A BREATH OF FRESH AIR: TOWARDS OPTIMAL INDOOR AIR QUALITY

INVESTIGATING INTERVENTION STRATEGIES FOR ENHANCING OCCUPANTS AWARENESS, COMFORT AND HEALTH

SUBMITTED IN PARTIAL FULFILLMENT FOR THE DEGREE OF MASTER OF SCIENCE

DANNY DE VRIES
14495643

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	UvA Supervisor
Title, Name	Dr. H. (Hamed) Seiied Alavi PhD
Affiliation	University of Amsterdam
Email	h.alavi@uva.nl

ABSTRACT

Suboptimal Indoor Air Quality (IAQ) have been identified to pose health risks and affect the cognitive performance of occupants within indoor environments. The study investigates occupants' awareness and perceptions of IAQ, facilitating occupants adoption of preventive measures. Employing a user-centered mixed-methods approach, the research employs Post-Occupancy Evaluation (POE) methods to elicit occupants' understanding of indoor air quality and utilizes sensory monitors to collect and measure common pollutants in specific indoor environments. These insights guide the development of 'Phair', an interactive data physicalization that visualizes real-time air quality data which was subsequently evaluated and usability-tested with occupants. The results of the user study reveal a lack of awareness among users regarding indoor air quality, while evaluations of the prototype demonstrate that physical hardware displaying real-time data can effectively increase occupants' awareness.

KEYWORDS

Human-Building interaction, Indoor air quality, Living Lab, Data physicalization, Smart buildings, User-centered design.

1 INTRODUCTION

Globally, it is estimated that people spend approximately 90% of their time indoors [23, 36] and breathe 11.000 liters of air per day [10]. 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 [21, 42].

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 [24]. Among these metrics, indoor air quality stands out as a crucial factor deserving special attention due to its invisibility to occupants [38], 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 [37], which contributes to occupants' perceived lack of control. Since these systems are typically automated [29] and cannot be directly regulated or controlled by occupants themselves [20].

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 [33] 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 [45] 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 [44].

While research on defining comfort within indoor buildings [2], gathering and analyzing sensory air quality data [10], and the effects of poor air quality are prevalent [23], 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.

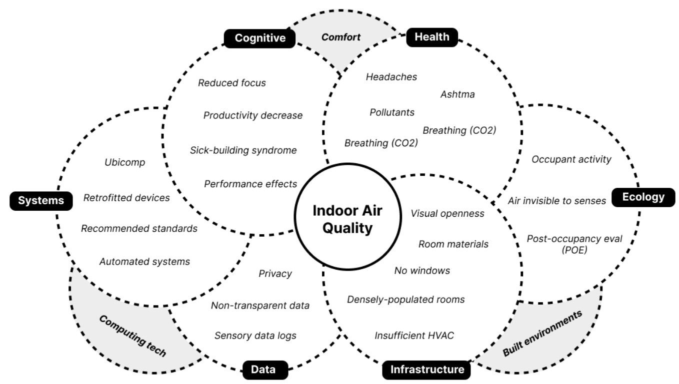

Figure 1: Complexity diagram providing an overview of the effects of IAQ and needs of occupants [2, 10, 21, 23, 36, 42]

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 (BE), 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 [26, 30], which means new inherent connections between 'people', 'built environments', and 'computing' research in an area called Human-Building Interaction (HBI) [1, 40]. This research area is dedicated to exploring the design of built environments that may incorporate computing to varying degrees [39]. A logical extension where indoor spaces are increasingly retrofitted with sensing devices [30]. 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. [41].

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 [35], and indoor spaces are designed without much thought of placing computing devices integrated within the environment [18, 22] 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) [24] indexes serve as metrics for assessing the aforementioned properties of comfort within indoor environments with Post-Occupancy Evaluation (POE) [13] and Perceived Environmental Qualities (PEQ) [38] methods being employed to gauge occupants' perceived comfort [9].

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. [38]. 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' [25] rather than perceiving comfort solely as 'static' properties of the building itself.

