A breath of fresh air: towards optimal Indoor Air Quality (IAQ)

Investigating intervention strategies for enhancing occupants perception, comfort and health

Milestone 2 - Literature review, Submitted on: **22-03-2024**

Danny de Vries
danny.de.vries@student.uva.nl
University of Amsterdam
Amsterdam, The Netherlands

Dr. Hamed Seiied Alavi PhD
h.alavi@uva.nl
University of Amsterdam
Amsterdam, The Netherlands

ABSTRACT

This milestone provides a comprehensive literature review for all the topics related to the thesis and answers parts of the main and sub-research questions based on the guidelines of the related work section of the Master Thesis. The first part is the introduction of the master thesis which also includes literature references and includes the research questions for context. Then the draft of the related work section starts and finally a section is provided that explains the methodology used for the literature review and search queries used.

KEYWORDS

Human-Building interaction, Indoor air quality, Persuasive technology, Living lab, Smart buildings, User-centered design.

METADATA

Literature review for the fullfiment of the *Master Thesis* for the Master Information Studies: *Information Systems (IS)*.

Institute: Informatics Institute
Faculty: Faculty of Science (FNWI)
Research Group: Digital Interactions Lab (DIL)
Supervisor(s): Dr. Hamed Seiied Alavi PhD
Supervisor(s): Shruti Rao Ph.D. Candidate

1 INTRODUCTION

Globally, it is estimated that people spend approximately 90% of their time indoors [19, 32] and breathe 11.000 liters of air per day [8]. Suboptimal indoor air quality (IAQ) conditions affect building occupants' experiences of comfort and insufficient ventilation in indoor environments is proven to play significant roles in occupants' well-being, health, and cognitive functions [17, 38].

The perceived comfort of occupants is influenced by the overall Indoor Environmental Quality (IEQ) consisting of several key metrics (e.g. mechanical ventilation, temperature regulation, natural lighting) to create a combined IEQ index for a specific indoor space [20]. Among these metrics, indoor air quality stands out as a crucial factor deserving special attention due to its invisibility to occupants [34], polluted air goes undetected by smell or sight, underscoring the importance of monitoring and maintaining optimal indoor air quality.

Furthermore, mechanical ventilation systems in buildings operate discreetly and are frequently insufficient for ventilation in densely populated small rooms like meeting rooms, laboratory offices, or hot-desking work areas [33], which contributes to occupants' perceived lack of control. Since these systems are typically automated [25] and cannot be directly regulated or controlled by occupants themselves [16].

This creates an interplay between occupants' effects on comfort, built environments, and computing technologies (see Figure 1) researched in an overarching interdisciplinary field of study, known as Human-Building Interaction (HBI) [1]. This research specifically focuses on understanding occupants' needs through in-the-wild [29] studies gaining insight into occupants' awareness, collecting indoor air quality data in designated spaces, prototyping data physicalization devices to visualize indoor air quality, and using these designs as data probing tool [41] evaluating their effectiveness with the overarching objective of obtaining insights into occupants' comfort levels and facilitating their adoption of preventive measures against poor indoor air quality [40].

While research on defining comfort within indoor buildings [2], gathering and analyzing sensory air quality data [8], and the effects of poor air quality are prevalent [19], there remains a research gap in understanding occupants' behavior and their subjective needs, along with limited research on how design solutions that visualize environmental data and computing installations can empower occupants, particularly within the field of physically visualizing data to convey IAQ to building occupants in real-time.

