Unstable air: How COVID-19 remade knowing air quality in school classrooms

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Abstract

Air quality is neither a stable material phenomenon, nor form of knowledge. This was made clear upon the arrival of COVID-19 in school classrooms when humans emerged as the primary source of poor indoor air quality (IAQ), and a host of new devices were placed into schools to monitor and clean IAQ. In this paper we examine this instability as it had consequences within a research-business project attempting to measure IAQ and assess the effectiveness of an air cleaning device in school classrooms pre- and post- the emergence of COVID-19. Using a 'near' Actor-Network Theory analytical framework we focus on how a network of 'science in action' became re-assembled to COVID-19. Drawing on IAQ data that we collected, government and industry statements and reports, and the direct involvement of the lead author using both reflexive and relational ethnographic approaches, we show how our IAQ measurements, combined with other material inscriptions, were powerful actants that changed the relationship between the air indoors and outdoors. We bring Maria Puig de la Bellacasa's concept of 'matters of care' into conversation with the project detailing how changing socio-material circumstances led to a more active role to reconfigure classroom IAQ, and how we might better care for IAQ in the future. We also relate our project to the wider – and ongoing – process of reassembling IAQ, asking how this might relate to questions of inequalities and responsibilities.

Keywords: Air pollution; COVID-19; Indoor air quality, Matters of Care, Actor-Network Theory

Introduction

Air quality is neither a stable material phenomenon, nor form of knowledge. What constitutes good or bad air seemingly consolidates in maps and graphs of gaseous or particle concentrations, in standards and thresholds, and in 'metrological regimes' of measurement and organized governance (Barry, 2002; Calvillo, 2018). However, air quality's stability is illusory. What is judged to constitute the safe and the harmful, the naturally clean and the human contaminated, is always a cultural matter that shifts over time (Douglas, 1966). For the air of contemporary worlds, developments in scientific knowing of the air and its consequences have been important in repeatedly moving on established understandings, along with innovations in technologies for appraising the air's constituent elements (Whitehead, 2009). As new material entrants into the air have been encountered where they were not before, and as the meaning and experience of being polluted (Bickerstaff, 2004) has become contested and politicised, investments in knowing, ordering, and organizing the governance of the air have also shifted and evolved. As scholars drawing on perspectives from science and technology studies (STS) have emphasised, the air and the diminishing of its quality is a thoroughly 'hybrid' sociomaterial phenomenon (e.g. Clifford and Travis, 2020; Cupples, 2009; Garnett, 2016). Thus, notwithstanding the air materially existing independently of us, "atmospheric scientists produce the air" (Cupples, 2009: 213), but not in a way that ever finally resolves what it is they are producing.

In this paper, we build on this foundation to examine how the air and its qualities became made, known, and organized differently following the arrival of SARS-CoV-2 – the virus that causes COVID-19 – into the atmospheric immersions of breathing bodies. Whilst evidently a truly global experience, we focus here specifically on how COVID-19 entered into a process of knowing and attempting to improve the air for vulnerable bodies that was already underway as the pandemic took hold. We trace how the virus, as a potently agentive actor, reconfigured some core constituent elements of an applied research-business project, both measuring indoor air quality (IAQ) in school classrooms and assessing the effectiveness of air cleaning technology in stripping out elements that had been generated indoors, and / or found their way inside from the outdoors. Using a 'near Actor-Network Theory' (near-ANT) analytical framework (Farías et al., 2020: xxii), we focus on how a network of 'science in action' (Latour, 1987) became re-assembled to a new and intensely problematic component of the air in-between breathing bodies.

In this paper we investigate the organization of breathing in school classrooms following the emergence of COVID-19, showing how a variety of human and non-humans were enrolled, changing definitions of what constituted good IAQ, and the relationship between the air indoors and outdoors. Moreover, we draw upon the direct involvement of the lead author – who was a key actant involved in the co-production of the materiality produced by the IAQ monitors and its subsequent recasting in practice – using both reflexive (Aull Davies, 2012) and relational (Desmond, 2014; Simon, 2013) ethnographic approaches to show how new 'matters of air-care' (Brown et al., 2020; Puig de la Bellacasa, 2011) were enacted as the goals of the research project actors changed. Through looking at our 'production' of the air, and its entanglement within a "complex assemblage of people, places, materials and technologies" (Weber, 2021: 181), we interrogate the particular organization of sociotechnical infrastructures that made perceiving and responding to the air possible. We finish by relating our case to the wider reassembling of classroom IAQ and speculating on whether these reconfigured pandemic assemblages are here to stay, and what that might mean for inequalities. We begin by outlining the reason for our focus on the air we breathe indoors, summarising aspects of the natural and social science literatures, as well as the implications of COVID-19 on this domain.

Literature review: The indoor-outdoor air continuum and the virus

For air quality science, outdoor 'ambient' air has long been its primary focus (AQEG, 2022). With increasing precision and differentiation, the emission, circulation, accumulation, and dispersion of pollutants into the atmosphere has been measured, analysed, and modelled, with a particular focus on urban and industrial settings. As a consequence, there is now a considerable body of knowledge (at least for some places) about what outdoor airs are made up of, including how air quality can vary spatially such as street by street (Apte et al., 2017), and change over time with the rhythms of its making and interaction with atmospheric processes (Walker et al., 2022). Much knowledge has also been accumulated on the consequences of breathing in polluted air, the extraordinary number of deaths per year this breathing is implicated in (HEI and IHME, 2020), and who is particularly vulnerable to these consequences. Amongst those deemed the most vulnerable, children figure centrally. Children have been found to be especially susceptible to outdoor air pollution due to a combination of factors (WHO, 2018). Behaviourally, children are more physically active than adults, and therefore have a higher inhalation rate relative to body mass, meaning that they breathe in more air pollution (Royal College of Physicians, 2016). Environmentally, these inhalations occur closer to the ground where outdoor air pollutant concentrations tend to be more concentrated (e.g. Kenagy et al., 2016). Physiologically, children have narrower airway passages that when inflamed have a proportionately greater airway obstruction and can exacerbate existing respiratory conditions such as asthma (Takenoue et al., 2012).

