Breathing Spaces: Modelling Exposure in Air Pollution Science

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Abstract
In this article, I materially situate air pollution exposure as a topic of social and political inquiry by paying attention to the increasing specificity of spaces and sites of exposure in air pollution and health research. Evidence of the unevenness of exposure and differential health effects of air pollution have led to a proliferation of studies on the risks different environments pose to bodies. There are increasingly different airs in air pollution science. In this research, bodies are often relegated to passive objects, exposed according to the environments they move between. Yet exposure implies a blurring of bodies and environments which also challenges the idea of a discrete body that is distinguishable from its material context. By studying the process of modelling indoor air pollution, I highlight how air pollution, buildings and bodies are co-implicated with one another in ways that demand new ways of materialising human exposure in science.

Keywords
body ecologies, breathing spaces, buildings, exposure, indoor air pollution, modelling

Introduction
In this article, I materially situate air pollution exposure as a topic of social and political inquiry by paying attention to the increasing specificity of spaces and sites of exposure in air pollution and health research. Evidence of the unevenness of exposure and differential health effects of air pollution have led to a proliferation of scientific studies on the risks different environments pose to bodies. For instance, indoor air pollution is often contrasted with outdoor air

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pollution and hotspots distinguished from background or ambient air pollution. The specifying of spaces of exposure shapes methods and how actions or interventions are defined. There are, then, increasingly different airs in air pollution science, the specificity of which is the subject of a growing body of research. In this research, however, bodies are often relegated to passive objects, exposed according to the environments they move between. At the same time, exposure implies a blurring of bodies and environments, which challenges the idea of a discrete body that is distinguishable from its material context. I draw on research conducted as part of an interdisciplinary scientific study examining air pollution exposure and health outcomes in the United Kingdom to consider the ways in which ideas about the body inform environmental health research and practice. Three instances wherein bodies disrupt the boundaries of indoor environments (as specific sites of exposure) in scientific data practices are drawn on from my ethnographic research. An empirical and conceptual discussion of breathing is then developed to help explicate the specific body–environment relations performed in the computational modelling of indoor exposure. I trace scientists’ attempts to model and make sense of the relations between air pollution, buildings and bodies, and how adjustments to the modelling process shaped the way in which human exposure was materialised.

The absence of matters of breath and breathing in science and policy discussions about air pollution and health is surprising. Although breathing is understood as the main mechanism of human exposure, the relationship between breathing and exposure often remains implicit or underdetermined in scientific accounts. For instance, epidemiological studies, which form the main body of evidence on short-term health effects (Tonne, 2017), use ambient pollution measurements as proxies for the air that people breathe. Another key field is toxicology, which locates exposure inside the body by materialising chemical pathways and biological responses. In the absence of a gold standard of exposure, along with a growing awareness that ‘we are all exposed’, interdisciplinary research methods are emerging that seek to connect air pollution and human health in new ways (Vineis et al., 2017). For instance, research is increasingly dedicated to understanding how different environments influence exposure, either by focusing on personal ‘micro-environments’ (Adams et al., 2015; Stephens et al., 2015) or through internal
markers of exposure, such as cellular changes in the lung (Vineis et al., 2017). Although increased attention is being paid to the social dimensions of air pollution and the uneven distribution of health outcomes (Hajat et al., 2015; Richardson et al., 2013), a tendency remains to characterise the environmental contexts of exposure in terms of their dynamism (either inside or outside bodies), seeing the body as a static container from which exposure’s effects play out (the body as something that environments shape). While air pollution science is developing new ways of researching bodily exposure, there is a risk that functional understandings of the body limit environmental health’s potential to adequately respond to the social and political questions it raises (Niewöhner and Lock, 2018).