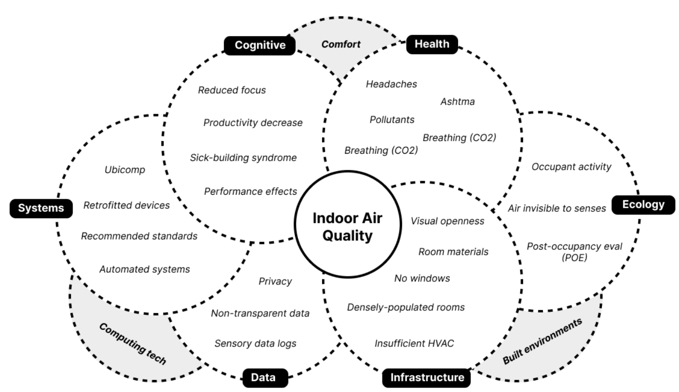

Figure 1: Complexity diagram providing an overview of the effects of IAQ and needs of occupants [2, 8, 17, 19, 32, 38]

1.1 Research questions

In order to research intervention strategies for improving indoor air quality, the following main research question is formulated:

RQ: *How can real-time sensory measurements and future predictions of air quality be physically visualised in specific indoor spaces integrating both environmental information and elements that increase awareness among occupants facilitating their adoption of preventive measures against poor air quality?*

To effectively answer this main research question, this research is guided by the following supporting sub-questions that also serve as objectives to delineate the necessary knowledge:

- **SRQ1:** *How can environmental information related to air quality, such as pollutant concentrations and ventilation rates, be incorporated into the visual representations?*
- **SRQ2:** *How do different types of physical visualizations impact occupants' understanding of air quality and their willingness to adopt preventive measures?*
- **SRQ3:** *How do occupants' perceptions and behaviors regarding indoor air quality change over time, from pre to post-installation of the physical representation of poor air quality?*

2 RELATED WORK

Given the focus of this research is studying Human-Computer Interaction (HCI) within Built Environments, this research draws from various related work including the subfield of Human-Building Interaction (HBI) and subsequently narrows its focus to Indoor Air Quality (IAQ) and Post-occupancy Evaluation (POE) for the scope of this research. Furthermore, it examines notable findings from previous approaches to mapping and encoding sensory data in a new area of research called Data Physicalization (DataPhys).

2.1 Human-Building Interaction

Buildings increasingly incorporate new forms of digital interaction [22, 26], which means new inherent connections between 'people', 'built environments', and 'computing' research in an area called Human-Building Interaction (HBI) [1, 36]. This research area is dedicated to exploring the design of built environments that may incorporate computing to varying degrees [35]. A logical extension where indoor spaces are increasingly retrofitted with sensing devices [26]. Understanding how people use different spaces in a building through computing can inform design interventions aimed at improving the utility of the space and the well-being of occupants. [37].

Current research into architecture and built environments indicates that a significant portion of the data collected by these computing devices is not necessarily transparent or comprehensible to occupants [31], and indoor spaces are designed without much thought of placing computing devices integrated within the environment [15, 18] leaving users with a perceived lack of control over their indoor comfort.

2.2 Comfort within buildings

Indoor occupant comfort is achieved in interaction with the environment and is represented in four respective dimensions; thermal, respiratory, visual, and acoustic [2]. Indoor Environmental Quality (IEQ) [20] indexes serve as metrics for assessing the aforementioned properties of comfort within indoor environments with Post-Occupancy Evaluation (POE) [10] and Perceived Environmental Qualities (PEQ) [34] methods being employed to gauge occupants' perceived comfort [7].

Studies on indoor environments focus on 'static' IEQ conditions using sensors to sense environmental conditions based on the buildings' physical characteristics to meet various recommended standards such as ASHREA 62.1 [1], ISO 16814 [2]. Discrepancies between measured IEQ conditions and occupants' perceptions have also been reported in studies. For instance, research indicates that occupants generally have a low awareness of Indoor Environmental Quality (IEQ). While occupants perceive the environment as 'satisfactory', actual sensory measurements within the environment reveal quality levels below recommended standards. [34]. Recent studies have shifted their focus towards the active role occupants play within the built environment, viewing their behavior within a building as akin to a 'living ecology' [21] rather than perceiving comfort solely as 'static' properties of the building itself.