However, breathing clearly happens both outdoors and indoors, and over recent years air quality science has increasingly been focused on indoor air, with attention to what is added to the air by indoor activities and technologies (for example, cooking, wood burners, paints, cleaning products etc.), how polluted outdoor air can get inside buildings and contaminate indoor environments, and the role of ventilation in mediating flows of indoor-outdoor air quality (which is often measured using carbon dioxide, a component of the air to which we later return). These flows are of particular concern for school IAQ research, with a wealth of studies exploring the links between traffic air pollution around schools and school children's health (e.g. An et al., 2021), and cognitive development (e.g. Sunyer et al., 2015). Despite people in Western industrialised countries spending more than 90% of their time indoors (Klepeis et al., 2001), and the potential for personal exposure to be greater indoors rather than outdoors (Vardoulakis, 2009), IAQ science has remained mostly "undone" (Frickel et al., 2010). Notwithstanding a growing interest in the materiality and politics of breathing, including some recent special issues (Kenis and Loopmans, 2022; Oxley and Russell, 2020), the indoor environment remains a comparatively less studied domain. Indeed, Biehler and Simon (2010: 172) have explicitly called for "more attention to indoor environments as active political-ecological spaces" that both engage with the material movement of ecological systems (such as outdoor air pollution drifting through an open window), but also "the assemblage of institutions and individuals vying to control the governance of those systems" (Biehler and Simon, 2010: 186). There have been some notable contributions in this space, including those focused on key themes to investigate in the urban indoors (Graham, 2015), on different modes of knowing the air indoors (Altman et al., 2008; Garnett, 2020; Shapiro, 2015), and on how uncertainty is politically weaponised (Grandia, 2020;

Murphy, 2006). The intersection of STS and organization studies is beginning to be examined for outdoor air quality, such as by Weber (2021) who looks at how the air outdoors is perceived through organized physical, chemical, and informational filters to create data. However, we can also bring these investigations indoors, outlining the processes and practices that shape sociomaterial relations within buildings.

The arrival of COVID-19 had consequences for both outdoor and IAQ. Outdoors was generally seen as a safer place for breathing in terms of viral transmission, but the impact of lockdown rules on emissions from traffic and industry precipitated the largest ever air pollution 'natural experiment.' Lockdowns and work from home directives led to drastic reductions in emissions from traffic and industrial sources (Doumbia et al., 2021), and, depending on the local weather (Matthias et al., 2021), and atmospheric composition (Kroll et al., 2020), reduced gaseous and particle concentrations in many locations (Rodríguez-Urrego and Rodríguez-Urrego, 2020; Venter et al., 2020). For the indoors, work from home directives (for those that could do so) are hypothesized to have increased residential indoor air pollution (Adam et al., 2021), including from new social practices around 'hygiene theatre' (Kale, 2021), which increased the use of surface disinfectants and hand sanitisers which exacerbated concentrations of certain volatile organic compounds (VOCs) indoors. More fundamentally though, viral transmission risks through the air in indoor environments became the object of intense attention, uncertainty, and controversy, with different scientific definitions of what constitutes 'airborne' (Randall et al., 2021), and focuses on different particle sizes, namely droplets or aerosols (Jimenez et al., 2022). In schools specifically, this led to the prioritisation of a host of different classrooms interventions, with proponents of droplet transmission favouring surface disinfection and lateral plexiglass barriers, versus aerosol transmission advocating for a 'paradigm shift' to increase ventilation rates through behavioural modifications (e.g. window opening) and mechanical technologies (e.g. heating, ventilation, and air condition [HVAC] systems, and air cleaning devices) (Morawska et al., 2021). These contestations neatly highlight how during the pandemic "the sociomaterialities of air, breath and the ventilation of spaces" became "central features of COVID-19 risk discourses, as have the policies, objects and practices used to manage air flow" (Lupton and Lewis, 2022: 131). This was very much the case for the project that provides the focus of our analysis, which we now introduce into the discussion.

Methods: Interrogating the project

The project in which the lead author of the paper was a participant was set up by a sustainable technologies company, in partnership with a leading behavioural change charity, an air cleaning technology developer, and NAQTS, a company that designs and develops IAQ monitors.[1] The project was established to see how well air cleaning technology works to provide safe IAQ. The focus of the project on school classrooms reflected the well-documented understanding of children's vulnerability to poor air quality, and the significant amount of time children spend at school.

In the initial project design, IAQ monitors were deployed for the 2020 spring term in 20 classrooms across England and Wales. However, these measurements took on a different character due to COVID-19, at least in part because we inadvertently ended up measuring – and filtering – the air of empty classrooms. Subsequently an additional measurement

[1] A company co-founded and run by the lead author.

campaign in 6 of the original 20 schools in the 2020 autumn term was planned to gather more data. These two terms can broadly be read as pre- and post-COVID-19 measures. This paper draws upon carbon dioxide (CO_2) measurements specifically, as an indicator of changing notions of good IAQ, driven by a renewed focus on ventilation due to COVID-19.

Some of the applied findings of the project feature in the account that is to follow, but we also draw upon the direct involvement of the lead author in the project, as the CEO of the company that designed and developed the monitoring technology, through examining correspondence between project partners during the process of setting up and carrying out the project.[2] This included emails, project meetings and notes, progress reports, and presentations over more than a year-long period. We look back on the process of the project by deploying a combination of reflexive and relational ethnographies to both look at how "the products of research are affected by the personnel and process of doing research" (Aull Davies, 2012: 4) and also how "configurations of connections, transactions, and unfolding relations" (Desmond, 2014: 574) influenced how the doing of science was adapted to deal with the emergence of COVID-19. This relational element importantly includes a sociomaterial perspective to highlight the role of non-humans in the construction of social worlds. The account is necessarily one of a 'partial perspective', recognising that the knowledge produced is inherently 'situated' (Haraway, 1988). This includes what was measured and with what devices, who made the measurements, and where they were taken. However, by attempting to hold on to "both ends of the

[2] Ethical approval was obtained from the Lancaster University Faculty of Science and Technology Research Ethics Committee (FST20161) to both use the air quality data generated in this project, and the ethnographic insights from correspondence between project partners.

dichotomy" (Haraway, 1988: 180) of objectivity and relativism, by both showing the contingency of our knowledge claims and the material reality of the air that we measured, we aim to explore how the doing of science was produced and how it was destabilised and had to reform in response to a potent new actant. We also analyse government and industry statements and reports on ventilation strategies during the pandemic.

To do so we draw upon Actor-Network Theory (ANT) to think through air quality's sociomaterial instability. ANT is an approach that envisages sociomaterial worlds as a set of ever shifting networks (Latour, 1987). ANT focuses on describing these worlds through tracing the relations between different actors in these networks (Latour, 2005). A key argument of ANT is all that entities in the world have the same potential agency to configure action, human or non-human (Sayes, 2014). In practice, ANT is less of a theory, or toolkit, and more "a highly mobile label for a stabilised conceptual repertoire concerned with generalised symmetry, networks and non-humans" (Farías et al., 2020: xxii). We position ourselves as working 'near' ANT (Farías et al., 2020), a term we mobilise both to recognise our close association with ANT, but also other more-than-human approaches to social inquiry (Farías et al., 2020). This does not mean to imply that we 'nearly' provide an ANT account. Rather, that we use ANT as a companion with "an adaptable, open repository. A list of terms. A set of sensitivities" (Mol, 2010: 253). We do mobilise some specific concepts from ANT that have been widely used in the social sciences, and in a sense transcend the ANT label. However, we also draw upon concepts that run alongside ANT, such as 'matters of care' (Puig de la Bellacasa, 2011). In using this near-ANT approach, we contribute to discourses around 'intervention' (Zuiderent-Jerak and Jensen, 2007), or 'intravention' (Estalella and Criado, 2018) in social research. This is of relevance both to increasing calls for ANT to positively intervene (López-

Gómez, 2020), and for air quality science to be more ‘critical’ (Booker et al., 2023) and think carefully about its sociomaterial implications.

