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

While smart buildings incorporate sensors and automated systems to regulate various aspects of comfort, Indoor Air Quality remains a significant concern due to its invisible nature and its impact on occupants' health and well-being. This research uses the Lab42 building at UvA Science Park as a case study to study occupants' comfort through in-the-wild studies, focusing on specific spaces like meeting rooms and measuring the quality of air using sensory data and datalogger devices. Prototypes of persuasive technologies and data physicalizations are developed to make Indoor Air Quality visible and comprehensible to occupants enabling them to take preventive and proactive measures to mitigate poor air quality risks.

KEYWORDS

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

METADATA

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

Institute: Informatics Institute
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1 INTRODUCTION

Globally, it is estimated that individuals typically allocate 90% of their time within various indoor environments [10]. 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 [16]. 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 the enhancement of informal learning spaces through ubiquitous computing: the following main research question is formulated:

How can ubiquitous computing impact student behavior to significantly enhance the quality of informal learning spaces and facilitate an optimal learning environment?

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 the characteristics, intentions, and goals of the students entering the building?*
- **RQ2:** *How do students of the building currently define and rate their comfort concerning subjective parameters of the building?*
- **RQ3:** *What sensory data about students and the environment is currently being collected and should this be enhanced?*
- **RQ4:** *How can ubiquitous computing devices nudge students into certain desired behavior?*
- **RQ5:** *Is there a difference in user behavior pre-installation and post-installation of the computing devices?*

As outlined in the *related work* existing research has explored human-building interaction, the field of persuasive technology, data physicalization, and informal learning spaces. While research on defining comfort within indoor buildings and gathering and analyzing sensory data is prevalent, there is a gap in understanding user behavior and their subjective needs. Moreover, limited research exists on how design solutions can empower users, providing them with control and enabling spaces (including buildings in general) to adapt to user needs.

1.2 Problem statement

Modern campus buildings (e.g. Lab42) are increasingly equipped with sensors and automated systems to regulate occupants' comforts, governed by parameters established through generic building policies and faculty staff Unfortunately, students in these buildings often encounter limitations in exerting personal control over their comfort and data gathered by these systems is invisible to the user and choices the system makes are not transparent.

This adaptation implies that buildings should embody empathy [13] and be adaptive (e.g. responsive to human signals such as emotions) with a focus on fostering user interaction with the environment. Researching to understand students' subjective needs, experiences, and behavior, coupled with a human-centric design approach, has the potential to elevate occupants' well-being and create optimal learning spaces. Furthermore, it provides valuable insights to faculty staff in making decisions to optimally arrange learning spaces and inform 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, data physicalization, and ubiquitous computing. Subsequently, the focus narrows down to more specific aspects relevant to the research context delving into persuasive technology and its possible application within learning environments.

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, such as sensors and cameras, 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.

2.3 Persuasive technology

Ubiquitous computing (ubicomp) facilitates new modes of computing, sensing, and actuation seamlessly integrated with physicality. The primary aim of ubiquitous computing devices is to seamlessly blend into the environment, essentially making computing devices 'disappear'[18]. Recent advancements in technology, such as lower-cost hardware (per Moore's Law), a diverse array of sensors and actuators, and improved protocol and communication technologies, have improved the capabilities of ubicomp devices. 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 integration of ubicomp and 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 [8]. 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 [9].

2.5 Informal Learning spaces

Universities are actively restructuring and redesigning campus buildings to the notion of 'sticky campuses' [6] aimed at enticing students to spend more time on campus. Primarily moving from strictly learning environments (e.g. lecture halls, classrooms) to more informal learning (e.g. collaborative spaces) spaces redefining universities as dynamic learning environments. The establishment of these informal learning spaces, a significant aspect of the Lab42

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

building, prompts crucial inquiries into student behaviors and the nature of 'learning' [5]. Notably, there is a growing body of research that delves into the relationship between the arrangement and control of learning spaces and student learning activities [7].