2.3 Indoor Air Quality

A suboptimal indoor environment has reportedly been associated with health-related problems such as headaches, throat irritation, and asthma [19] as well as a decrease in cognitive functions such as tiredness, effects on performance and productivity and a lack of focus [38] [9]. A phenomenon referred to as the Sick Building Syndrome (SBS) [12, 24]. Many of these symptoms are primarily associated with respiratory comfort and are closely tied to Indoor Air Quality (IAQ) concerns [17]. Effective ventilation strategies have been shown to significantly alleviate SBS symptoms [12].

The advancements of real-time IAQ monitoring systems leveraging Internet of Things (IoT) sensor technology have facilitated progress in both the measurement of IAQ and the implementation of interventions aimed at enhancing it [23]. Indications of poor air quality are gathered by measuring common pollutants with a focus on molds and allergens (humidity), volatile organic compounds (VOC), and carbon dioxide (CO2) [19] where occupant behavior and the number of occupants within indoor space have a specific negative effect on CO2 levels [11]. These indoor climate factors are related to the building occupants' behaviors and need special attention to be considered in assessing the IEQ conditions and determining if adequate ventilation is present [9]. It is crucial to recognize that when occupants experience symptoms, it signifies that a suboptimal air quality situation has already occurred.

The existing literature on IAQ offers quantifiable and validated methods for measuring IAQ through sensory data. It underscores the complexities associated with IAQ and emphasizes the significance of developing solutions to ensure occupants receive adequate ventilation.

[1] https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2
[2] https://www.iso.org/standard/42720.html

2.4 Data Physicalization

The research domain known as data physicalization [3] has emerged as a notable area of study, emphasizing the creation of physical data visualizations making the invisible tangible and interactible by encoding data in physical artifacts [27]. This shift from focusing on individual artifacts to a broader environmental context facilitates the physical embodiment of computing. Data physicalization has the potential to positively influence the perception and exploration of data [14], presenting distinct advantages over traditional 'screen-focused' data representations, such as 2D canvas displays (dashboards) [13], particularly in the context of Indoor Air Quality (IAQ) where a 'physical data visualization' serves as a fitting metaphor for rendering 'invisible' indoor air.

These tangible artifacts usually come in the form of ubiquitous computing (ubicomp) [6] device that seamlessly blends into the environment, essentially making the computing devices 'disappear' [39]. These devices are frequently employed as persuasive technology, strategically designed to gently nudge individuals towards behavior change leveraging the emerging notion of pervasive sensing to subtly enhance users' awareness regarding the impacts of their decisions [4, 28]. This method of persuasive design serves as a powerful tool in calmly extending users' awareness, helping users understand gathered data, and the consequences of their actions, and gaining insight into their behavior [5]. A systematic analysis of over 60 representative data physicalization papers [30] show that only numerous approaches to studying computing devices within indoor spaces and interactivity with occupants have been explored in prior research to nudge occupants to a desired behavior but no design solutions have been developed and explored to focus specifically on IAQ awareness within indoor environments.

This framework of data physicalization and persuasive technology establishes the theoretical foundation for the creation (prototyping) and the evaluation (usability testing) of the design solution within this research.

3 SEARCH QUERIES

The exploration of relevant literature started with seven seminal papers recommended by my supervisor. Based on the keywords and related work of those papers a systematic approach was adopted, employing a combination of specific search queries tailored to the research focus. The academic database from the UvA, University Library Catalogueplus [3], was used with the following queries:

- "Human-Building Interaction" OR "HBI" AND "Built Environments"
- "Indoor Air Quality" OR "IAQ"
- "Post-occupancy Evaluation" OR "POE"
- "Indoor Environmental Quality" OR "IEQ"
- "Data Physicalization" OR "DataPhys" OR "Tangible Data"
- "Ubiquitous Computing" OR "Ubicomp" AND "Persuasive Technology" OR "Behavior Change"
- "Sick Building Syndrome" OR "SBS" AND "Respiratory Comfort" OR "Cognitive Functions"
- "Thermal Comfort" OR "Acoustic Comfort" AND "Indoor Occupant Comfort" OR "Comfort Dimensions"

