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EDITED BY
Pier Luigi Sacco,
University of Studies G. d'Annunzio Chieti and Pescara, Italy

REVIEWED BY
Jovan Pantelic,
KU Leuven, Belgium

*CORRESPONDENCE
Donald Derrick
donald.derrick@canterbury.ac.nz

†These authors share first authorship

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Human aeroecology

Donald Derrick[1*†], Bryan Gick[2,3†] and Mark Jermy[4]

[1]New Zealand Institute of Language, Brain & Behaviour, University of Canterbury, Christchurch, New Zealand, [2]Linguistics Department, University of British Columbia, Vancouver, BC, Canada, [3]Haskins Laboratories, New Haven, CT, United States, [4]Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand

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Introduction

Airspace has been recognized as *habitat* for at least a decade (Diehl, 2013). However, the ecology of airspace has generally been defined with respect to airborne lifeforms such as birds and insects (e.g., Chilson et al., 2017). Humans are as much creatures of the air as lifeforms that walk the ocean floor are creatures of the sea. Yet, little is understood about the full scope of human interaction with the airspace, much of which is normally invisible and intangible. Topics relating to human aeroecology have long remained isolated at the periphery of many disparate fields. For example, humans interact biophysically with the air in obvious ways, as through breathing and heat loss, but also through releasing particulates (shed skin cells and clothing fibers) and inhaling and releasing airborne organisms (viruses, some bacteria, and body-dwelling insects) and allergens. Humans interact with other humans through the air by speaking and through transfer of volatiles (perfumes, body odor and pheromones). These chemical interactions can be strong and person-to-person over short distances, or weaker and affecting larger numbers of people over room-scale distances.

The importance of airborne cross-infection in the COVID-19 pandemic spurred much investment into research on human airspaces, and in response many researchers began pushing across divides between traditional disciplines involved in understanding the complex relationships between humans and the airspaces we live in and share. Partly as a result of this cross-pollination, a new interdisciplinary field is emerging, which we here call Human Aeroecology. Articulating the bounds of this field will, in our opinion, provide a conceptual framework enabling the development of new research questions and identification of common ground and connections between previously disconnected areas of study.

The portion of the aeroecology that humans normally occupy, or *perihuman* environment (Licina et al., 2017), is equivalent to the benthic zone in marine ecology terms. Of the vast aeroecological habitat of the troposphere, this human-adjacent *benthosphere* is shared with countless other terrestrial and airborne organisms whose functions and relations in this zone extend beyond the scope of the present paper, but unquestionably demand attention. Within this sphere, human aeroecology conceptually addresses not just interactions with the air proper, but also aspects of the air as a medium and as a living space, including (but not limited to) areas typically associated with human acoustic ecology (Wrightson, 2000; Paine, 2017), visual ecology (Ather et al., 2022), and combined sensory ecology (La Malva et al., 2015). We hope the present work can begin to shape a more convergent dialogue around this vital area, enabling the creation of human airscapes that reflect a deeper understanding of human health, communication, and human experience within our aeroecology.

Here we identify five broad areas within human aeroecology that researchers have developed over the past years, and which we argue would benefit from focused collaboration. These include but are not limited to: Airscape Design; Air Quality for Comfort, Health, Education and Productivity (Air Quality for CHEaP); Shared Airspaces for Social Connection; Auditory, Aerotactile, Olfactory, and Visual Communication; and Pathogen Transmission, as seen in Figure 1.

Some areas of inquiry in human aeroecology

Airscape design

Indoor and outdoor air quality is essential in human aeroecology. There is active work in the use of transportation (Guo et al., 2020), placement of parks and water (Qui and Jia, 2020), landscaping (Connors et al., 2013), phytoremediation (Pilon-Smits, 2005), outdoor air systems (Mumma, 2001), and roofing (Vijayaraghavan, 2016) to control outdoor heat, humidity, CO_2, volatiles, and particulates.