3 METHODOLOGY

Integration of user studies throughout the entire process, employing a systematic approach to data collection and prototyping design solutions are the main focusses of this research. The chosen methodologies are project-oriented and form part of in-the-wild studies aimed at examining user behavior and space utilization. These studies are complemented by data collected from sensing devices which all go through a processes of data cleaning, transformation, and analysis. As a culminating step, a prototype of persuasive technology will be developed and subjected to usability testing to assess potential changes in user 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 the creation of a persuasive technology prototype that is both informed by empirical data and responsive to user needs.

3.1 User studies (elicitation study)

Collecting information about users within the Lab42 building will involve assessing their intentions within the buildings and their emotional 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 users' comfort levels more comprehensively will also be used. The findings will be documented in methods such as personas, and empathy maps, and employing the MoSCoW method, providing an overview of user needs and current behavior within the building aiming to address the following questions:

- What are the objectives and motivations of students upon entering the building?
- What specific learning objectives do students aim to achieve during their time in the building?
- What factors contribute to students choosing to work on campus instead of working from home?

3.2 Space behavior (sensing devices)

Analyzing current space behavior by utilizing the data generated from the automated systems already installed within the building. To augment this dataset, prototyped sensing devices may be introduced to collect specific sensory data not covered by the existing infrastructure. Concurrently, observations of students will be conducted to cross-reference the data with their actual behavior. The findings will be documented through methods such as field trials, customer journeys, and observation reports aiming to address the following questions:

- What is the current distribution of space usage within the building?
- How frequently and for what duration do students typically spend time in the campus building?
- What criteria influence students' decisions in selecting a particular space for their work within the building?

3.3 Prototyping (computing devices)

After user research the aim is to formulate a design solution for behavior change, emphasizing the concept of calm technology—prompting users to undertake preventive actions with minimized interruption costs. 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 a microcontroller: development of a sensing device utilizing a microcontroller (e.g., ESP32 platform [4]) to gather specific user behavior data in select spaces within the building.
2) Real-time API-Integrated Storage: creation of a storage system with a real-time API for persistent data storage in the backend. Visualizations for stakeholders will be displayed in a front-end dashboard for further analysis. This system is likely to be developed using frameworks such as Svelte [6] and the GraphQL query language [7].
3) Tangible Data visualization: crafting a physical, tangible data visualization presenting the collective output of the sensory data to influence behavior. This may involve utilizing platforms such as Raspberry Pi [8] or Arduino [9], with possible visualization creation using Processing [10].

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.

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[11]. A survey on user emotions across various spaces in the building was performed by Ph.D. candidate Shruti Rao [12].

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 [11] and Jupyter [12]. Subsequently, the data will be subjected to analysis and visualization through graphs created using visualization libraries like Seaborn [13].

[4] [5]
[6] https://svelte.dev/
[7] https://graphql.org/
[8] https://www.raspberrypi.org/
[9] https://www.arduino.cc/
[10] https://processing.org/
[11] https://python.org/
[12] https://jupyter.org/
[13] https://seaborn.pydata.org/

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.

4.1 User studies

While the research is not entirely dependent on the available existing data, incorporating survey data and interviews with users 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 Building data

There is the possibility that access to data building is limited to gathering significant data about space behavior. 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 with prototype sensing devices to gather data as a proof of concept. Also, only relying on data is a risk factor and incorrect processing of the data can lead to incorrect evaluation of space behavior.

4.3 Building access

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. While no objections have been raised in prior research, the 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 users is data collection that users might deem as privacy-invasive. Careful considerations should be made to mitigate these concerns and users should be confident that data for this research is gathered anonymously and only for collective monitoring. Interacting with users within the building will be in alignment with the principles outlined in the UvA code of conduct [14] and an application to the Ethics Committee for Information Sciences (ECIS) [15] 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 and analyzing user data. The subsequent phase focuses predominantly on prototyping design solutions and

[14] https://www.uva.nl/en/about-the-uva/policy-and-regulations/
[15] https://ivi.uva.nl/research/ethical-code/ethical-code.html

iterative refinement. The final phase includes usability testing and evaluation. 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.

