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

Investigating intervention strategies for enhancing occupants perception, comfort and health

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ABSTRACT

This master thesis investigates the integration of sensory measurements of indoor air quality (IAQ) into specific indoor spaces to raise occupants' awareness and help occupants take preventive measures against poor air quality. Conducted at Lab42 the study employs human-building interaction principles and persuasive technology to visualize IAQ data. Key research questions address methods for collecting accurate IAQ measurements, integrating environmental data into visual representations, and evaluating the impact of physical visualizations on occupants' understanding and behavior. The overall aim is to inform the development of effective interventions, contribute to healthier indoor environments and inform building design decisions.

KEYWORDS

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

METADATA

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1 INTRODUCTION

Globally, it is estimated that individuals typically allocate 90% of their time within various indoor environments. New 'smart' buildings are often retrofitted with sensors and automated systems that aim to regulate comfort in a multi-dimensional approach encapsulated in thermal, respiratory, visual, and acoustic dimensions.

One of these dimensions that can have far-reaching implications for occupants' comfort and health is the quality of indoor air (IAQ). Insufficient ventilation in indoor spaces leads to poor air quality and an increased occurrence of discomfort and diminished well-being experienced by occupants. The essence of air quality is its invisibility to occupants; polluted air is not easily detected by smell or sight. Additionally, mechanical ventilation systems in buildings operate discreetly, contributing to occupants' perceived lack of control. These systems are typically automated and cannot be directly regulated or controlled by occupants themselves.

This thesis focuses on understanding occupants' needs through in-the-wild studies measuring indoor air quality in specific spaces (e.g. meeting rooms) and prototyping various persuasive technologies and data physicalization devices to visualize indoor air quality and evaluating their effectiveness with the overall goal of gathering insights into occupants' comfort levels and helping them to take preventive action against poor indoor air quality. This creates an interplay between occupants' health and comfort, architecture and built environments, and computing technologies.

1.1 Research questions

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

How can sensory measurements of air data 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:

- **RQ1:** *What are effective methods for collecting sensory measurements of air data in specific indoor spaces while ensuring accuracy and reliability?*
- **RQ2:** *How can environmental information related to air quality, such as pollutant concentrations and ventilation rates, be incorporated into the visual representations?*
- **RQ3:** *How do different types of physical visualizations impact occupants' understanding of air quality and their willingness to adopt preventive measures?*
- **RQ4:** *How do occupants' perceptions and behaviors regarding indoor air quality change over time, from pre-installation to post-installation of the physical representation of poor air quality?*

As outlined in the *related work* section existing research is performed on human-building interaction, the field of persuasive technology, data physicalization, and indoor air quality. While research on defining comfort within indoor buildings, gathering and analyzing sensory air data, and the effects of poor air quality are prevalent, there is a gap in understanding occupants' behavior and their subjective needs. Moreover, limited research exists on how design solutions visualizing environmental data and computing installations can empower occupants, providing them with control and taking preventive action.

1.2 Problem statement

Modern campus buildings are increasingly equipped with sensors and automated systems to regulate occupants' comforts, governed by parameters established through generic building policies, international standards, and faculty staff. Unfortunately, environmental data that is gathered such as indoor air quality and the parameters automated ventilation systems function upon are invisible to occupants in these buildings, and choices the system makes are not transparent. Occupants often encounter limitations in awareness of air quality and exerting personal control over their comfort.

Researching occupants' subjective needs, experiences, and behavior, coupled with a human-centric design approach, has the potential to improve occupants' well-being and create indoor environments with good indoor air quality. Furthermore, it provides valuable insights to faculty staff in making decisions in setting up ventilation systems, arranging indoor spaces, and informing architecture and interior design studios on making decisions about structuring spaces and integrating computing technologies within built environments.

1.3 Lab42 building

This study will be conducted in association with the Digital Interactions Lab [1] and will utilize the recently opened Lab42 [2] building at the UvA Amsterdam Science Park [3] as its primary case study. Lab42 is an energy-neutral, flexible, and adaptable faculty building that facilitates collaborations among students, researchers, and businesses [4]. 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 as shown in the building impression photographs in appendix C. The overarching interior theme in the design revolves around 'tech' and 'nature' aiming to cultivate a fresh, light, and warm comfortable ambiance. Sensing devices are installed throughout the building to automatically adjust lighting, air, and temperature [15].