Unsurprisingly, our study is not the first to cast COVID-19 as a strikingly powerful actant. Indeed, Latour argues that it is an “incredible demonstration of network theory” showing “how quickly something can become global just by going from one mouth to another” (Watts, 2020). COVID-19 has been mobilised in all sorts of contexts, enacting the agency of a variety of non-humans including facemasks and toilet paper (Sikka, 2021); educational technologies and digital infrastructures to facilitate remote learning (Pischetola et al., 2021); and algorithms for contact tracing and risk assessments (Liu, 2021). We now turn to characterising the classroom assemblage as it was configured before the emergence of COVID-19.

Assembling the school classroom and its air: pre-COVID-19

A school classroom can be conceptualised as an assemblage of human and non-human actants, including pupils, teachers, assistants, cleaners, governors, textbooks, desks, computers, school timetables, school rules, curricula, among a host of other things. Given our analytical focus, we would also add windows, doors, ventilation systems, breath and breathing, the air itself, and its chemical and particulate constituent elements to this network of actants.

Our research project, with its intent to both monitor and intervene in air-relevant elements of the assemblage, added two new material actants into the school classrooms: an air quality monitor and an air cleaner. For these devices to be successfully enrolled it was pivotal that they did not disrupt the functioning classroom, and that they would slip away into the background as intermediaries free to measure and filter the air quality uninterrupted. As shown in Figure 1, both devices were however in plain sight in the classroom, in part because for them both to function well, they needed to be in close association with the breathed air of the classroom.

Figure 1: One of the school classrooms where we measured and cleaned the air

The IAQ monitor, the NAQTS V2000 (hereafter referred to as the 'V2000') is a micro-sized air quality monitoring station (NAQTS, 2022), designed and developed by the company that the lead author runs. It was selected for this project due to its capability to measure a range of different air pollutants and environmental conditions, coming from a range of different sources. This pliability was designed in to the V2000 to both align with dominant scientific and medical research focuses on specific pollutants, but also to respond to emerging pollutants of concern, namely ultrafine particles (UFPs): the smallest size fraction of particulate matter (PM) (AQEG, 2018). These pollutants are outlined in Figure 2, taken from an internal project presentation. Indeed, without the V2000, many of these elements would remain intangible as perceiving them is "inherently intertwined with the technical infrastructures that produce our relation to it" (Weber, 2021: 176). The V2000, a literal 'black box', acted in this capacity for the project, with its role being understood as air in, data out, with its internal workings of air quality sensors, electronics, and algorithms remaining hidden from view. The V2000's role was to collaborate closely with the air cleaner, which continuously filtered a wide range of pollutants using different technologies from filters for particulates and gases, to disinfecting lamps.

Figure 2: Overview of the air pollutants considered in the project, both for IAQ measurement and cleaning.

The V2000 became an obligatory passage point (OPP) for the project, as only air that would pass its sensors would be enrolled into the process of knowing the air in the classroom and would come to count. Indeed, even with the array of different measurements provided by the V2000, such is the nature of air quality science that one cannot measure the air in its entirety: some elements are destined to remain intangible, unmonitored, and unknown. None more obvious than SARS-CoV-2 itself, as it would only be after COVID 19's emergence and combination with other material inscriptions that it would emerge as something that was being measured (albeit indirectly, a point we return to later). The V2000 also acted as the 'spokesperson' for NAQTS during the day-to-day running of the project. That is, the actant that defined the interests of the group. Its role was to demonstrate its effectiveness at measuring a wide array of different air pollutants, as a business technological offering. As with the V2000, the air cleaner also acted as the spokesperson for its makers and sellers, providing a demonstration of its agency in cleaning the air, shifting from the laboratory to the real-world.

Carbon dioxide as a proxy for indoor air quality

As shown in Figure 2, CO_2 was one of the parameters measured in the project in its pre-COVID-19 form. CO_2 in indoor environments is primarily the consequence of human exhalation, and has been an integral part of understanding IAQ and building ventilation for over 150 years (ASHRAE, 2022). Despite historical disputes over whether it is an excess of CO_2 or a reduction of oxygen that causes the tangible sensations of 'stuffiness' and 'bad air' indoors, since 1872 CO_2 has been seen as a useful surrogate for bad air, rather than an air pollutant in of itself (Janssen, 1999). There is still considerable ongoing research evaluating the effects of CO_2 on a range of different health outcomes, including worsened cognitive functions, and sick building syndrome symptoms. Nonetheless, it is still not possible to judge whether CO_2 itself is responsible (Lowther et al., 2021).

This surrogacy, or proxy status, has underpinned the development of modern standards for managing ventilation. Indeed, CO_2 has its own centres of calculation where knowledge production is stabilised, so that the construction and dissemination of knowledge can move more easily to other places. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the European Committee for Standardization (CEN), underpin most modern North American and European ventilation requirements. In 1989 ASHRAE designated a limit of 1000 parts per million (ppm) of CO_2 as an indicator of an appropriate air ventilation rate per person (ASHRAE, 2022). However, despite this figure not being based not on IAQ per se, but on the perception of human body odour by building occupants, it has commonly been misunderstood as an indicator of acceptable IAQ (ASHRAE, 2022), and has continued to permeate ventilation practice in a range of different settings.

The governance of the air in school classrooms is a fractured affair. There are a variety of different standards and protocols to organize the school's air and air infrastructure, from standard building codes, to health and safety regulations, to specific requirements for special rooms such as science labs. Building Bulletin 101 (BB101) is the main reference document for ventilation, thermal comfort and IAQ in school buildings in the UK and was initially released in 2006 and last updated in 2018. As of the 2018 update, it provides performance standards for CO_2, with the following key recommendations on concentrations (ESFA, 2018):

- For mechanically ventilated buildings, a daily average concentration of CO_2 of less than 1000 ppm, during the occupied period. The maximum concentration should also not exceed 1500 ppm for more than 20 consecutive minutes each day.

- For naturally ventilated buildings, a daily average concentration of CO_2 of less than 1500 ppm, during the occupied period. The maximum concentration should also not exceed 2000 ppm for more than 20 consecutive minutes each day.

Despite these standards, neither BB101 as guidance, nor the CO_2 sensors that were installed in some school classrooms had enrolled sufficient support to in practice control the CO_2 content of the air in school classrooms. Indeed, research carried out in school classrooms prior to COVID-19 demonstrated that many classrooms regularly exceeded the limits outlined in BB101 (Chatzidiakou et al., 2012; Mumovic et al., 2009). Similar trends can be seen in the first phase of 'pre-COVID-19' measured data the V2000 produced in our project (see Figure 3), with the daily mean CO_2 concentrations varying from school to school, and some not complying with the BB101 thresholds.