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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

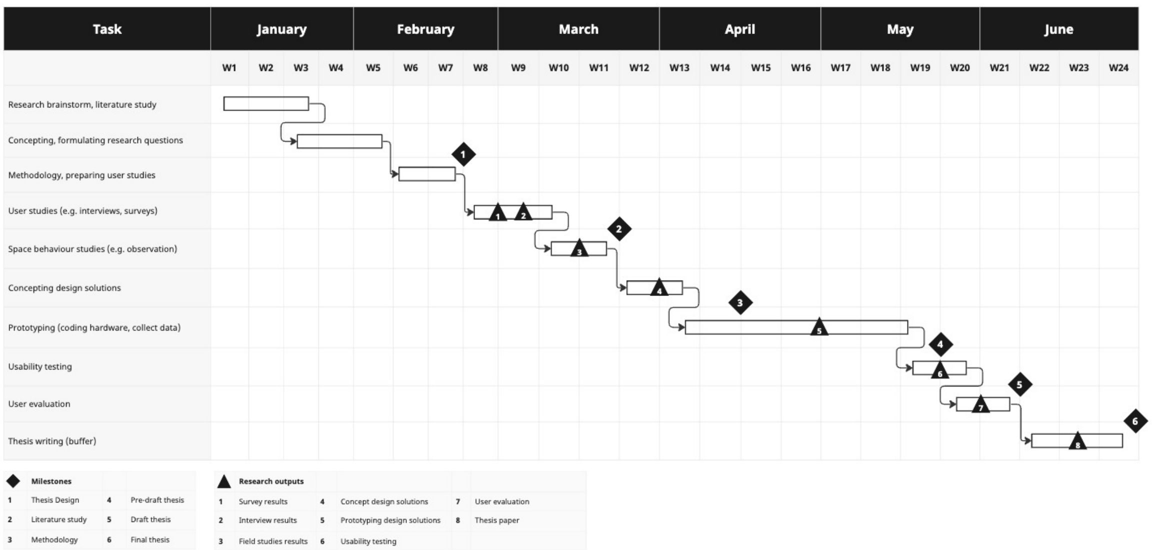

Figure 1: Project timeline that shows the weekly schedule

Appendix C BUILDING IMPRESSIONS

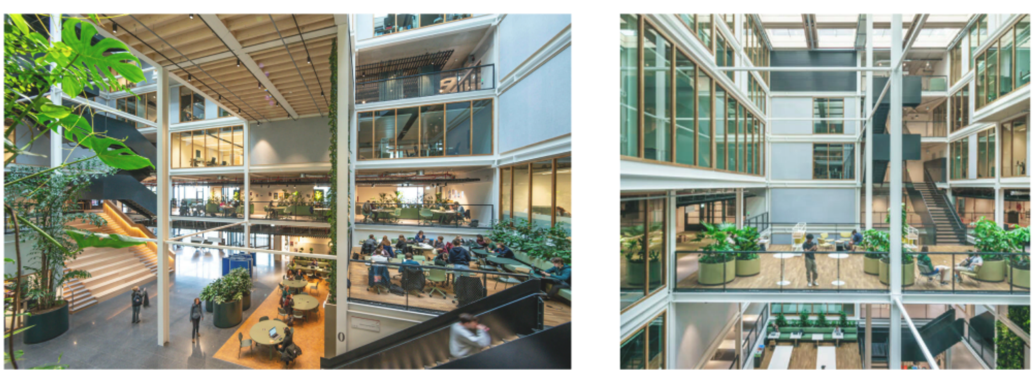

Figure 2: Photographs for impressions of the Lab42 building