[3]https://lib.uva.nl/discovery/

In CataloguePlus, filters were utilized to aim for peer-reviewed articles published within the last 5 years (2019 - 2024). Notably, several pivotal papers, constituting the state of the art, were featured in special issues of particular journals. Consequently, the latest issues of these journals were reviewed to access the most recent studies within the subfield. Given the central focus on Human-Computer Interaction (HCI), key papers were frequently found within the ACM library [4]. Consequently, searches within this repository were systematically refined upon the identification of relevant literature.

4 METHODS

The related work section does not serve as a conventional background section; rather, it predominantly highlights the state-of-the-art advancements within the research fields, with minimal coverage of foundational literature. It assumes a scientific audience with a preliminary knowledge of the researched subfields. Each subsection includes a paragraph outlining the differences between this research and prior works, thereby establishing the specific research gap addressed in the study.

To organize the topics introduced in the thesis and delineate the associated research questions the citation management tool Zotero [5] was used, and specific subfolders were created to accommodate these topics which translated to the subsections outlined in the related work draft. Through the integration of the Zotero connector plugin into web browsers, relevant scholarly papers could be conveniently pinned to the appropriate folders. Subsequently, within the Zotero application itself, sorting and labeling functionalities were employed to categorize the pinned papers according to their respective topics. Furthermore, the integration of Zotero with the beta version of Research Rabbit [6], a tool designed to construct visual knowledge graphs of papers contained within Zotero collections, was used. This integration facilitated cross-referencing of papers and provided recommendations for related works based on similar works and references within the paper thereby enabling the exploration of subfields and author networks.

REFERENCES

[1] Hamed S. Alavi, Elizabeth F. Churchill, Mikael Wiberg, Denis Lalanne, Peter Dalsgaard, Ava Fatah gen Schieck, and Yvonne Rogers. 2019. Introduction to Human-Building Interaction (HBI): Interfacing HCI with Architecture and Urban Design. *ACM Transactions on Computer-Human Interaction* 26, 2 (March 2019), 6:1–6:10. https://doi.org/10.1145/3309714

[2] Hamed S. Alavi, Himanshu Verma, Michael Papinutto, and Denis Lalanne. 2017. Comfort: A Coordinate of User Experience in Interactive Built Environments. In *Human-Computer Interaction – INTERACT 2017 (Lecture Notes in Computer Science)*, Regina Bernhaupt, Girish Dalvi, Anirudha Joshi, Devanuj K. Balkrishan, Jacki O'Neill, and Marco Winckler (Eds.). Springer International Publishing, Cham, 247–257. https://doi.org/10.1007/978-3-319-67687-6_16

[3] Jason Alexander, Petra Isenberg, Yvonne Jansen, Bernice E. Rogowitz, and Andrew Vande Moere. 2019. Data Physicalization. *Dagstuhl Reports* 8, 10 (April 2019), 127. https://doi.org/10.4230/DagRep.8.10.127

[4] Patrick Bader, Alexandra Voit, Huy Viet Le, Paweł W. Woźniak, Niels Henze, and Albrecht Schmidt. 2019. WindowWall: Towards Adaptive Buildings with Interactive Windows as Ubiquitous Displays. *ACM Transactions on Computer-Human Interaction* 26, 2 (March 2019), 11:1–11:42. https://doi.org/10.1145/3310275

[5] S. Sandra Bae, Clement Zheng, Mary Etta West, Ellen Yi-Luen Do, Samuel Huron, and Danielle Albers Szafir. 2022. Making Data Tangible: A Cross-disciplinary Design Space for Data Physicalization. https://doi.org/10.48550/arXiv.2202.10520 arXiv:2202.10520 [cs].