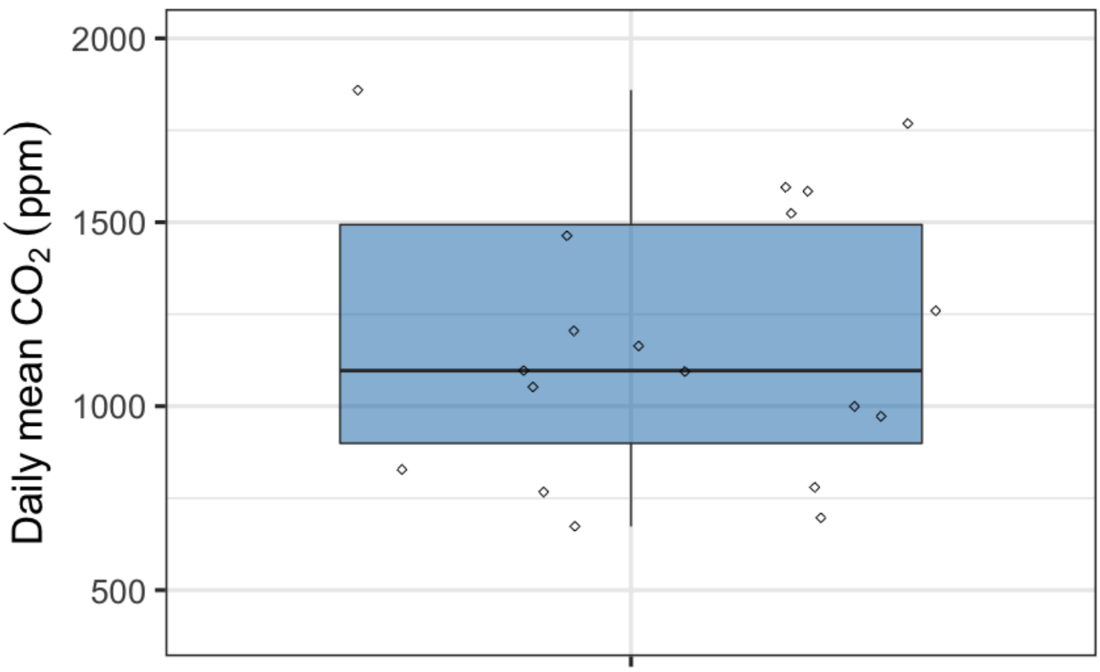

Figure 3: Box plot of the daily mean CO_2 concentrations across the 20 schools before the first COVID lockdown. Each point is a school. The lower and upper box boundaries represent the 25th and 75th percentiles respectively. The line inside the box is the median value.

This shows that BB101, prior to COVID-19, was not a particularly forceful actant in the school classroom assemblage. This changed however, and we will show how the creation of a ‘structured envelope’ – that is, the social, technical, and political context that permits or prevents the mobility and durability of certain actants – around BB101 (Law, 1984), including the installation of CO_2 sensors, became an ongoing process of stabilising BB101 as a more forceful actant.

Assembling the school classroom and its air: with COVID-19

The airborne spread of COVID-19 through viral particles quite radically shifted the focus of IAQ in the project from non-human to human actants as responsible for enrolling harmful air contaminants into the assemblage of the school classroom. This change in focus – in part due to the urgent nature of the crisis – led to a critical role for ventilation in bringing in outdoor air to dilute the concentration of the virus (Morawska and Cao, 2020). Often referred to as ‘fresh air’, a notion steeped in the focus on the health effects of exposure to certain pollutants, the promotion of ventilation reinforces the long-standing idea that bringing in outdoor air improves the quality of the air that we breathe indoors, a point we will return to later. In this section we outline how the entry of COVID-19 destabilised the applied research project, now re-directed towards the demands and priorities of the pandemic.

Measuring ‘fresh’ air

To measure how much outdoor air is being brought indoors, we were able to turn to the V2000 as an already present part of the classroom assemblage. Its capacity to generate a wide range of measurements meant that we could readily adapt to the new most important elements of concern, namely CO_2. Directly measuring concentrations of ultrafine particles (UFPs) may have seemed the obvious choice given that the aim of managing pandemic breathing is to dilute the number of indoor airborne viral particles. Indeed, this was something that NAQTS preferred, given its measurement of UFPs is its most novel business technological offering. However, as Latour (2000: 116) remarks, the objects of science, in our case UFPs "will have no scruples whatsoever in […] behaving in the most undisciplined ways, blocking the experiments, disappearing from view, dying refusing to replicate, or exploding the laboratory to pieces." For us, the fact that UFPs (as measured) are so unstable made them hard to discipline: they can be found in very high or low concentrations, they react with other elements of the air including sticking to themselves, and they come from many sources indoors and outdoors. Moreover, to measure UFPs the V2000 simply counts the number of particles in a cubic centimetre with no specific information on what a particle is made of. With thousands of particles typically in a cubic centimetre of indoor air, attributing any one of those to COVID-19 is akin to trying to find a needle in a haystack. All-in-all this makes it difficult to say with any certainty whether high or low concentrations of UFPs necessarily relate to risks of airborne virus transmission. Here the intangibility of SARS-CoV-2 becomes clear, as while it was directly measured, this was not enough for it become known as it is indistinguishable from any other measured particle.

We found a much more willing and enrollable ally in CO_2. Whilst this shift in focus to CO_2 could have destabilised the project by, for example, being at odds with the interest of NAQTS as it side-lined the most novel aspect of its technology offering, this did not happen. As noted earlier, CO_2 in indoor environments primarily comes from human exhalation, so it is a useful proxy for exhaled airborne viral particles (Rudnick and Milton, 2003). It is also very stable, both in the sense that it is an inert gas immune from chemical reactions in normal environmental conditions, and that its outdoor concentrations do not vary greatly. That all means that by measuring changing rates of CO_2 indoors, you can see the rate at which outdoor air is coming in and diluting indoor air. In other words, it can be used as an indicator of ventilation.

The process of measuring the rate by which outdoor air replaces indoor air is typically expressed as the air change rate (AC/H), the measure of the air volume added to or removed from a space in one hour. This is calculated using the CO_2 concentration decay method, which has an experimental logic: 1) CO_2 is injected into a space, 2) the injection is then stopped and the CO_2 is given time to mix so it is more uniform across the space, and 3) the decrease of CO_2 begins and is recorded over a given amount of time, or until the CO_2 concentration reaches a certain threshold (Cui et al., 2015). In our real-world, setting, the injection of CO_2 is provided by the occupants of the school classroom through exhalation. Looking at the variation of CO_2 taken from one of the schools over a week, five distinct peaks can clearly be seen (Figure 4).