2 RELATED WORK

The desk research and literature review span several key domains within the field of human-computer interaction. Initially, a theoretical framework is established with the notion of human-building interaction, comfort within buildings, and persuasive technology. Subsequently, the focus narrows down to more specific aspects relevant to the research context delving into data physicalization, and defining indoor air quality.

2.1 Human-building Interaction

Buildings increasingly incorporate new forms of interactivity, which means new inherent connections between 'people', 'built environments', and 'computing' in an emergent research area called Human-Building Interaction (HBI) [1]. This research area is dedicated to exploring the design of built environments that may incorporate computing to varying degrees. Understanding how people use different spaces in a building can inform design interventions aimed at improving the utility of the space [17]. Current research highlights that a significant portion of the data collected by these computing devices within buildings is not readily apparent to visitors and residents, and buildings are not optimally architected to allow computing devices to be integrated within the environment.

2.2 Comfort within buildings

Comfort is achieved in interaction with the environment and is represented in four respective dimensions; thermal, respiratory, visual, and acoustic [3]. Comfort can be studied and designed as an interactive experience with the built environment itself [2]. Indoor Environmental Quality (IEQ) indexes serve as metrics for assessing comfort, with Post-Occupancy Evaluation (POE) being employed to gauge occupants' perceived comfort. In current scenarios, technology is typically retrofitted onto a new or existing building and users indicate a perceived lack of control and engagement with these systems, primarily because many automated buildings operate based on arbitrarily set parameters, and data these sensors gather are often invisible to end users.

2.3 Persuasive technology

The primary aim of ubiquitous computing (ubicomp) devices is to seamlessly blend into the environment, essentially making computing devices 'disappear'[18]. 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 [14]. This method of persuasive design serves as a powerful tool in calmly extending users' awareness, helping users understand the consequences of their actions, and gaining insight into their behavior [19].

2.4 Data physicalization

The research domain known as data physicalization 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 [6]. 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, presenting distinct advantages over traditional 'screen-focused' data representations, such as 2D canvas display [7].

2.5 Indoor Air Quality (IAQ)

Globally, it is estimated that individuals typically allocate 90% of their time within various indoor environments [8]. Insufficient ventilation in indoor spaces leads to poor air quality and an increased occurrence of discomfort and diminished well-being experienced by occupants [16]. Poor air quality can have adverse impacts on health such as increased risk of asthma, headaches, and allergies [10] as well as impact cognitive performance and productivity [5]. Health Authorities worldwide recommend that one of the best solutions is to simply open the windows 2-3 times a day [9]. When occupants experience symptoms of sick building syndrome (SBS) [11] the hazardous situation has already occurred. The goal is to recognize the role of humans as active users of a building and helping them prevent these situations before they occur.

[1]https://uva-dilab.com/
[2]https://lab42.uva.nl/
[3]https://www.amsterdamsciencepark.nl/

3 METHODOLOGY

Integration of user studies throughout the entire process, employing a systematic approach to data collection, and prototyping design solutions are the main focuses of this research. The chosen methodologies are project-oriented and form part of in-the-wild studies aimed at examining occupant behavior. These studies are complemented by data collected from sensing devices which all go through a process of data cleaning, transformation, and analysis. Prototyping of sensing devices, persuasive technology, and data physicalizations will be developed and subjected to usability testing to assess potential changes in occupant behavior before and after installation. The overarching goal is to inform the design through data, utilizing design as a probing tool for data collection and vice versa. This approach ensures a comprehensive understanding of user interactions and space dynamics, ultimately contributing to a design solution that is both informed by empirical data and responsive to occupant needs.