[4]https://dl.acm.org/

[5]https://www.zotero.org/

[6]https://www.researchrabbit.ai/

[6] Genevieve Bell and Paul Dourish. 2007. Yesterday's tomorrows: notes on ubiquitous computing's dominant vision. *Personal and Ubiquitous Computing* 11, 2 (Jan. 2007), 133–143. https://doi.org/10.1007/s00779-006-0071-x

[7] Alexandra Boissonneault and Terri Peters. 2023. Concepts of performance in post-occupancy evaluation post-probe: a literature review. *Building Research & Information* 51, 4 (May 2023), 369–391. https://doi.org/10.1080/09613218.2022.2132906 Publisher: Routledge _eprint: https://doi.org/10.1080/09613218.2022.2132906.

[8] R. V. Corlan, R. M. Balogh, I. Ionel, and St Kilyeny. 2021. The importance of indoor air quality (IAC) monitoring. *Journal of Physics: Conference Series* 1781, 1 (Feb. 2021), 012062. https://doi.org/10.1088/1742-6596/1781/1/012062 Publisher: IOP Publishing.

[9] Bowen Du, Marlie C. Tandoc, Michael L. Mack, and Jeffrey A. Siegel. 2020. Indoor CO2 concentrations and cognitive function: A critical review. *Indoor Air* 30, 6 (2020), 1067–1082. https://doi.org/10.1111/ina.12706 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/ina.12706.

[10] Mohamed Elsayed, Sofie Pelsmakers, Lorenza Pistore, Raúl Castaño-Rosa, and Piercarlo Romagnoni. 2023. Post-occupancy evaluation in residential buildings: A systematic literature review of current practices in the EU. *Building and Environment* 236 (May 2023), 110307. https://doi.org/10.1016/j.buildenv.2023.110307

[11] Hermann Fromme. 2023. Indoor Environment: Background Information. In *Indoor Air Quality: Occurrence and Health Effects of Contaminants*, Hermann Fromme (Ed.). Springer Nature Switzerland, Cham, 1–36. https://doi.org/10.1007/978-3-031-40078-0_1

[12] Sonal Gawande, Rajnarayan Tiwari, Prakash Narayanan, and Ashwin Bhadri. 2020. Indoor air quality and sick building syndrome: Are green buildings better than conventional buildings? *Indian Journal of Occupational and Environmental Medicine* 24, 1 (Jan. 2020), 30–30. https://go-gale-com.proxy.uba.uva.nl/ps/i.do?p=AONE&sw=w&issn=09732284&v=2.1&it=r&id=GALE%7CA618547062&sid=googleScholar&linkaccess=abs Publisher: Indian Association of Occupational Health.

[13] Eva Hornecker, Trevor Hogan, Uta Hinrichs, and Rosa Van Koningsbruggen. 2023. A Design Vocabulary for Data Physicalization. *ACM Transactions on Computer-Human Interaction* 31, 1 (Nov. 2023), 2:1–2:62. https://doi.org/10.1145/3617366

[14] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and Challenges for Data Physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Association for Computing Machinery, New York, NY, USA, 3227–3236. https://doi.org/10.1145/2702123.2702180

[15] Stine Schmieg Johansen, Jesper Kjeldskov, and Mikael B. Skov. 2019. Temporal Constraints in Human–Building Interaction. *ACM Transactions on Computer-Human Interaction* 26, 2 (April 2019), 8:1–8:29. https://doi.org/10.1145/3301424

[16] Hakpyeong Kim, Taehoon Hong, and Jimin Kim. 2019. Automatic ventilation control algorithm considering the indoor environmental quality factors and occupant ventilation behavior using a logistic regression model. *Building and Environment* 153 (April 2019), 46–59. https://doi.org/10.1016/j.buildenv.2019.02.032