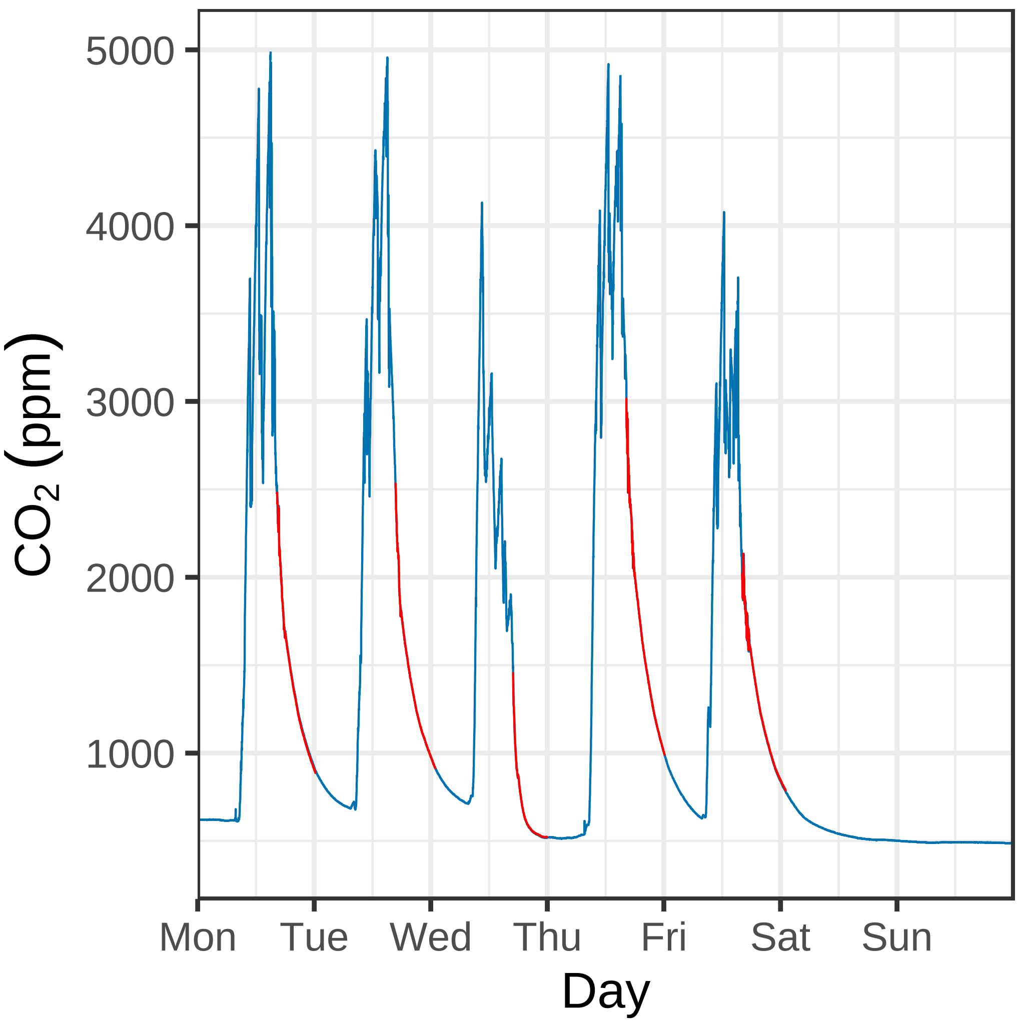

Figure 4: Trends for CO_2 across the week in a single school classroom showing periods of occupancy and non-occupancy. The air change rate is calculated from the decay (in red) at the end of the school day.

The peaks and troughs in Figure 4 are associated with school timetabling, including children leaving the classroom for their breaks. The end of the school day is indicated by the red sections of the line, showing the exponential decay in CO_2 concentrations that occurs when no people are present in the classroom. It is from this period that we were able to calculate the AC/H to understand the rate by which outdoor air is coming in and diluting indoor air. In this way, the translation of a host of different human and non-human actants into a single measure, or material inscription, created an ordered representation of networked interactions, allowing us to provide a quantified judgement of how well a building's ventilation system was performing. This allowed scientific knowledge to effectively circulate both within our project, but also other larger networks concerned with classroom IAQ.

Evidencing potential harm

On their own, the inscriptions generated of CO_2 concentrations in the classroom and ventilation rates did not constitute a powerful mediator that would “transform, translate, distort, and modify the meaning or the elements they are supposed to carry” (Latour, 2005: 39). As explained earlier, measuring CO_2 as an indicator of IAQ has a long history, but with relatively little obvious practical consequence. However, it was the enrolment of a host of other actants, including scientific calculations, and COVID-19 scientific advisory bodies and task forces, that allowed COVID-19 to reassemble the sociomaterial functioning of our project.

The use of the Wells-Riley equation (Riley et al., 1978; Wells, 1955) – a simple and quick assessment of the infection risk of airborne transmissible diseases – was a particularly powerful inscription device during COVID-19. The Wells-Riley equation contains several variables, including ventilation rates, the infectivity of a virus, and the breathing rate of a susceptible individual. Figure 5, applying the formula-based logic of the equation, highlights the importance of ventilation in managing COVID-19 – and other disease – risks, with small improvements in the volumetric flow rate (another measure of ventilation) having significant reductions to the probability of infection. Accordingly, each of the 20 schools’ data for the pre-COVID-19 spring measurement campaign were analysed. When performing the calculation other infectious diseases were used for comparative purposes, to highlight – and make ‘real’ – the airborne infectivity of COVID-19. The different coloured lines on Figure 5 represent different types of infectious diseases, and the dots on each line represent a different school. An increase in *Q*, the volumetric flow rate in metres cubed per hour (m^3 / h), decreases the risk of infection for various diseases. Figure 5 shows that there was the potential for huge reductions in the probability of infection with modest improvement to ventilation. For example, for COVID-19, a *Q* of 50 m^3 / h would see an around 80% probability of a pupil being infected during one school day in the presence of one infected person in the classroom. Whereas a *Q* of 100 m^3 / h would see this probability drop to around 40%.