Focusing on one source of particulates: At the room or outdoor BBQ/storefront level, cooking produces typically pleasant social signals (Bordiga and Nollet, 2019), is used as a lure for social and commercial interaction (Morrin, 2011), yet is a sign of hazard when something is burning due to smoke.

Outdoor air control, exchange of outdoor and indoor air, outdoor (Luo et al., 2021) and indoor humidity control (Baughman and Arens, 1996), indoor ventilation (Ackley et al., 2022), heating and cooling (Chen et al., 2022), oxygen production and CO_2 removal (Azuma et al., 2018) are studied to control indoor atmosphere, pathogens (Atkinson, 2009), and mold (CDC, 2023). Airscape design also includes intentional design of soundscape factors, which are known to affect well-being (Medvedev et al., 2015). Done well, good airscape design facilitates Air Quality for CHEaP.

Air quality for comfort, health, education, and productivity

Indoor air quality for CHEaP involves creating indoor environments that facilitate comfortable temperatures and air circulation, limit pathogen spread, facilitate effective communication, and nurture social and work-supporting connections. Design methods include controlling ventilation, insulation (Kumar et al., 2020), and airflow control to facilitate comfort (Tham, 2016), reduce noise (see De Salis et al., 2002), control odor (see Matson and Sherman, 2004), and mitigate pathogen spread through effective air supply (Pantelic and Tham, 2013). Both the ventilation flow rate and the direction of flow are important. Improving indoor air quality in this way promotes comfort (Ma et al., 2021), health (Cincinelli and Martellini, 2017), productivity (Wyon, 2004), and learning (Pulimeno et al., 2020; Sadrizadeh et al., 2022). In the sensory space, noise pollution also negatively impacts learning (Klatte et al., 2013), and good aromas enhance a mild sense of calm (Cooke and Ernst, 2000). We argue that a holistic design approach including all of these factors is essential for creating airscapes that promote *Social Connection and Development*.

Shared airspaces for social connection

While we know how important it is to make airspace comfortable and safe, we are in the early days of understanding how being in a shared airspace facilitates social connection and development. New research into brain activity (Zhao et al., 2023) shows the importance of in-person interactions. Shared airspaces must be well-lit (Montoya et al., 2017), have good acoustics (Reinten et al., 2017), have good air quality (Wargocki et al., 2020) and facilitate airflow (Cao et al., 2014) to facilitate human comfort (see Melikov, 2015), learning (Wargocki et al., 2020), and largely unstudied connections to community and social interaction.

As an example, even pleasant particulate matter emitted from cooking can be harmful to cooks (Torkmahalleh et al., 2017), particularly if the cooking temperature is too high for the oil used, or the cooking fuel burns inefficiently. These aerosols can increase "acute pulmonary illness, asthma, cardiovascular disease, and lung cancer" amongst those doing the cooking (Lachowicz et al., 2023). Cooking aerosols are also a significant portion of nearby outdoor particulate matter (Abdullahi et al., 2013). Ventilation, lower emission fuels, careful cooking, and even the instruments that are part of Internet of Things (Pantelic et al., 2023), can be used to mitigate these risks, in a manner that recognizes that there are many costs and benefits to the effects of cooking on shared airspaces.

The "personal cloud" in human-adjacent airspaces simultaneously facilitates deleterious volatile particle inhalation (Licina et al., 2017; Pantelic et al., 2020) and useful olfactory communication (Roberts et al., 2020), so it must be carefully managed. We argue that this is perhaps the least studied of the five broad categories of human aeroecology we list here, and improved understanding of shared airspaces has the potential to produce massive social benefits to humanity due to the impacts on *Auditory, Aerotactile, Olfactory, and Visual Communication*.