[17] Jimin Kim, Taehoon Hong, Minhyun Lee, and Kwangbok Jeong. 2019. Analyzing the real-time indoor environmental quality factors considering the influence of the building occupants' behaviors and the ventilation. *Building and Environment* 156 (June 2019), 99–109. https://doi.org/10.1016/j.buildenv.2019.04.003

[18] David Kirsh. 2019. Do Architects and Designers Think about Interactivity Differently? *ACM Transactions on Computer-Human Interaction* 26, 2 (April 2019), 7:1–7:43. https://doi.org/10.1145/3301425

[19] Neil E. Klepeis, William C. Nelson, Wayne R. Ott, John P. Robinson, Andy M. Tsang, Paul Switzer, Joseph V. Behar, Stephen C. Hern, and William H. Engelmann. 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology* 11, 3 (July 2001), 231–252. https://doi.org/10.1038/sj.jea.7500165 Publisher: Nature Publishing Group.

[20] Priyanka Kulshreshtha, Sumanth Chinthala, Prashant Kumar, and Barun Aggarwal (Eds.). 2024. *Indoor Environmental Quality: Select Proceedings of ACIEQ 2023*. Lecture Notes in Civil Engineering, Vol. 380. Springer Nature, Singapore. https://doi.org/10.1007/978-981-99-4681-5

[21] Jared Langevin, Jin Wen, and Patrick L. Gurian. 2016. Quantifying the human–building interaction: Considering the active, adaptive occupant in building performance simulation. *Energy and Buildings* 117 (April 2016), 372–386. https://doi.org/10.1016/j.enbuild.2015.09.026

[22] Eleni Margariti, Vasilis Vlachokyriakos, and David Kirk. 2023. Understanding occupants' experiences in quantified buildings: results from a series of exploratory studies.. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3544548.3581256

[23] Jovan Pantelic, Negin Nazarian, Clayton Miller, Forrest Meggers, Jason Kai Wei Lee, and Dusan Licina. 2022. Transformational IoT sensing for air pollution and thermal exposures. *Frontiers in Built Environment* 8 (Oct. 2022). https://doi.org/10.3389/fbuil.2022.971523 Publisher: Frontiers.

[24] Guiseppe Ryan Passarelli. 2009. Sick building syndrome: An overview to raise awareness. *Journal of Building Appraisal* 5, 1 (July 2009), 55–66. https://doi.org/10.1057/jba.2009.20

[25] Andrew Persily. 2015. Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62. *Building and Environment* 91 (Sept. 2015), 61–69. https://doi.org/10.1016/j.buildenv.2015.02.026

[26] Andrew Pulsipher and Michail Giannakos. 2023. Towards a Taxonomy of Human-Building Interactions. In *Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing & the 2023 ACM International Symposium on Wearable Computing (UbiComp/ISWC '23 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 411–416. https://doi.org/10.1145/3594739.3610730

[27] Champika Ranasinghe and Auriol Degbelo. 2023. Encoding Variables, Evaluation Criteria, and Evaluation Methods for Data Physicalisations: A Review. *Multimodal Technologies and Interaction* 7, 7 (July 2023), 73. https://doi.org/10.3390/mti7070073 Number: 7 Publisher: Multidisciplinary Digital Publishing Institute.

[28] Yvonne Rogers, William R. Hazlewood, Paul Marshall, Nick Dalton, and Susanna Hertrich. 2010. Ambient influence: can twinkly lights lure and abstract representations trigger behavioral change?. In *Proceedings of the 12th ACM international conference on Ubiquitous computing (UbiComp '10)*. Association for Computing Machinery, New York, NY, USA, 261–270. https://doi.org/10.1145/1864349.1864372

[29] Yvonne Rogers and Paul Marshall. 2017. Moving Into The Wild: From Situated Cognition to Embodied Interaction. In *Research in the Wild*, Yvonne Rogers and Paul Marshall (Eds.). Springer International Publishing, Cham, 11–20. https://doi.org/10.1007/978-3-031-02220-3_2