What concepts of the body might help apprehend contemporary environmental conditions? Scientific processes where embedded ideas about the body and bodily integrity are disrupted have proven generative in body studies, enabling critical reflection and engagement with scientific and biomedical concepts, ideas and practices (Blackman, 2010: 9; see also Martin, 2010; Shildrick, 2010). Science and Technology Studies scholar Hannah Landecker (2011) has traced how 20th-century models of metabolism, as composed of universal chemical processes, have been replaced by a ‘new metabolism’ that is individualised though molecular processes of gene expression. She identifies food and metabolism as a primary site for the social and political reshaping of the body and intervention at the molecular scale. The ‘boundary-dissolving’ capacity of biological processes that Landecker describes reflects developments in the life sciences and new biologies wherein the belief that biological processes are universal and unaffected by circumstance or history no longer holds (Blackman, 2016; Meloni et al., 2016; Niewöhner and Lock, 2018). Nutritional epigenetics posits bodies as continuous with their landscapes, challenging the idea of a discrete body as ‘clearly bounded and differentiated such that we know what is inside and what is outside’ (Blackman, 2010: 1). In other fields, too, molecular and chemical processes are revealing the body in ways that trouble biological and political notions of the individual (e.g. Aryn Martin’s (2010) work on maternal–foetal microchimerism). Studying scientific materialisations of bodies can both engage with debates in human health fields and expand sociological concepts and theories of the body.
In the examples drawn upon above, the body is situated as part of its environment, and rather than stable, bounded individuals, subjects are shown to coexist with shared ecologies (Blackman, 2010). However, and as Kim Fortun (2014: 325) describes with reference to the contemporary air quality crisis, it is also our coexistence with the atmosphere we all breathe and live that produces a conceptual haze and makes it difficult to see the conditions of our times. Claire Waterton and Kathryn Yusoff (2017: 5) similarly write of the struggle to apprehend different categories of the body among ‘the volatile flows of late-capital’, in which subjects move in and out of recognition, and insides/outsides dissolve and are remade. This blurring of boundaries is engaged with by Magdalena Górska in the project *Breathing Matters*, in which she offers a post-humanist analysis of breath by attending to the relationalities enacted through breathing. She writes that breathing is ‘an event of bringing the outside in and the inside out’ (Górska, 2016: 28). Górska’s research emphasises the transformative nature of breath, which she describes as a continuous metabolism extending the human beyond conventional boundaries of embodiment. What understandings of bodies might attending to matters of breath enable for engaging with our everyday atmospheres? What are the multiple articulations of bodies and environments that breathing coalesce? (Kenner 2019).

Responding to the shifting of boundaries that breathing always enacts is an opportunity to rethink the body and its relations with air pollution exposure. This is significant empirically, as already outlined, but also socially and politically because part of the challenge of pollution and toxicity is its lack of containment, persistence and uneven effects (Liboiron, 2016; Liboiron et al., 2018; Murphy, 2017; Shapiro, 2019). Claire Waterton and Kathryn Yusoff (2017: 5) propose the building of multiple narratives to try and establish objects of concern (pollution, for instance) in more compelling ways. This article examines sites of exposure as breathing spaces to help better understand and interrogate how bodies, environments and disease are shaped (Mitman, 2008).

To do this, I draw on ethnographic research of an interdisciplinary public health project about air pollution in the United Kingdom to specify and characterise nascent understandings of the body in air pollution exposure and public health research. The collaboration emerged from a series of previously funded projects studying the relationship between the built environment and various health outcomes, including
one study that examined the effects of climate change and overheating in dwellings. These projects require the combining of specific disciplinary expertise, including building physics, architecture and epidemiology. I became interested in how different disciplinary understandings of air materialised around some specific sites of exposure (including people’s homes). Current estimates suggest that people spend 90% of their time indoors and exposure from indoor sources is increasingly a target of concern for policy and public health (Cincinelli and Martellini, 2017; Greater London Authority, 2018; NICE, 2017). Unlike outdoor air pollution, indoor air pollution is not monitored in ‘real time’ by the UK government, which means computer models are required to simulate indoor air chemistry to estimate exposure.