3.1 Space measurements (sensing devices)

Analyzing current space with regards to air quality by utilizing the data measured from the automated systems already installed within the building exposed by the building API and augmenting this dataset with commercially available indoor climate data loggers from Atal [4]. Concurrently, observations of occupants will be conducted to cross-reference the data with their actual behavior. The findings will be documented through methods such as data frames, data processing, and data visualizations aiming to address the following questions:

- What are the variations in indoor air quality currently within specific spaces over a defined period?
- When does indoor air quality reach suboptimal levels, and what are the thresholds indicating poor air quality?
- Can systems accurately predict periods of poor air quality within a specified timeframe?

3.2 Occupant behavior (elicitation study)

Collecting information about occupants within the specific spaces within the building will involve assessing their comfort states. Surveys are anticipated to be the primary data collection method distributed across the course of the thesis projects. Additionally, conducting one-on-one interviews using open-field questionnaires to explore occupants' comfort levels more comprehensively will also be used. The findings will be documented in methods such as personas, field trials, customer journeys, and observation reports aiming to address the following questions:

- What is the level of awareness among occupants regarding indoor air quality and its influence on comfort?
- To what extent do occupants perceive and experience symptoms associated with poor indoor air quality?

3.3 Prototyping (computing devices)

After gathering data and some preliminary occupant studies the aim is to prototype a design solution for behavior change, emphasizing the concept of calm technology—prompting occupants to undertake preventive actions with minimized interruption costs. Most likely in the form of a tangible visualization of the air quality within a room. The designed solution will undergo usability testing and subsequent data analysis, enabling a comparative evaluation of user behavior both before and after installation. The prototyping process is expected to comprise three interrelated components:

1) Sensing device using microcontrollers: development of a sensing device utilizing a microcontroller (e.g., ESP32 platform [5]) to gather specific user behavior data in select spaces within the building (e.g. sensors to detect if windows are opened).
3) Tangible data visualization: crafting a physical, tangible data visualization presenting the collective output of the sensory data to influence behavior (e.g. interactive installation installed on the walls that displays air quality). This may involve utilizing platforms such as Raspberry Pi [7] or Arduino [8], with possible visualization creation using Processing [9].

3.4 Datasets

For the existing building used for this case study a dataset is provided which consists of "building data" to regulate automated systems, represented by an object list utilizing 'TAG encoding.' This list categorizes each installation and connection point, encompassing both generic elements like safety installations (e.g., smoke detectors), electrical components (e.g., wall sockets), and utilities (e.g., boilers), as well as sensory devices such as air quality regulators and light sensors controlling shutters. Additionally, the dataset includes floorplans and room number overviews.

This data will be supplemented by the aforementioned dataloggers installed in designated areas such as meeting rooms within the buildings for a certain period to gather air quality data. Supplementary data comes from prior studies conducted on the Lab42 building. Master Student Jan Ramdohr conducted studies using air quality and light sensors for specific measurements in designated areas[12]. A survey on user emotions across various spaces in the building was performed by Ph.D. candidate Shruti Rao [13].

Any additional data acquired from the user studies, space behavior observations, and prototype sensing devices will be processed (e.g. data cleaning, transformation, sentiment analysis) using Python [10] and Jupyter [11]. Subsequently, the data will be subjected to analysis and visualization through graphs created using visualization libraries like Seaborn [12].

4 RISK ASSESSMENT

This research approach is dependent on in-the-wild research and placing and testing several devices throughout an actively used building, this proposes certain constraints that are discussed in this section.

[4] https://www.atal.nl/atu-ct-climatrend-binnenklimaat-datalogger

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[7] https://www.raspberrypi.org/
[8] https://www.arduino.cc/
[9] https://processing.org/
[10] https://python.org/
[11] https://jupyter.org/
[12] https://seaborn.pydata.org/

4.1 Occupant behavior studies

While the research is not entirely dependent on the available existing data, incorporating survey data and interviews with occupants is crucial for comprehensive insights. In the event of limited survey responses or challenges in conducting interviews, there is a potential risk of information saturation. However, given the research timeline and the building's visitor frequency, this scenario is considered unlikely.

4.2 Air quality and building data

There is the possibility that only relying on access to building data is limited to gathering significant data about comfort and air quality. It is reported that not all sensors listed in the overview are confirmed to be active and running. This can be mitigated by enhancing the already existing sensors by installing dataloggers in designated areas to gather data besides the already existing sensors present in the building.