Auditory, aerotactile, olfactory, and visual communication

Shared aeroecology is especially important for human communication and interaction. In addition to the airspace

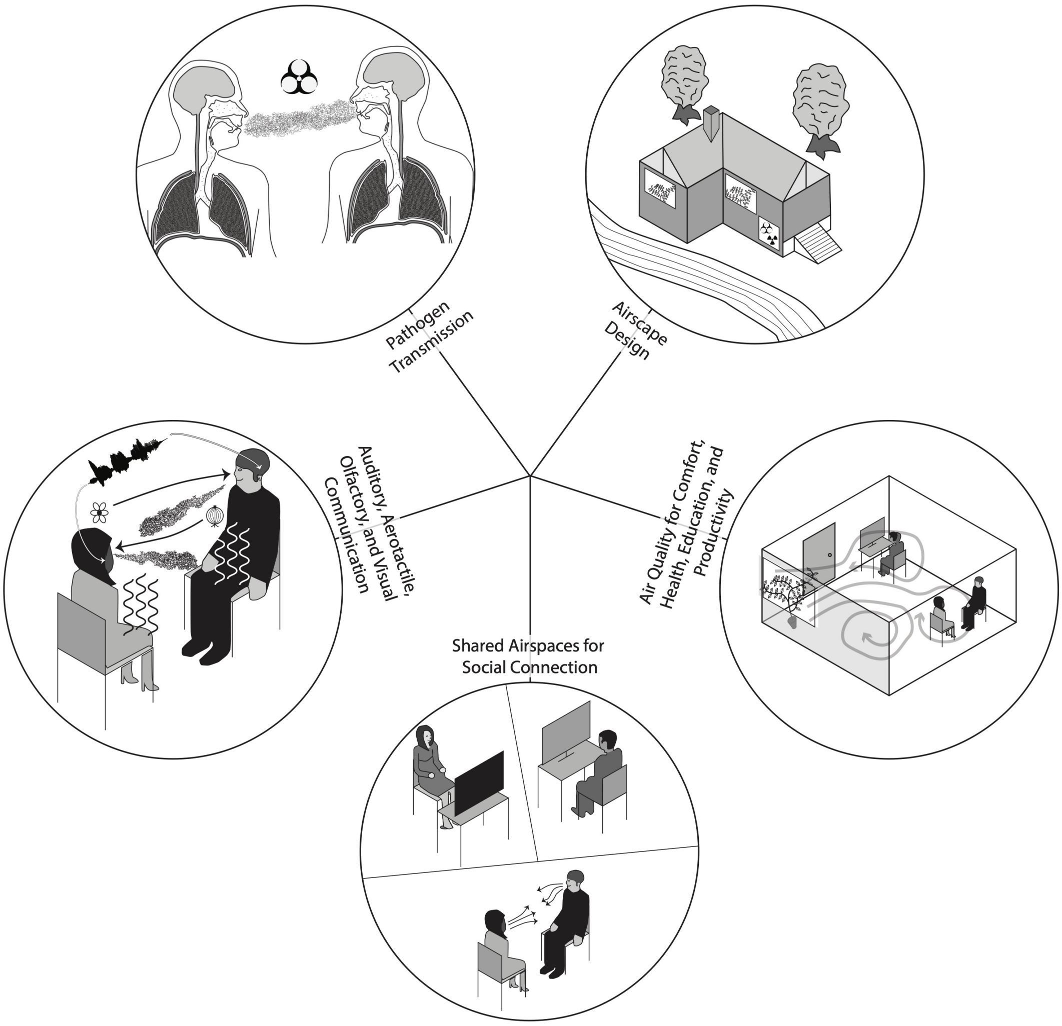

FIGURE 1
A mapping of areas of research in human aeroecology.