Driven by a shared aim of understanding the occupant exposure risks different dwellings across the United Kingdom pose, this project was premised on the idea that there are similar bodies and different airs. For the research team, the main aim of modelling was to specify aspects of the built environment that produce air pollution and increase ‘occupant’ exposure risk. However, what to include in the environment was something the modelling process also sought to clarify. As well as physical properties, buildings are partly defined by humans and non-humans. Indeed, human occupants and indoor ecologies have been shown to significantly influence microbiological dynamics and indoor air chemistry (Adams et al., 2015; Mavrogianni et al., 2014; Stephens et al., 2015). In this project, more-than-human bodies posed a series of challenges to researchers. Focusing on how the scientific team responded to these challenges, I will trace how corporeal processes and affects were incorporated into modelling in ways that afforded new ways of materialising air pollution exposure. I will begin by outlining the concept of breathing spaces through a discussion of social science and humanities literature on exposure and toxicity. Following a brief overview of methods, the empirical case study that forms the main content of this article is structured into three sections, each detailing the specific ways in which the indoor environment was constituted, disrupted and remade through research practices.

**Bodies, Buildings and Breath**

Exposure blurs the interior and exteriors of bodies in ways that are inherently ambivalent. In Peter Sloterdijk’s theory of atmospheres,
he draws on Kant to define space ‘as the condition that allows the being-together of bodies whilst simultaneously implying the faculty of separating them’ (2005: 226). Sloterdijk argues that, paradoxically, in ‘explicating’ (making latent things apparent) the air we merge more with it, so that ‘the air has become the element, not of our exposure or containment, but of our immixture with, our inextricability from the outside world’ (Sloterdijk, 2009: 31). This inextricability of bodies and air has been taken up across disciplines to critically engage with contemporary atmospheres and notions of exposure and containment. In architect and researcher Nerea Calvillo’s (2014) project *Aeropolis*, the material agencies of air and ordinary practices of exposure are visualised to show that air pollution is an interior not an exterior to our continuing sustenance and shelter. In related work, Calvillo extends Sloterdijk’s concept of architecture, which she argues negates the way built environments are made, by calling for modes of attention that move beyond boundaries (like walls) to what is between them, by including ‘humidity, pressure, smell, toxicity and breath’ (2018: 43). David Gissen (2009), too, presents architecture as a practice of mutual tinkering *with*, rather than accommodation of, an external techno-natural environment. This work is significant for thinking about exposure (and containment) because how we imagine buildings are part of the way in which the social and cultural imagination functions and forms (Connor, 2004).

Bodily integrity is closely tied to ideas of immunity from an external environment (Blackman, 2010). Biological entities in contemporary environments, from viruses to toxic particles and gases, trouble bodies (Cohen, 2011) and valued human integrities (Chen, 2012). Mel Y Chen’s (2012) discussion of lead panic in 2007 America demonstrates how the mobility of lead particles and their travelling to inanimate objects like children’s toys create new subjects and objects of toxicity. Their work is important for understanding the materiality of toxicity and the ways in which particles and gases in the air might challenge prevalent ways of thinking about the agents of contagion, exposure and immunity. Donna Haraway’s (1991) work on the politicisation of the immune system in the 20th century informs Chen’s argument that toxicity is ‘threatened immunity’ and therefore an intertwining of scientific, public and political cultures. While immune systems might be considered private, toxicity is often
understood as a violation of an integral bounded self (Chen, 2012: 194). Indeed not everyone has the same capacities to build a ‘safe place’ for a body (Murphy, 2006). Nik Brown (2017), for instance, argues that for people with cystic fibrosis achieving safe breathing spaces relies on a multitude of technical things.