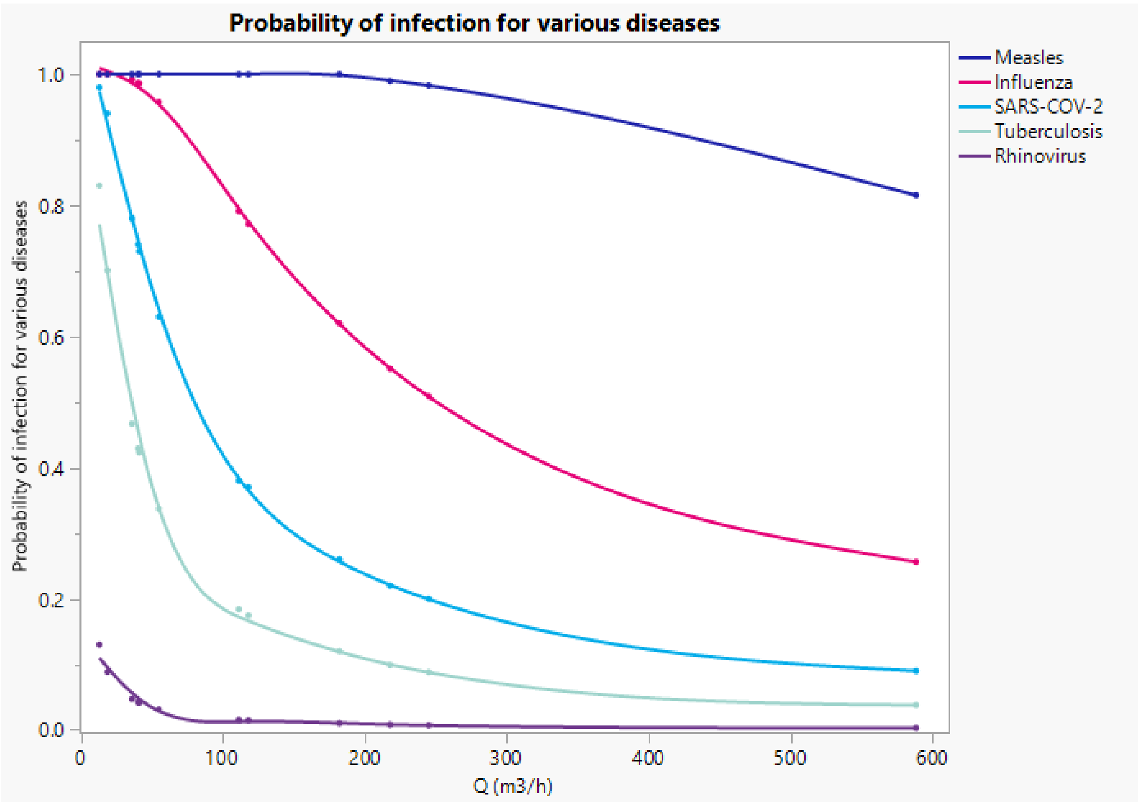

Figure 5: The infection risk of various airborne transmissible diseases calculated using the Wells-Riley equation

It was the use of the Wells-Riley equation that allowed for a figure to be put on the likelihood of contracting COVID-19 based on the measured classroom CO_2 concentrations (Rudnick and Milton, 2003). This helped to form a structured envelope around CO_2 inscriptions, that would permit them to become what Latour refers to as an ‘immutable mobile’ (Latour, 1987), that is, an object that is stabilised by actor-networks and permit the reproduction of actions across different contexts and places. What constitutes breathable air in classrooms was stabilised around this immutable mobile, allowing us to feedback information to the schools on how to improve their IAQ (something that we expand on in the next section). That is not to say that the contents of this immutable mobile, or black box, went undisputed. For the Wells-Riley model, the 'quantum' which represents the 'infectivity' of a virus was a point of contention within the project. The value of this quantum, *q*, is of great significance to the Wells-Riley model, with a greater *q* value increasing the likelihood of infection. Indeed, deciding what *q* to use for our project was a challenging point. An initial choice was made and explained as follows:

> "I have picked the quantum […] related to individuals doing light exercise while talking. This will be a worst case scenario where all kids move around the classroom all day, at full capacity and without any face protection." (Email between project participants, 3rd July 2020).

However, this quantum was later changed, in part considering that using the absolute 'worst case scenario' could lead to unwarranted worry and concern. This highlights the challenges of providing scientific advice when "facts are uncertain, values in dispute, stakes high and decisions urgent' (Funtowicz and Ravetz, 1993: 744).

These inscriptions that we generated destabilised the way the science for the second part of the project was done, and the goals of the research project actors. Indeed, all of a sudden, the V2000 would become not just an intermediary but a powerful mediator in the network. It was no longer transporting traces without meaning, as the CO_2 inscriptions it produced were strengthened by their combination with other scientific equations, forming an immutable mobile, by the humans who spoke on behalf of the network. This immutable mobile would alter the relationship between people at the school and their ventilation systems (whether that be natural or mechanical). We evidence this reassembling in the next section of the paper.

Matters of air-care

Despite early contestations around the ‘airborne’ nature of SARS-CoV-2 (Morawska and Cao, 2020), building engineering advice was early to recommend “that indoor spaces should be ventilated as much as reasonably possible” (CIBSE, 2021: ii) to manage the spread of COVID-19. These industry recommendations were endorsed in written advice by the UK government’s Scientific Advisory Group for Emergencies-Environment and Modelling Group (SAGE-EMG), stating that “ventilation should be integral to the COVID-19 risk mitigation strategy for all multi-occupant public buildings and workplaces” (SAGE-EMG, 2020: 3). These actions were seen as even more important during winter where it was stated that ventilation should be “the primary mitigating measure” (Burridge et al., 2021: 15), as buildings tend to be less well ventilated in winter in order to maintain thermal comfort indoors.

In this context, within the project it was no longer ethically viable for us to remain in the background as intermediaries free to measure and filter the air quality uninterrupted, because the contours of the social fabric surrounding the school classroom and its air had now been made materially visible. Instead, we had to take on a more active role to reconfigure the assemblage during the autumn term through the various inscriptions that were generated. Indeed, the focus of our inscriptions became to *improve* ventilation to minimise airborne virus transmission, rather than to just characterise the effectiveness of the air cleaner. In a sense these are “competing air regimes” (Brown et al., 2020), as increasing ventilation rates can reduce the effectiveness of an air cleaner, as it is much easier to remove an air pollutant from a sealed room, than it is to have the room open to more outdoor air permanently coming in. As Dr Gary Fuller, a prominent air quality measurement scientist aptly puts it, filtering outdoor air is “like trying to take the milk out of your tea” (Fuller, 2018).

Between the two phases of the campaign, the behavioural change charity fed back to the schools on the data collected from the spring campaign through a series of bespoke reports. These reports highlighted the importance of increasing ventilation rates to reduce the infection risk of COVID-19, as well as signposting to other resources to develop clean air action plans to tackle air pollution in and around the school. Ventilation was enacted as a material practice to create breathable classrooms: AC/H increased, and the daily mean CO_2 concentrations in classrooms substantially decreased. Figure 6 illustrates this, with the boxplots on the bottom showing the increase in ventilation rates between the two campaigns, and the boxplots on the top showing the reducing daily mean CO_2 concentrations.

