survey)

Amounting to a position that holds stoves in a positive regard aesthetically and environmentally, these preconceptions are reflected in wider research on public knowledge of residential stove pollution. A recent survey of 2000 UK stove users found half to be unaware that stoves can have a negative impact on health, a third associated stove use with positive aesthetics, and one fifth considered wood burners and coal fires to be the most environmentally friendly ways of heating homes (HETAS 2020).

Taken together, the absence of knowledge about indoor emissions linked with the 'cosiness' aesthetic and 'environmentally friendly' moniker to create a relatively positive baseline perspective on stoves. The preconceptions underpinning this position were not passive and, instead, were pulled into the cognitive appraisal process by the ambiguity created by the sensor data. As Lazarus and Folkman (1984, p. 106) note, '[e]ven in situations where there are cues signalling harm or danger, ambiguity can be used to reduce threat by allowing alternative—perhaps reassuring—interpretations of the meaning of the situation'. The quantitative data, presented using WHO 24-h average thresholds and colour coded real-time displays, was not relatable enough to stand alone as a persuasive source of information about the risks posed by the indoor emissions being produced. Instead, this data presentation format encouraged a search for meaning in preconceptions, minimised the perceived threat and did little to alter the positive perception of stoves already established in the minds of users.

Discussion

Stove users experience high but variable 'peaks' of indoor PM from their residential stoves (Chakraborty et al. 2021). Perceptions of this exposure as a 'stressor' varied, with participants falling into one of two groups; those that did not conceive of the 'peaks' as harmful and those that did. The former group did not change their behaviour, as no threat was perceived, while the latter pursued problem-focused coping efforts to reduce exposure. These concentrated on changing stove management practices, mirroring existing studies where similarly individualised attempts at avoiding or mitigating air pollution were also triggered by sensor technology (Boso et al. 2020; Heydon and Chakraborty 2020; Bales et al. 2019; Wong-Parodi et al. 2018). Over the four-week period in which air quality sensors were installed, users in this group reported a reduction in concern to such an extent that it was not perceived at the conclusion of the study. As such, while both groups followed different coping pathways, sensor use resulted in similar responses to the data; a perception that indoor emissions produced by stoves are not harmful. Implicated in this was how the data presentation format triggered a search for meaning elsewhere, in more relatable actions, importing pre-conceptions about these activities into the cognitive appraisal process and influencing how the data was interpreted. This has two key consequences for the participatory sensing literature.

First, the way in which sensor data is presented has a substantive bearing on user perceptions. Echoing existing research on public interpretations of air pollution data (Bickerstaff 2004; Bickerstaff and Walker 1999), widely used WHO thresholds, display formats based on 24 h averages, and PM exposure expressed as UG/M3 are experienced as overly quantified and unrelatable. This is compounded by the effect of 24-h averages obfuscating the significance of peaks-orientated patterns of indoor stove emissions (see Chakraborty et al. 2021; Vicente et al. 2020). When coupled with its almost wholly quantified format, the 'threat' associated with exposure to high intensities of PM over shorter periods of time is not made explicit by such approaches (see Orellano et al. 2020). This adds an additional dimension to the participatory sensing literature, where the focus tends to be on the outcome of sensor engagement instead of the process by which that outcome is produced (Bales et al. 2019; Wong-Parodi et al. 2018; Oltra et al. 2017). Future research should prioritise the ways in which data is presented within participatory sensing projects, addressing questions of suitability to situation and relatability to person as a matter of priority. Relying on quantified representations alone risks repeating past errors by uncritically transporting the 'deficit model' of public understandings of scientific information into the participatory sensing projects of the future (Bickerstaff and Walker 1999). The danger of doing otherwise, by continuing to rely primarily on quantification alone, could impede the potential for this technology to become an effective means of communicating information on environmental risk.

Second, the ambiguity created by an unrelatable data presentation format encourages a search for more relatable markers from which to derive meaning. By failing to act as a singular source of information whose relevance to the person is clear, the sensors actively draw wider socio-cultural knowledges of air pollution into the appraisal process, filling the interpretive space. Under this scenario, participatory sensing becomes both a trigger and gateway to existing, incomplete or imprecise understandings of air pollution as opposed to a source for new and accurate meanings. While not exhaustive, a cluster of specific preconceptions stepped into the space created by the data ambiguity. For instance, normative understandings of cooking emissions as harmless were used as a comparator by which to judge data on stove emissions, rendering them similarly harmless in the minds of users. However, research has consistently found this not to be the case (Torkmahalleh et al. 2017; Seltenrich 2014). Participatory sensing initiatives should thus be more alert to the influence of wider social constructions of polluting behaviours—including the absence of these constructions—within the processes by which laypersons interpret scientific data (Hofflinger et al. 2019; Cupples et al. 2007).

The absence of accurate understandings of indoor emissions intersects with other preconceptions, mainly around the aesthetic of stoves being ‘cosy’ and ‘environmentally friendly’, to create a cognitive terrain characterised by favourability. Not only do such positions work against the introduction of air quality policies in local areas (Boso et al. 2017, 2018; Bhullar et al. 2014), but they render air pollution data from sensors less persuasive. As such, participatory sensing alone cannot be relied upon to change perceptions and behaviour on air pollution. Its effectiveness is contingent on parallel socio-cultural meanings around emissions-producing behaviours, which step into the space when data is presented inappropriately to the situation or experienced as unrelatable by users.

Taken together, participatory sensing holds many promises. It can increase sensitivity to environmental problems (Boso et al. 2020), allow access to otherwise unavailable and personalised data on issues that are meaningful to people (Heydon and Chakraborty 2020), and empower communities to effect positive change (Coulson et al. 2018). However, its transformative potential is contingent on the processes by which data is interpreted by users. Though the technologies are well-placed to make invisible emissions visible, the consequences of that visibility hinge on factors at - and far beyond - the point of data presentation. As such, the potential for participatory sensing initiatives to improve air quality may only be realised when combined with wider public information campaigns aimed at changing preconceived ideas of air polluting behaviour.

Conclusion

This study has illustrated that sociological arguments about the relationality of scientific-lay understandings, and air pollution data passing through mediating processes informed by both normative experience and context during interpretation, still apply to the relatively new world of participatory sensing. It reinforces the idea that socio-cultural context needs to be understood as integral to decision-making informed by sensor use and not peripheral to it. As Bickerstaff and Walker (2003, p. 45) noted almost two decades ago, with regard to public interpretations of more general air pollution data, these processes are embedded in an 'entangled interaction of society-environment-technology'. This study has shown that data derived from participatory sensing is no different. Research must interrogate the spaces between these components, treating the junctures as opportunities for understanding to facilitate the transformative potential of participatory sensing initiatives in the future.

Declarations

Conflict of interest The authors report no potential competing interest.

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