By reflecting on the assumptions that underpin approaches to exposure in science social and cultural analyses of toxicity and containment can also shift. In their work on the spatial dimensions of vector-borne diseases, Ann Kelly, Hermione Boko Koudakossi and Sarah Moore, (2017) propose an immunological vision that attends to the vicinities of domestic interiors. Rather than vector-free (or indeed pollution-free) spaces, the paper develops a spatial understanding of immunity – ‘spatial repellency’ – that is mutually achieved and flexible in character. The paradox of delineating a contained interior and the need for other forms of action in response to toxicity is also explored by Astrid Schrader (2010) in her paper about the material agencies of *Pfiesteria piscicida* (the Fish Killer). She argues that toxicity is an indeterminate process because *Pfiesteria* co-produce the environment while transforming themselves in relation to it. This means that what causes toxicity cannot be separated from the exposed fish. Drawing on Karen Barad’s (2007) idea that bodies are constituted by intra-actions, Schrader demonstrates how responding to *Pfiesteria*’s agency does not involve separating what is toxic from that which is exposed. If subjects and objects, bodies and environments are never materialised in isolation (Schrader, 2010; cf. Barad, 2007), then air pollution’s effects cannot be presumed to be located and measured in a discrete or contained body (e.g. Calvillo, 2018; Liboiron et al., 2018; Murphy, 2017; Shapiro, 2015). The concept of spatial repellency is useful here because it foregrounds the agencies that shape spaces and bodies, and in doing so encourages a more situated understanding of exposure and containment, toxicity and immunity. Attuning to the social, political and spatial configurations that mediate and produce situations of exposure are also starting points for reimagining it (Also see discussions on toxicity by Liboiron et al. 2018).

The late-industrial condition of breathing toxic air has encouraged creative interventions into contemporary atmospheres. As Timothy Choy demonstrates, air pollution opens human bodies up to all kinds of differences (Choy, 2012), in ways that generate, ‘texture and expand concepts of agency and action’ (Schrader, 2010: 283). Breathing, in
particular, reveals the ambiguity of corporeal agency in relation to environments (McCormack, 2015: 88). Sasha Engelmann (2015), for instance, has shown that breathing encourages new and creative ways of registering the materiality of air and atmospheric space, and Timothy Choy (2012: 12) materialises ‘breathers’ as a way to point out connections between practices, experiences, weather events and economic relations. By examining how agencies materialise through breathing, these authors have shone light on what is required to sustain life in specific circumstances and how human ‘costs’ are accounted for, or not. They also offer a critical approach to breathing that acknowledges its political and ethical stakes (see also Kenner 2019), wherein environmental conditions that lead to struggles to breathe might begin to be thought more laterally, for instance in relation to race (e.g. Sharpe, 2017).

In light of the emerging work around toxicity and ideas of immunity and containment, and how discussions of breath and breathing speak to these, I am now going to outline the ethnographic methods and air pollution case study I will use to work through these arguments in order to empirically flesh out the concept of breathing spaces in relation to public health research and science.

**Modelling Breathing Spaces**

The ethnographic material drawn upon in this article is based on research with a multi-institutional and interdisciplinary public health project studying the relationship between air pollution and health in the United Kingdom (2011–2014). My specific focus will be on the interactions between building physicists and epidemiologists trying to measure indoor air pollution exposure and health outcomes. The building physicists built a computer model to simulate indoor atmospheres and the epidemiologists intended to use statistical methods to estimate the risks these posed to human occupants, although the focus of this article is on the former. Characterisations of dwelling types were shared investigative sites for studying the heterogeneous spaces of exposure produced by built environments. Tasked with understanding how interdisciplinary knowledge is achieved in practice, the research involved participant observation of weekly meetings, in-depth interviews and studying project documentation practices (bid proposals, emails, presentations and publications). Building on my analysis of interdisciplinary discussions around
developments in the building model simulations during weekly team meetings, I conducted a series of interviews with the modellers to better understand how indoor environments as sites of exposure are technically produced and in what ways they anticipated being able to answer questions relating to human health. I learned that human occupants pose a challenge for building modelling because they significantly affect indoor air quality, but how and in what ways cannot necessarily be quantified (qualitative data are not available beyond small case studies) nor predetermined (and therefore simulated). However, because calculations defining indoor environments had to be made relevant to questions of exposure and human health, finding ways to manage and work around human bodies in the modelling process remained a shared concern.