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

2.3 Indoor Air Quality

A suboptimal indoor environment has reportedly been associated with health-related problems such as headaches, throat irritation, and asthma [23] as well as a decrease in cognitive functions such as tiredness, effects on performance and productivity and a lack of focus [42] [12]. A phenomenon referred to as the Sick Building Syndrome (SBS) [15, 28]. Many of these symptoms are primarily associated with respiratory comfort and are closely tied to Indoor Air Quality (IAQ) concerns [21]. Effective ventilation strategies have been shown to significantly alleviate SBS symptoms [15].

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 [27]. 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) [23] where occupant behavior and the number of occupants within indoor space have a specific negative effect on CO2 levels [14]. 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 [12]. 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.

2.4 Data Physicalization

The research domain known as data physicalization [3, 17] 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 [31]. This shift from focusing on individual artifacts to a broader environmental context facilitates the physical embodiment of computing [11]. Data physicalization has the potential to positively influence the perception and exploration of data [17], presenting distinct advantages over traditional 'screen-focused' data representations, such as 2D canvas displays (dashboards) [16], 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) [8] device that seamlessly blends into the environment, essentially making the computing devices 'disappear' [43]. 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 [6, 32]. 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 [7]. A systematic analysis of over 60 representative data physicalization papers [34] 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 METHODOLOGY

To answer the research question this study uses a human-centered approach commonly found in Human-Computer Interaction studies consisting of four phases; 1) user studies to *understand* the user, 2) *data collection* methods and analysis of the situation as field trials, 3) *ideation* and experimental design of a prototype and 4) *evaluation* and usability testing of the prototype [19, 45]. This mixed-methods approach (both qualitative and quantitative) helps understand occupants' needs and informs the design and technical set-up of the prototype evaluating the effectiveness by focusing on the user's needs from the start of the study [33]. For the first phase, an online questionnaire was conducted to *understand* occupants' awareness of indoor air quality (see Section 3.2), for the second phase a lab setting was created with IAQ monitors to do *data collection* and gain insight into environmental data which in turn informed phase three the *ideation* and creation of the prototype. In the last phase participants *evaluated* the prototype and performed usability tests.

3.1 Case study building

This study will be conducted in association with the Digital Interactions Lab [3] and will utilize the recently opened Lab42 [4] building at the UvA Amsterdam Science Park [5] as its primary case study location. Lab42 is an energy-neutral, flexible, and adaptable faculty building that facilitates collaborations among students, researchers, and businesses [5]. The buildings's layout is strategically organized into different zones, each serving various functions, ranging from quiet individual work to spaces that allow for collaborative work. Lecture halls, learning rooms, and open learning spaces make up the two lower floors, with the upper four being primarily assigned to the university academic staff, meeting rooms, and external offices (see Appendix H). The overarching interior theme in the design revolves around 'tech' and 'nature' aiming to cultivate a fresh, light, and warm comfortable ambiance. Lab42 is an example of a smart building or living lab where sensing devices are retrofitted throughout the building to automatically adjust lighting, temperature, and the focus of this research regulating air [4]. This already provides a base of environmental data that can be used and extended for further analysis. Since most of the space within the building is designated as informal learning space and another large part of the building are designed as meeting rooms (see Appendix H), working areas these functions of focussed work and collaborative meetings can be heavily influenced by reduced cognitive performance as a result of poor indoor air quality.

[3]https://uva-dilab.com/
[4]https://lab42.uva.nl/
[5]https://www.amsterdamsciencepark.nl/

3.2 Questionnaire

3.3 Data collection

3.4 Ideation

3.5 Prototyping

3.6 Evaluation

4 RESULTS

Write about your results here. Good captions to tables and/or figures are key.

5 DISCUSSION

Write your discussion here. Do not forget to use sub-sections. Normally, the discussion starts with comparing your results to other studies as precisely as possible. The limitations should be reflected upon in terms such as reproducibility, scalability, generalizability, reliability and validity. It is also important to mention ethical concerns.

6 CONCLUSION

Write your conclusion here. Be sure that the relation between the research gap and your contribution is clear. Be honest about how limitations in the study qualify the answer on the research question.

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] Architectenweb. 2022. LAB42, Faculteitsgebouw Uva Science Park. https://architectenweb.nl/p44033 *Last accessed: 2024-03-25.*

[5] Benthem Crouwel Architects. 2022. LAB42 - Project case study. https://www.benthemcrouwel.com/projects/lab42 *Last accessed: 2024-03-25.*

[6] 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

[7] 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].