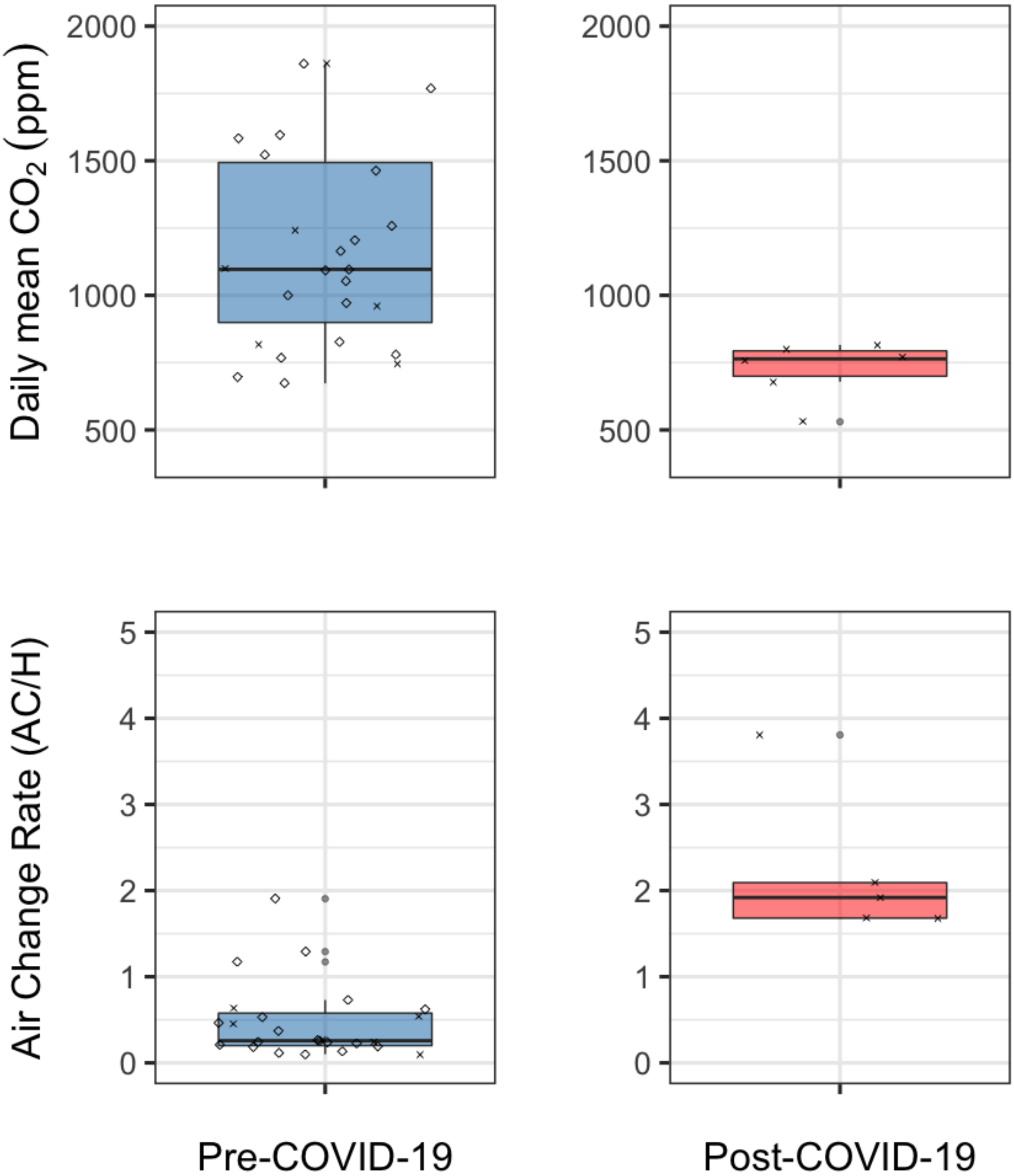

Figure 6: Daily mean CO_2 and AC/H pre- and post-COVID-19 measures. The lower and upper box boundaries represent the 25th and 75th percentiles respectively. The line inside the box is the median value Each point is a school. Pre-COVID_19 figures display data from all the 20 schools. Data points marked with a cross represent schools that were involved in both the pre- and post-COVID-19 measures monitoring campaigns.

These representations enabled the connection of humans to the air in school classrooms to be revealed, and enabled judgements to be made about attempts to reconfigure classroom air to make this connection less prominent. The changed understanding of good IAQ led to CO_2 becoming the dominant measure of IAQ and this, alongside the calculations provided by the Wells-Riley equation, formed the immutable mobile that stabilised our network of science in action and permitted the reproduction of actions across different contexts, ultimately leading to altered material practices around ventilation across the schools in our project. While the extent to which these increases in ventilation were the result of our interventions – rather than wider public messaging – are unknown, they nonetheless highlight a willingness to intervene in the continual unfolding of the classroom assemblage.

The inscriptions which were presented as ‘matters of fact’, denoted where the air was good or bad, breathable or non-breathable. However, Latour’s (2004) concept of a ‘matter of concern’ presents the oft-touted ‘matters of fact’ as being part – and a result – of a wider set of entangled social and political interests. It is easy to see how the enrollment of IAQ monitors and air cleaners, and the business and research interests that they represented can place the matter of facts that we generated into a wider socio-political regime of knowing, and organizing the governance of the air indoors (Whitehead, 2009). However, we argue that the entry of COVID-19 into the school classroom, and the subsequent human willingness to intervene in the continual unfolding of the classroom assemblage, shifted the air from a matter of concern, to a ‘matter of care’ (Puig de la Bellacasa, 2011). Puig de La Bellacasa (2017: 64) argues that “transforming things into matters of care is a way of relating to them, of inevitably becoming affected by them, and of modifying their potential to affect others” (Puig de La Bellacasa, 2017: 64). This distinction extends the care analogy of a matter of concern to advocate for both the material practice of taking practical responsibility and *doing* care, but also as an ethico-political obligation concerned with how “ways of studying and representing things can have world-making effects” (Puig de la Bellacasa, 2011: 86).

Practicing "air care" (Brown et al., 2020) for matters related to air pollution might mean caring for "those who can be harmed by an assemblage but whose voices are less valued […] – for example […] babies in prams whose noses stroll at the level of SUV's exhaust pipes…" (Puig de la Bellacasa, 2011: 92). For matters more directly related to the airborne spread of disease (including COVID-19), it might also mean coughing in the right place at the right time to resolve and displace "pollution anxieties to the immediate atmosphere of the body, to other surfaces, objects, clothing, fabric, hands, materials and handkerchiefs" (Brown et al., 2021: 275)**.** Maybe we were already doing care for the air and its particularly vulnerable breathers by making it visible through monitoring IAQ and filtering it with air cleaners. However, the COVID-19 induced reconfiguring of the role of science in this project produced a stronger ethic of care, becoming less about gathering evidence, and instead focused on intervention and improvement (Levy, 2021).

The principle of action over description following the arrival of COVID-19 raises the question of what IAQ science might look like if general air quality was treated with an iota of the same urgency. Indeed, these tensions form part of a wider discussion on the appropriate role of science when we know that the air is harming people already (Booker et al., 2023). As well as what role ANT accounts can have in a world where producing 'neutral' accounts is less palatable, and instead ANT should aim to positively intervene in the making of our sociomaterial worlds (López-Gómez, 2020)**.**

Still unstable air

In this paper we have shown how the arrival of COVID-19 in school classrooms changed how the air and its qualities became made, known, and organized within our applied research project. However, these orderings remain more generally unstable. Different interpretations of research evidence on transmission pathways for COVID-19, that is whether they are transmitted by droplets or aerosols (Jimenez et al., 2022), has led to the prioritisation of a host of different classrooms interventions. Our project tended towards the aerosol transmission interventions of ventilation and demonstration through CO_2 measurement. However, this raises the question of to what extent our project showcases a process of reassembling that is in some form being reproduced on a wider scale. Moreover, whether this reassembling is here to stay, and how it might relate to questions of inequalities.