Models play a variety of roles in science: as forms of measurement, for exploring theories, as instruments for intervening in the world (Morgan and Morrison, 1999) and processes that redistribute expertise (Landström et al., 2011). In this project, the building model was used to estimate the air quality in different types of dwellings while also functioning as an interdisciplinary tool of inquiry. In other empirical sites, models have been shown to render their objects knowable to practitioners in experimental ways, and in ways that reveal the material, epistemological and ontological contingency of knowledge making (Myers, 2015). Thinking of modelling as experimental involves paying attention to its other processual effects, for instance in terms of how it may evolve to compose new interdisciplinary practices for studying and materialising exposure and health (Landström et al., 2011; Sanchez Criado and Rodriguez-Giralt, 2017). Catharina Landström and co-authors (2011), for instance, argue modelling forms ‘new relationships that become constitutive of agency in relation to the matter of concern’ (p. 1618). The authors suggest that modelling has ontological as well as epistemological implications. Similarly, I examine how modelling creates spaces for knowing and doing air pollution research. For instance, the building model became both a new site of encounter between disciplines and between researchers and their material objects (bodies, buildings, pollutants). As such, the modelling process was an animated ethnographic site for inquiring into the way bodies, air pollution and spaces of exposure are handled in interdisciplinary air pollution science.
In the sections that follow, I present the various practices through which bodies and buildings were made to relate in interdisciplinary negotiations of indoor air pollution and human health. I specify three different disruptions bodies posed to the insides/outsides, bodies/buildings, subjects/objects that shaped the way exposure was materialised.

The Case Study: Modelling Indoor Air Pollution Exposure Risk

The interdisciplinary framework of the project meant that different ways of apprehending the air were made explicit in scientific discussions. These differences underpinned the wider ethnographic study of air pollution science in action. A work package dedicated to the study of domestic environments responded to a wider concern in air pollution science; that improved methods and interdisciplinary ways of working are required to measure the air that people actually breathe (Kelly and Fussell, 2015, author’s emphasis). The project therefore addressed a criticism that epidemiology dedicates too much attention to estimating risk and population vulnerability to outdoor environmental hazards at the expense of ignoring others, including, for instance, the variation in kinds of housing and dwelling may influence exposure in the indoor environment (Taylor et al., 2016; see also Krieger, 2001). Indeed, studies of domestic environments have shown exposure to pollutants from indoor sources is specific to these spaces rather than purely the result of pollutants from the outside infiltrating the inside (Shrubhole et al., 2012). Indoor air like outdoor air is spatially varied and measuring how buildings ‘modify’ population exposure risk significant for public health and policy legislation.

By focusing on the practices and processes involved in developing and running a building model, I was able to examine how indoor air quality and health outcomes were studied, articulated and made to relate in scientific research practices. This directly engages with the challenge of insides/outsides inherent to questions of exposure. It does so, in the first instance, in a common-sense way: the building is framed as producing an inside/outside distinction and this is modelled through an equation called the inside/outside ratio (I/O) that calculates the rate at which air moves between the inside and outside.
of buildings. This ratio is affected by diverse things and processes that are important for understanding indoor air quality. In some ways, the I/O ratio is analogous to breathing because it involves a flow and transformation of air inside and outside in ways that also blur their co-relation. However, to model the I/O ratio and make it relevant to questions of human health requires the iterative addition of things beyond a building’s physical properties, including people, bodies and wider atmospheric dynamics and processes.

**Insides/Outsides 1: Building an Exterior for Measuring Indoor Exposure**

A series of architectural layouts of different dwellings were carefully placed on the table in the meeting room where I had arranged to meet one of the air pollution project’s PhD students, Amy. Amy was developing a ‘representative stock’ of UK dwellings. Building stock are data sets containing qualitative and numerical measures of the material composition, form and geographic location of different kinds of buildings. Using data collected by the English Housing Survey, and through secondary research of architectural layouts, Amy’s research involves developing details about the geometry of dwellings. She told me that later she would include the size, age, cardinal direction, level of ventilation and fabric of these dwellings based on a UK database of data on home energy efficiency. Together, the different data formed the baseline inputs for the building model.