[30] Kim Sauvé, Miriam Sturdee, and Steven Houben. 2022. Physecology: A Conceptual Framework to Describe Data Physicalizations in their Real-World Context. *ACM Transactions on Computer-Human Interaction* 29, 3 (Jan. 2022), 27:1–27:33. https://doi.org/10.1145/3505590

[31] Holger Schnädelbach, Nils Jäger, and Lachlan Urquhart. 2019. Adaptive Architecture and Personal Data. *ACM Transactions on Computer-Human Interaction* 26, 2 (March 2019), 12:1–12:31. https://doi.org/10.1145/3301426

[32] Christian Schweizer, Rufus David Edwards, Lucy Bayer-Oglesby, William James Gauderman, Vito Ilacqua, Matti Juhani Jantunen, Hak Kan Lai, Mark Nieuwenhuijsen, and Nino Künzli. 2007. Indoor time-microenvironment-activity patterns in seven regions of Europe. *Journal of Exposure Science & Environmental Epidemiology* 17, 2 (March 2007), 170–181. https://doi.org/10.1038/sj.jes.7500490

[33] Marielle Ferreira Silva, Stefan Maas, Henor Artur de Souza, and Adriano Pinto Gomes. 2017. Post-occupancy evaluation of residential buildings in Luxembourg with centralized and decentralized ventilation systems, focusing on indoor air quality (IAQ). Assessment by questionnaires and physical measurements. *Energy and Buildings* 148 (Aug. 2017), 119–127. https://doi.org/10.1016/j.enbuild.2017.04.049

[34] Young Joo Son, Zachary C. Pope, and Jovan Pantelic. 2023. Perceived air quality and satisfaction during implementation of an automated indoor air quality monitoring and control system. *Building and Environment* 243 (Sept. 2023), 110713. https://doi.org/10.1016/j.buildenv.2023.110713

[35] Holly Sowles and Laura Huisinga. 2021. Introducing Intelligent Interior Design Framework (IIDF) and the Overlap with Human Building Interaction (HBI). In *Advances in Artificial Intelligence, Software and Systems Engineering (Advances in Intelligent Systems and Computing)*, Tareq Ahram (Ed.). Springer International Publishing, Cham, 483–489. https://doi.org/10.1007/978-3-030-51328-3_66

[36] Roohollah Taherkhani and Mohamadmahdi Aziminezhad. 2023. Human-building interaction: A bibliometric review. *Building and Environment* 242 (Aug. 2023), 110493. https://doi.org/10.1016/j.buildenv.2023.110493

[37] Himanshu Verma, Hamed S. Alavi, and Denis Lalanne. 2017. Studying Space Use: Bringing HCI Tools to Architectural Projects. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 3856–3866. https://doi.org/10.1145/3025453.3026055

[38] Chao Wang, Fan Zhang, Julian Wang, James K. Doyle, Peter A. Hancock, Cheuk Ming Mak, and Shichao Liu. 2021. How indoor environmental quality affects occupants' cognitive functions: A systematic review. *Building and Environment* 193 (April 2021), 107647. https://doi.org/10.1016/j.buildenv.2021.107647

[39] Mark Weiser. 1999. The computer for the 21 st century. *ACM SIGMOBILE Mobile Computing and Communications Review* 3, 3 (July 1999), 3–11. https://doi.org/10.1145/329124.329126

[40] Sailin Zhong, Denis Lalanne, and Hamed Alavi. 2021. The Complexity of Indoor Air Quality Forecasting and the Simplicity of Interacting with It – A Case Study of 1007 Office Meetings. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–19. https://doi.org/10.1145/3411764.3445524

[41] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 2007. Research through design as a method for interaction design research in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. Association for Computing Machinery, New York, NY, USA, 493–502. https://doi.org/10.1145/1240624.1240704