Methods of managing COVID-19 are more generally stabilising around aerosol transmission and hundreds of thousands of CO_2 sensors having been deployed in schools around the UK, with specific advice from the UK Department for Education (DfE) about where to place the sensors, how to interpret their readings, and what actions to take if concentrations are above certain thresholds (DfE, 2022b). Surveys undertaken by the DfE in June 2022 suggest that:

> "96% of settings that responded to the survey confirmed they had begun using the CO_2 monitors provided… Of those settings that had begun using the monitors: 95% confirmed they were able to use them to identify when ventilation in a room needed to increase" (DfE, 2022a).

However, the pandemic infrastructures that have been enacted are consequences of a particular moment in time, and there is no guarantee that they will stay. For CO_2 sensors, this consolidation is threatened by different organizations attempting to become centres of calculation with disputes over what is an 'acceptable' CO_2 concentration. For example, the National Education Union (NEU) have suggested different thresholds of acceptable IAQ based on CO_2 of 800 ppm (NEU, 2022), after following advice from SAGE EMG (2020), and CIBSE (2020). The UK government, on the other hand, sticks by its previous recommendations in BB101 and uses 1500ppm (UK Parliament, 2022). These disagreements highlight that despite their name, immutable mobiles are not always interpreted and acted upon in similar ways. For example, teachers remain an obligatory passage point for schools, in practice implementing natural ventilation, deciding when or not to open windows and doors. Even in mechanically ventilated classrooms, where the reach of metrological regimes of measurement and organized governance (Barry, 2002; Calvillo, 2018) place CO_2 data in a 'structured envelope' (Law 1986), there may well still be a human in the loop. This is often a school caretaker, who is dictating how much classrooms breathe based on criteria that may well extend beyond the airborne transmission of viruses, such as thermal comfort and energy efficiency. This highlights that "government and science operate in contingent places (as opposed to an abstract, frictionless space of absolute science and government)" (Whitehead, 2009: 213). This contingency denotes that the form the assemblage takes will vary from location to location, and how humans will interpret and use these immutable mobiles is far from stable. Particularly in a context where teachers have many competing demands, including the energy crisis that currently looms over the UK.

It is within this variation that we might ask questions about inequalities. IAQ scientists were undoubtedly delighted to see the widespread monitoring of IAQ in UK schools, providing a large dataset for a previously 'undone science'. However, they have cautioned for a long time that IAQ is far more than just CO_2. IAQ is a much more complicated mixture of primary pollutants originating from social practices and material technologies both indoors and outdoors, and secondary pollutants emerging from chemical reactions in the air (e.g. Habre et al. 2022). This is important to recognise, as how IAQ is defined influences relations between actants. Indeed, the school classroom is not a hermetically sealed box, detached from its physical or social location. In fact, reassembling classroom air to manage pandemic breathing has made classroom IAQ *more* connected to its location, through the direct consequence of bringing in more outdoor air, fresh or otherwise. This is important for questions of inequalities because the assumption that outdoor air is 'fresh' is problematic, as in many urban locations in particular, we may be replacing one problem with another: in this case, viral particles with polluted outdoor air.

Furthermore, the socio-technical re-ordering and deployment of hundreds of thousands of CO_2 sensors is reinforcing IAQ as a matter of 'personal care' (Whitehead, 2009). While the UK government does signify IAQ a matter of concern through the proliferation of CO_2 sensors, it does not hold itself accountable for the actual mitigation of harmful levels of pollution in the first place. Instead, the UK government's response was to enrol CO_2 sensors to enact ventilation through behaviour change, and to make it explicitly clear that "remedial work to improve ventilation remain the responsibility of individual settings" (Balogun and Wiebe, 2022: 34). However, solely focusing on changing behaviours to reduce exposures fails to account for individual actions being limited by social-technical structures (Booker et al., 2023), such as the quality of the air outdoors. Indeed, defining CO_2 as IAQ, and placing the onus on the individual to change their behaviours to reduce their exposures, is perpetuating "the notion that indoor spaces may be physically and socially isolated from the world at large" (Biehler and Simon, 2010: 175). IAQ becomes the responsibility of those inside the building, even though outdoor air pollution does not bounce off the front door. Indeed, concentrations of outdoor air that are so poor that they are deemed illegal can flow into the indoor environment and suddenly become the problem of the inhabitants.

The enrolling of CO_2 sensors has been a positive step in terms of making the invisible visible indoors, and we should be wary to let perfect be the enemy of good. However, just as Latour's door stopper conditions us on the socially acceptable use of a door (Johnson, 1988), so do CO_2 sensors condition us on how to relate to the air indoors. They define what is breathable and non-breathable air indoors, and influence the unfolding relations between humans and non-humans in managing and controlling the relationship between the air indoors and outdoors. The long-term implications of this still are still being played out.

Conclusion

As Sloterdijk (2009: 19) has noted, a "theory of unbreathable spaces is still obscure", despite the development of tools and technologies over hundreds of years aimed to protect breathers from their surrounding environment (Kenner, 2021). Where contributions have been made, they mainly relate to the air outdoors while "indoor environments remain considerably less theorized" (Biehler and Simon, 2010: 175). We contributed to discussions on unbreathable spaces in indoors environments by showing how the air became destabilized due to the arrival of COVID-19 in school classrooms. In doing so, the air's qualities became made and known differently, transforming the air from "the medium of everyday life to an object of concern and daily intervention" (Nguyen, 2020: 457). In this paper we have shown how a research-business project became re-assembled to COVID-19. The redefinition of air pollution to account for COVID-19 led to a focus on removing viral particles emanating from humans indoors through bringing in outdoor air. Despite the considerable scientific and political apparatus that utilised CO_2 as an indicator of good IAQ through bringing in outdoor air (pre-existing COVID-19's emergence), it had not been a particularly forceful actant in school classrooms. However, measurements of CO_2 were ultimately strengthened by their alliance with Wells-Riley inscriptions, forming an immutable mobile, that would alter the relationship between people at the school and their ventilation systems. These were powerful actants structuring the school classroom assemblage to decrease the connection of humans to the air in school classrooms through increasing ventilation rates. However, the air remains unstable, and whether these actants will continue to be a significantly agentive is unresolved, with different organizations attempting to become centres of calculation, and teachers remaining an obligatory passage point in many schools.

COVID-19's central role in organizing IAQ is likely to eventually fade, and as it does "social scientists must carefully identify and challenge the normalization and institutionalization of these pandemic infrastructures, connections, and norms that have the potential to reshape post pandemic institutions, social orders, and everyday life" (Liu, 2021: 22). Moreover, as other everyday digital infrastructures have been shown to have inequality generating mechanisms (Liu 2021), this raises the question of who gets to benefit and who is harmed through configuring the school classroom in this way. This both relates to the effects of ordering the air through CO_2 inscriptions, potentially replacing one problem with another: in this case, viral particles with dirty outdoor air, as well as making IAQ an issue of 'personal care'.

It is in this space that we might to consider how to better care for indoor air in the future. In particular how we might do a more 'critical' air quality science (Booker et al., 2023), that practices care by thinking further than measuring the damage caused by air pollution with increased precision. This means a more interventionist approach focused not only on reduced exposures and emissions, but also appraising carefully what world(s) air quality science is both making visible, but also promoting for the future.

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