From these baseline inputs, the broad archetypal descriptions are complemented with variables that change over time. There are many different possible variable combinations that can be calculated, from testing different building fabrics to measuring the effect of different number of occupants in a dwelling. The parameters for which variables to test were set according to those considered most significant to air quality. To do this, Amy worked through a subset of dwellings in London to better understand which variables might be most relevant for the project’s interest in air pollution exposure and health outcomes:

So, we simulated them, and the combination was a few hundred, then we simulated the flats, because within the nine geometrics we had to simulate them three times for ground floor, mid floor and top floor. In total, we had twenty-seven archetypes, and then we simulated them with and without night ventilation [e.g. windows open, or not], which
makes a huge difference [...] We simulated four different orientations because you don’t know exactly the percentage of houses orientated North or South. (Amy, Interview, February 2011)

Working out what combination of variables matter involved a series of preliminary simulation runs, the results of which were then shared in several of the weekly team meetings. By differently arranging combinations of variables, indoor environments could be specified according to specific variables of interest. The variable of window opening is emphasised by Amy in the quote above. Window opening is a difficult variable to model because it is influenced by human behaviour and building characteristics. Although the effects of open and closed windows can be modelled, uncertainties around when windows are open are more difficult to model. Window opening also disrupts I/O ratios in ways that destabilise the quantifiable relationship of the movement of air between the inside and outside of buildings. By sharing the preliminary simulation runs with the team, window opening as a concern in building physics converged with interests in epidemiology, and the material and relational dimensions of the indoor environment became relevant to questions for public health (Landström et al., 2011).

**Insides/Outsides 2: Unfolding Relations between Bodies and Buildings**

The movement of outdoor air pollution inside (infiltration) and the movement of indoor air pollution outside (ventilation) cannot be quantified by building structure and fabric alone because people influence rates of air flow through their interactions with buildings (Fabi et al., 2012). Occupancy scenarios are often used to test different kinds of human interactions with buildings. In this project, occupancy scenarios were developed through primary research, based on one researcher’s family (Interview, March 2012), and drawing on findings from previous empirical studies (Dubrul, 1988; Shrubsole et al., 2012). The scenarios developed used the same two parent, two children family living in a semi-detached house for which specific quantifiable building characteristics had been identified. Keeping the scenarios and buildings the same and just changing window opening practices meant how window opening influenced indoor air quality could be better understood. Infiltration rates were calculated according to the permeability of externally exposed
facades and internal doors were modelled as closed. Simulations were then run for two different window opening occupant scenarios: one in which windows are always closed and one in which windows are open at night, during cooking and if temperatures increased to 25°C.1 By using the same occupancy scenario, the quantifiable effect of window opening was estimated and changes to exposure risk could then be explained through the opening and closing of windows.

During the presentation of these results by the building modellers at a weekly meeting, where the effects of window opening were further demonstrated, Tim, an epidemiologist, asked ‘[if] it all boils down to window opening, which is partly driven by outdoor or inside temperature, can we assume a constant ratio for everywhere [that is, everywhere with certain temperatures]?’ (Field notes, April 2013). Given the challenge of modelling occupant behaviour and managing unruly bodies (Murphy, 2006), this proposal from the epidemiologist suggests that indoor environments can be studied without bodies if the variable of concern shifts to temperature (rather than human occupants). If temperature is related to window opening and temperature’s role in shaping certain kinds of human behaviour standardised, then perhaps a separation between building and body could be maintained?

Reducing building–body relations to the variable of temperature was disrupted by other processes affected by window opening, however. Indeed, the results also showed that in hot periods temperature-dependent window opening increased specific kinds of pollutants. As well as controlling for the agencies of human bodies, particles also play a role in shaping indoor air quality through window opening. Subjects and objects blurred here because the object of concern air pollution became the subject affected by buildings and bodies. If temperatures rise inside and windows are opened, then outdoor fine particulate matter (e.g. PM2.5) can be higher inside buildings than outside them. This pattern wasn’t consistent across all building kinds. Based on the London simulation results, researchers found that in areas where dwellings are less dense exposure risk to PM2.5 increases as temperatures increase and windows are opened (Field notes, team meeting, February 2014).