[8] 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

[9] 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.

[10] 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.

[11] Pierre Dragicevic, Yvonne Jansen, and Andrew Vande Moere. 2020. Data Physicalization. In *Handbook of Human Computer Interaction*, Jean Vanderdonckt, Philippe Palanque, and Marco Winckler (Eds.). Springer International Publishing, Cham, 1–51. https://doi.org/10.1007/978-3-319-27648-9_94-1

[12] 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.

[13] 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

[14] 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

[15] 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.

[16] 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

[17] 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

[18] 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

[19] Jonathan Lazar, Jinjuan Heidi Feng, and Harry Hochheiser. 2017. *Research Methods in Human-Computer Interaction*. Vol. Second edition. Morgan Kaufmann, Cambridge, MA. https://search.ebscohost.com/login.aspx?direct=true&db=e000xww&AN=1158797&site=ehost-live&scope=site

[20] 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

[21] 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

[22] 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

[23] 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.

[24] 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

[25] 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

[26] 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

[27] 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.

[28] 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

[29] 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

[30] 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

[31] 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.

[32] 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

[33] 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

[34] 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

[35] 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

[36] 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

[37] 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

[38] 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

[39] 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

[40] 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

[41] 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

[42] 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

[43] 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

[44] 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

[45] 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

Appendix A ACKNOWLEDGEMENTS

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Appendix B ETHICAL CONSIDERATIONS

Before user studies were conducted, an application to the Ethics Committee for Information Sciences (ECIS) [6] about the methodology of this research, how data is being gathered and stored was made. Advice from the committee is still pending.

Prior to conducting the questionnaire survey and evaluation procedure, a domain expert from the Informatics Institute at the University of Amsterdam reviewed the methodologies involved. All individuals participating in the survey and evaluation process were obliged to confirm their voluntary involvement by carefully reading and signing a letter of consent, with the assurance that they retained the right to withdraw from participation at any point without the need for explanation. To uphold confidentiality and privacy, survey participation occurred anonymously, and all evaluation data underwent anonymization following the conclusion of the evaluation sessions.

Interacting with occupants within the building and interacting with participants of the usability tests of the prototype adhered to the the principles outlined in the UvA code of conduct [7].

Appendix C DATA STORAGE AND ARCHIVAL

Take some parts of the ethical application to describe data storage and archival of the devices etc.

Appendix D SOURCE CODE

In the spirit of open research, to support reproducibility and enable future work in this problem space the datasets, research notebooks, and prototypes in this work are publicly available on a GitHub organization with the working title 'viszlab' [8] using the MIT License. Several code repositories for different parts of the research can be accessed. The readme.md of the repository described the contents and how to perform the technical set-up:

(1) **Prototype**. Code and models for the physical prototype.
https://github.com/viszlab/prototype
(2) **Datasets**. Code and models for the physical prototype.
https://github.com/viszlab/prototype

A one-page website was created for shareability of this research. It's an online website which gives an overview of the research, allows for viewing the source coded of the prototype and allows for downloading of this paper. A live version is deployed on:

(1) **One-pager**. Code and models for the physical prototype.
https://viszlab.github.io/

[6] https://ivi.uva.nl/research/ethical-code/ethical-code.html
[7] https://www.uva.nl/en/about-the-uva/policy-and-regulations/
[8] https://github.com/viszlab

Appendix E FLOORPLAN AND LAB SET-UP

A diagram indicating where the sensors where installed. This shows the lab set-up in the two meeting rooms.