4.3 Building access and hardware installation

There is a possibility of restricted access to the building due to construction safety or administrative reasons, hindering the testing of the design solution and placement of sensing devices. Coordination with building faculty staff is essential to address this potential constraint. It needs to be noted that no objections have been raised in prior research, but this risk can be mitigated by testing the prototype in an alternative context to assess device usability.

4.4 Privacy and ethical considerations

Sensing and gathering sensory data from occupants is data collection that occupants might deem as privacy-invasive. Careful considerations should be made to mitigate these concerns and occupants should be confident that data for this research is gathered anonymously and only for collective monitoring. Interacting with occupants within the building will be in alignment with the principles outlined in the UvA code of conduct [13] and an application to the Ethics Committee for Information Sciences (ECIS) [14] about how data is being stored and gathered has been made. Advice from the committee is still pending.

5 PROJECT PLAN

The master thesis project will be conducted on a part-time basis, initiated with concepting and ideation in November/December 2023. The main research phase will span from January 8, 2024, to June 30, 2024, concluding with thesis submission. The project's first phase involves gathering space air air quality and occupant behaviour. The subsequent phase focuses predominantly on prototyping design solutions and iterative refinement. The final phase includes usability testing and evaluation of the design solution. A detailed weekly overview, in the form of a project timeline, is provided in appendix B. While the goal is for the research and design solutions to scale to other university buildings, the project's scope is limited to the Lab42 building due to uncertainties in the context of other buildings.

[13]https://www.uva.nl/en/about-the-uva/policy-and-regulations/

[14]https://ivi.uva.nl/research/ethical-code/ethical-code.html

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Appendix A GITHUB REPOS

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' using the MIT License. Several code repositories for different parts of the research can be accessed:

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

Appendix B PROJECT TIMELINE

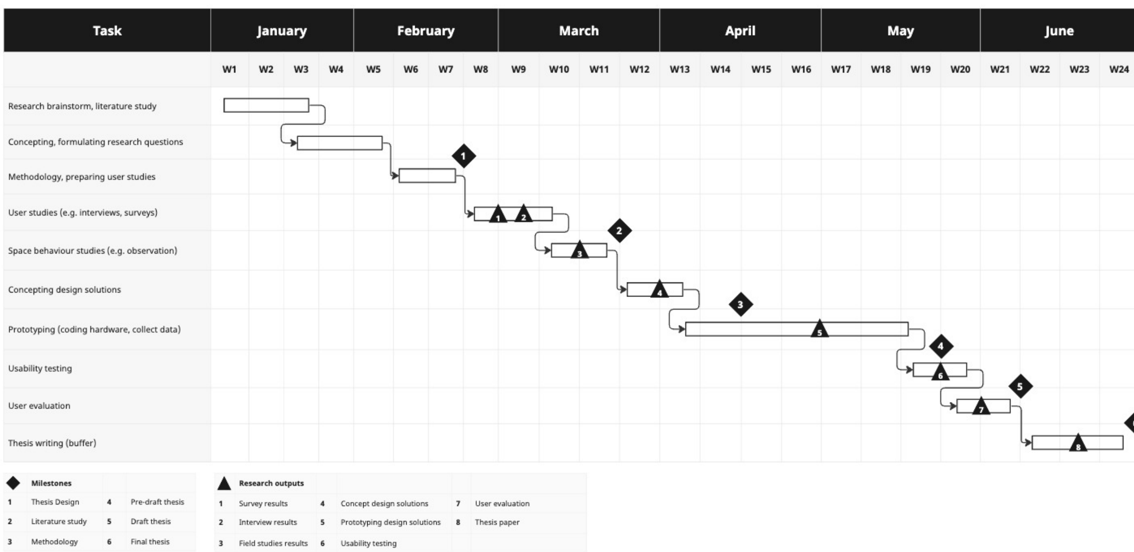

Figure 1: Project timeline that shows the weekly schedule

Appendix C BUILDING IMPRESSIONS

Figure 2: Photographs for impressions of the Lab42 building