Based on these findings, the modellers proposed that in densely populated areas dwellings might have a protective effect because the
model showed that indoor PM$_{2.5}$ was not as high in urban centres as suburban peripheries:

[... ] in urban centres, there are flats and in the suburbs semi-detached and detached houses. The grouping of multiple dwellings in urban and non-urban spaces also effect levels of particles inside buildings. (Building modeller, team meeting, February 2014)

This conclusion challenged the anticipated finding that urban centres increase exposure risk because of higher ambient (background, outdoor) air pollution. The model outputs showed that even if the air pollution outside is lower than in more populated urban centres occupant exposure was relatively higher inside buildings. As well as a building’s physical characteristics, the modelling results indicated that the spatial relationship between buildings had a modifying effect on exposure risk. The effect of temperature on window opening practices could not be assumed as a constant ratio everywhere, as Tim initially proposed.

*Insides/Outsides 3: Blurring the Subjects and Objects of Exposure*

As well as confirming the measurable effects of window opening on exposure risk, the simulation results determined new relations between bodies, buildings and air pollution. Occupant bodies were shown to participate in the way buildings breathe and shift inside/outside relations in ways that reveal new relationalities (e.g. between buildings and between particle kinds). Through modelling different dwelling typologies in London, indoor air quality was not only defined by the physical characteristics of dwellings but also through the arrangements of similar and different buildings. By extending beyond the building’s parameters to its proximal relationship with other buildings, ‘the building’ in the building modellers work could be made to relate health in terms of socio-geographic place, and, potentially, the different kinds of spaces places produce.

Window opening, then, performed exposure in new ways. The inside/outside relation was, subsequently, reconsidered because indoor air was partly defined by human and non-human bodies. Pollution does not just move inside and outside in ways that affect the amount or concentrations of pollutants because what the chemical composition of air is was also shown to transform. The particles
animated through the modelling of occupancy scenarios shone light on emergent, fractured and indeterminate spatial and atmospheric mixings. In addition to the agencies of human bodies, which were partially managed through occupant scenarios, particle bodies were also seen as ‘behaving’ in buildings in ways that influenced other bodies and processes (other particles, human occupants and building infrastructures).

Instead of infiltration/ventilation, which assumes a stable inside/outside relation, other concepts for describing atmospheric dynamics were deployed by the building physicists to help manage and respond to this new disruption of bodies. Specifically, the concepts of suspension and deposition were proposed as a way to account for the way air moved, and particles accumulate or disperse. For example, vigorous walking, dusting and vacuuming lead to a resuspension of particles in the air that are more easily inhaled (Long et al., 2001). By understanding the circumstances in which particles are held in the air (i.e. suspended) or settle on surfaces (i.e. deposited), the ‘domestic coordinations that mediate and produce’ (Kelly et al., 2017) situations of exposure, where concentrations of breathable particles increase, could be calculated.

By iteratively including the outside inside (Philippopoulos-Mihalopoulos, 2016), the different objects and subjects of concern (of ‘environments’ and ‘bodies’, primarily) further blurred. Human occupants were revealed as shaping the composition of particles and these particles then behaved in response to the respiratory dynamics of buildings and bodies. Unlike the concept of indoor environments, attention to the ways in which different bodies shape spaces of exposure is encouraged by thinking through breath. It also draws attention to the composition of air as a dynamic interplay of more-than-human agencies and transformations. Breathing spaces are sites where the social relations of bodies and environments are reshaped and specified (Biehler and Simon, 2011: 174). For instance, suspension/deposition highlighted the different scales at which indoor air quality is affected: from the macro-infrastructural factors that influence the physical arrangements of dwellings (inside/outside 2) to the more micro-material processes like cleaning that comprise lived domestic environments (inside/outside 3) (Wakefield-Rann and Fam, 2018). These alternative narratives of toxic agency (Waterton and Yusoff, 2017) were enabled through the decentring of the bounded human
body as a site of exposure. Rather than different airs and similar bodies, which underpinned the project’s concept of exposure when starting out, the iterative tinkering to the model simulations rendered visible the way bodies participate in their co-composition, expanding the non-linear and intra-acting agencies that had been accounted for in order to understand and measure health risk.