providing the medium of spoken and visual communication, subtle information from speech airflow affects auditory speech perception (Derrick et al., 2009; Gick and Derrick, 2009), interacting with visual and auditory information (Keough et al., 2018; Derrick et al., 2019b). While we have seen limitations in the effect of airflow on speech (Derrick, et al., 2019c; Hansmann et al., 2023), we know that speech airflow itself conveys speech information that adds to auditory and visual speech (Bicevskis et al., 2016; Derrick et al., 2019b), and interacts with speech perception along the autism spectrum (Derrick et al., 2019a). The airflow also contributes heat (Derrick et al., 2022) and communicative smells (Acosta-Acosta and El-Rayes, 2020; Roberts et al., 2020). Given that face masks limit (Campagne, 2021; Derrick et al., 2022), and distance meetings eliminate these communicative advantages, sometimes leading to subjective sense of fatigue (Ribeiro et al., 2022; Nesher Shoshan and Wehrt, 2022), the study of *Airscape Design*, *Air Quality for CHEaP*, and *Shared Airspaces for Social Connection* all provide many of the most useful tools to help control *Pathogen Transmission*.

Pathogen transmission

Breathing, talking (Derrick et al., 2022), singing (Alsved et al., 2020), coughing (Li et al., 2021), and medical therapies (Jermy et al., 2021) all move air and can spread pathogens and allergens (Levetin et al., 2023). We know that, in increasing efficacy, surgical masks, respirators (Collins et al., 2021) and especially Tyvek suits can reduce pathogen transmission, and have long been a part of hospital protocol in high-pathogen environments. However, face masks cover the face, block some heat transfer and most speech airflow (Derrick et al., 2022), and muffle speech (Magee et al., 2020). Because of this, effective personal protective equipment impedes good communication (Toscano and Toscano, 2021), and contributes other largely under-appreciated stresses to the users (Campagne, 2021).

Therefore, a human ecology approach has long been proposed for studying the costs and benefits of interventions in airborne pathogen transmission (e.g., Wells, 1955; Yan et al., 2018).

Specificfindings (Yan et al., 2018) indicate the need for careful and nuanced consideration of patient access based on the interaction of pathogen transmission and pathogen breakthrough (infection after vaccination). Overall, recent findings on airborne transmission (reviewed by Stevenson et al., 2023), underscore the benefits of an interdisciplinary approach to understanding pathogen dissemination within shared spaces, with implications for infection control and public health. The best protocols often lead back to control of *Airscape Design* and *Air Quality for CHEaP*.

Research methods in human aeroecology

These interconnected fields of research incorporate an astonishing array of methodologies, which include but are not limited to: indoor and outdoor environmental modeling (Freijer and Bloemen, 2000); behavioral studies (Barnes, 2014); EEG for neural responses to indoor and outdoor environments (Shan et al., 2019); modeling and simulation of gas and particulate transport (CFD) (Mohamadi and Fazeli, 2022; Tan et al., 2022; Zong et al., 2022); measurement of air, heat, trace species, and particulate flow with schlieren (Sun et al., 2021); particle samplers (Wang et al., 2020); study of colony forming units for pathogens (e.g., Lykov et al., 2020); DNA analysis of airborne microorganisms (Grinshpun et al., 2015); and volatile compound samplers (Ras et al., 2009). Therefore the technical span of human aeroecology matches the disciplinary span, supporting the need for a conceptual connection across these multivariate fields of research.

Conclusion

Human aeroecology is emerging as a transformative interdisciplinary field, integrating knowledge spanning many traditional disciplines. The need for a more clearly articulated paradigm for this field has been underscored by the recent pandemic, and demands a holistic approach to studying and shaping the spaces we collectively inhabit. We recommend: 1) Attaching keywords to research so that topics in human aeroecology are easier to identify; 2) Intentional wide-ranging research collaboration in human aeroecology; 3) Conferences and conference sessions on human aeroecology; and 4) Documentation and communication of the benefits of careful human aeroecology in urban and building design.

Author contributions

DD: Conceptualization, Writing – original draft, Writing – review & editing. BG: Conceptualization, Writing – original draft, Writing – review & editing. MJ: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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