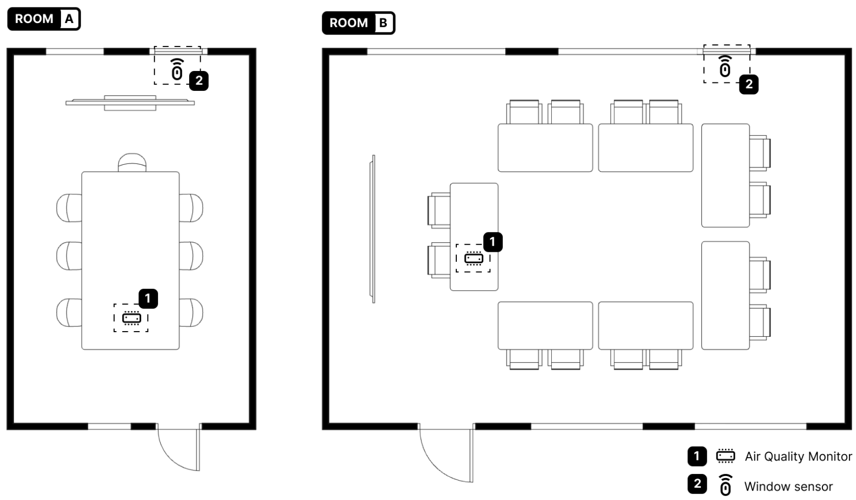


Figure 2: Diagram of the floorplan with sensors installed

Appendix F IOT ARCHITECTURE OF THE PROTOTYPE

System diagram which shows the IoT architecture of the prototype.