**Concluding Discussion**

The practices involved in computer modelling indoor air made explicit the differences performed by researchers around what to include in the ‘inside’ and therefore what counts as exposure (Landecker, 2011). Natasha Myers (2015) has shown how modelling encourages livelier ontologies in science. In one anecdote she describes the ways in which modellers let protein molecules ‘breathe’ by capturing their affects and behaviours through embodied research practices. In this case study, exposure could only be measured if the way bodies breathe and transform sites of exposure were captured in the building model. It was by including the material transformations of bodies and air inside and outside buildings that their mutual respiratory dynamics were made tangible and the object of further scientific inquiry.

Focusing on the modelling process, this article traced how people’s bodies disrupted practices of measuring exposure, and unpacked how these were then addressed by team members. Starting out with attempts to define the inside of buildings from the outdoor environment, the first disruption I presented was window opening. The challenge of window opening meant calculations for determining a contained interior within which people breathe had to be modified. Although attempts to standardise the role of occupant behaviour (e.g. when and in which rooms windows are open) on air flow rates in domestic environments momentarily held stable the body as a discrete entity (by using proxies of temperature), particles inside buildings were also found to affect and be affected by window opening. The movement of particles inside and outside buildings could only be estimated if the way in which occupants influence the quantity and chemical composition of particles was modelled. These more-than-human processes and affective qualities of air were ultimately formalised as relations of suspension and deposition, which
are different to infiltration and ventilation because rather than defining the interior through its relation to the exterior the inside emerges from an intermingling and mixing of different agencies. These disruptions challenge notions of bodily and environmental integrity, revealing new concerns, including the role of human bodies in the composition of indoor air pollution and the respiratory dynamics of buildings (Brown, 2017). The implications of this empirical reorienting towards the nonlinear and relational (Wakefield-Rann and Dam 2018) co-constitution of indoor environments were twofold. First, the body ecologies that compose buildings and breathing spaces made visible corporeal agencies that affect environmental conditions. Second, developing a geographic attunement to potential differences in exposure foregrounded the social and political structures that shape pollution and health. For instance, how buildings are spatially situated and arranged was shown to be crucial to estimating the specificities of toxicity, and therefore rather than the domestic environment in isolation, its relation to wider urban infrastructures and social processes were made relevant to the project’s framings and findings of the issue. I built on the concept of breathing space (Mitman 2008) to draw out the ways in which indoor ecologies affect the material and chemical composition of bodies and air (Stephens et al., 2015). Attempts to calculate exposure risk, and thereby find ways to mitigate it, proved tricky because a contained interior in which human occupants live and breathe could not be materialised. By disrupting the idea of a stable inside, breathing bodies produced new atmospheres of concern that were constituted through the respiratory dynamics of occupants and dwellings and human and non-human bodies. Examining what breathing spaces bring into view indicates the need for a different immunological vision (Kelly et al., 2017) in public health approaches to air pollution. Including the ways in which bodies and buildings breathe offers a broader range of possibilities in scientists’ thinking, imaginings, narratives and practices around air pollution exposure (Blackman, 2010: 3).

Breathing spaces responds to sociological and anthropological discussions of bodily integrity and immunity to demonstrate the multiple ways in which insides and outsides are produced, and to find a way to contribute to discussions about how they might be better managed (Roberts, 2017; See also Wakefield-Ran et al.,
As the modelling process highlighted, defining sites and spaces of exposure in relation to a stable human occupant risks ignoring complex urban geographies and in between spaces that can determine social differences in exposure, the subtle yet (as the scientific research that informs this article suggests) significant effects of dwelling differently, (e.g. that don’t conform to the nuclear family model) and the everyday practices that might ‘design’ and transform the air (Zee, 2015; see also Calvillo and Garnett 2019). Domestic environments are clearly relevant for public health research around air pollution; however, by attending to bodies as generative of spaces through breathing, corollary questions can follow, about what spaces matter because of the bodies that live and breathe in them. Finally, interrogating the ways in which bodies and air are imagined in models of exposure – either in domestic environments or other spaces of concern – is a starting point for asking more critical questions about air pollution itself.

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Note
1. This temperature threshold was based on temperature-related comfort standards from the Chartered Institution of Building Services Engineers.

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