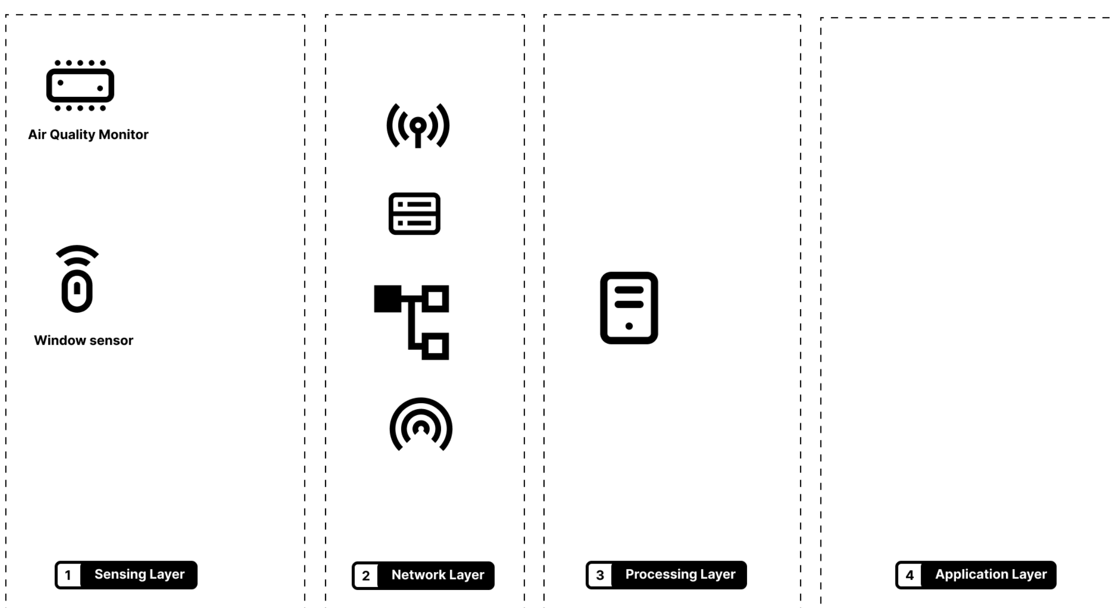


Figure 3: System diagram that shows the technical set-up of the prototype

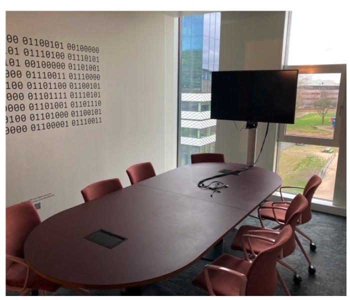
Appendix G MEETING ROOM IMPRESSIONS

Figure 4: System diagram that shows the

Figure 5: System diagram that shows the

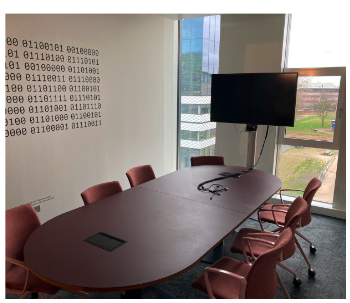
Appendix H BUILDING IMPRESSIONS

(a) first



(b) second

(c) third



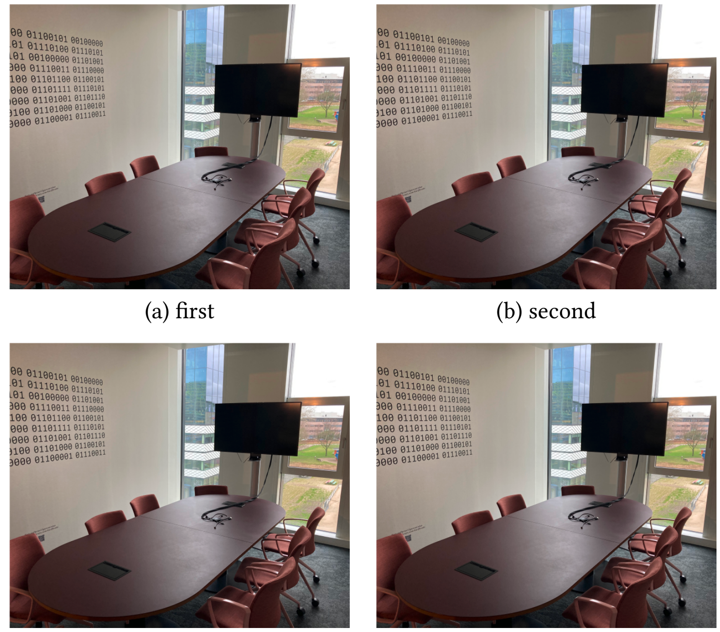
(d) fourth

Figure 6: caption

Figure 7: System diagram that shows the

Appendix I PROTOTYPE IMPRESSIONS

Figure 8: System diagram that shows the



(a) first (b) second

(c) third (d) fourth

Figure 9: caption

Appendix J WEEKLY SCHEDULE

Horizontal boxplot that indicates an average week of booking in the meeting rooms scheduled.

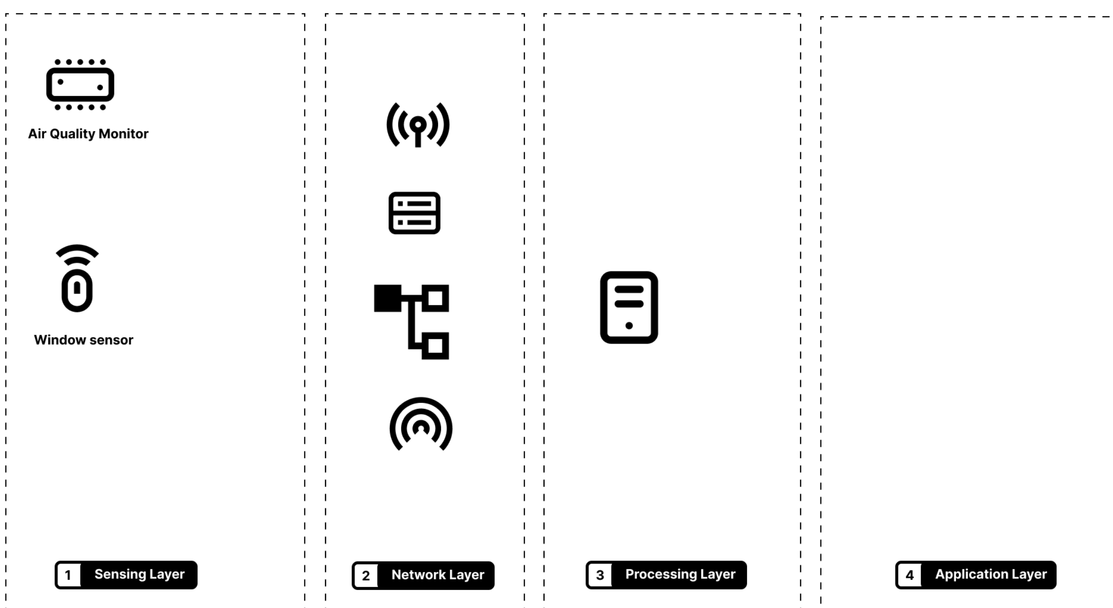


Figure 10: System diagram that shows the technical set-up of the prototype

Appendix K AIR QUALITY MONITORS SAMPLE DATA