Designing and Exploring Interfaces for Raising Awareness about the Environment through Interspecies Encounters

by

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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or processional qualification except as specified. The document follows the guidelines and requirements of the University of the West of Scotland and the CTR Harvard referencing style. The main body of the thesis does not exceed the maximum permitted length of 40,000 words.

Jessica Broscheit

Abstract

Due to the global climate crisis, new challenges have emerged to mediate the relationship between human beings and their changing world. While interactive technologies are increasingly being used to raise awareness about the environment in the cultural sector, little is known about the user's experience during an interaction. With the aim of enabling an aesthetic and social encounter with the air, this study contributes to the field of human–computer interaction through theoretical, practice-based, and empirical research. To fulfil this aim, the author has organized this case study into three parts. The first part explores the design and interaction space to formulate a conceptual framework that can be used for the creation of an expressive interface representing the state of the air. Based on the conceptual framework, the second part involves the design and implementation of an initial interface that employs the metaphorical representation of a sentinel species, more specifically the miner's canary, to convey the state of the air as physiological behaviour and materiality. The interface was then presented to the culturally interested society in various exhibition spaces. The third part draws on these initial field observations and develops a body-worn interface for exploring high particle concentrations in a speculative art installation. The body-worn interface is then evaluated with 14 participants while interacting in a prototypical arrangement in the laboratory. Collectively, these parts build on one another and provide important implications for the following topics: (a) expressive interfaces that can be used as discursive objects to raise awareness about the atmospheric environment in the cultural sector, and (b) promising conditions for transdisciplinary knowledge transfer between science and society.

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List of Publications

The main publications that have emerged from this dissertation:

1. **Broscheit, J.**, Draheim, S., von Luck, K., and Wang, Q. (2023), Sentinel Species: Towards a Co-Evolutionary Relationship for Raising Awareness About the State of the Air. In Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI'23), February 26–March 1, 2023, Warsaw, Poland. ACM, New York, NY, USA, 13 Pages.
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2. **Broscheit, J.**, Wang, Q., Draheim, S., and von Luck, K. (2021), Towards Atmospheric Interfaces. In Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI'21), February 14–17, 2021, Salzburg, Austria. ACM, New York, NY, USA, 7 Pages.
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3. **Broscheit, J.**, Draheim, S., and von Luck, K. (2019), IVORY: A Tangible Interface to Perceive Human-Environment Interrelationships. In Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI'19). Association for Computing Machinery, New York, NY, USA, 491–497. doi: 10.1145/3294109.3301266

Previous research that have contributed to this dissertation:

1. **Broscheit, J.**, Draheim, S., von Luck, K. and Wang, Q. (2021), REFLECTIONS ON AIR: An Interactive Mirror for the Multisensory Perception of

Air. In Augmented Humans International Conference 2021 (AHs'21), February 22–24, 2021, Rovaniemi, Finland. ACM, New York, NY, USA, 8 pages. doi: 10.1145/3458709.3458961

2. **Broscheit, J.** (2020), Embodied Atmospheres: A Symbiosis of Body and Environmental Information in the Form of Wearable Artifacts. In Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI'20). Association for Computing Machinery, New York, NY, USA, 899–903. doi: 10.1145/3374920.3374958

3. Meyer, U., Becker, J., **Broscheit, J.** (2019), Visualising Air Pollution Datasets with Real-Time Game Engines. In: Rocha Á., Adeli H., Reis L., Costanzo S. (eds) New Knowledge in Information Systems and Technologies (WorldCIST'19). Advances in Intelligent Systems and Computing, vol 932. Springer, Cham. doi: 10.1007/978-3-030-16187-3_30

4. **Broscheit, J.**, Jeworutzki, A., Draheim, S., and von Luck, K. (2018), Colored Raindrops: A Fiction-Driven Workshop for Girls. Positioning paper for the workshop "Sustaining Girls' Participation in STEM, Gaming and Making" that was part of the ACM Interaction Design and Children (IDC) conference in Trondheim, Norway. https://idc2018girls.files.wordpress.com

5. **Broscheit, J.**, Draheim, S., and von Luck, K. (2018), How Will We Breathe Tomorrow? Published by BCS Learning and Development Ltd. Proceedings of EVA Copenhagen 2018, Denmark; In Politics of the Machine – Art and After (POM). doi: 10.14236/ewic/EVAC18.10

Other publications that refer to studies mentioned above:

1. **Broscheit, J.** (2023), Ivory & Reflections on Air. In: Meißner, S., Sontopski, N., Bronsky, M. (Hg.): Digital ist besser?!. ISBN: 978-3-948058-13-5

2. Kohler, M., Draheim, S., **Broscheit, J.**, Meyer, U., and von Luck, K. (2022), Lab Cultures - Hochschullabore im Kontext von Wissenstransfer und digitaler Innovation. In: Pfannstiel, M.A./ Dautovic A. (Hg.): Transferinnovationen und Innovationstransfer zwischen Wissenschaft und Wirtschaft. Springer-Verlag. ISBN: 978-3-658-37156-2

List of Abbreviations

ACM Association for Computing Machinery

AH Augmented Human

CAD Computer-Aided Design

GUI Graphical User Interface

HCI Human–Computer Interaction

I/O Input/Output

MSP Max Signal Processing

OSC Open Sound Control

PM Particulate Matter

SMA Shape Memory Alloy

SLA Stereolithography

TEI Tangible, Embedded, and Embodied Interaction

TUI Tangible User Interface

TI Tangible Interaction

UART Universal Asynchronous Transmitter Receiver

Ubicomp Ubiquitous computing

UDP User Datagram Protocol

UI User Interface

UX User Experience

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Chapter 1

Introduction

Due to the global climate crisis, new challenges have emerged to mediate the relationship between human beings and their changing world. This study therefore presents the design, implementation, and evaluation of interactive technologies that aim to raise awareness about the atmospheric environment in the cultural sector. To clarify the relevance and scope of this study, the following sections describe the contextual background (1.1), research aim (1.2), research contributions (1.3), role of the researcher (1.4), and the thesis structure (1.5).

1.1 Contextual Background

Interactive technologies designed to raise awareness about the environment play an important role in addressing environmental concerns in the cultural sector, which encompasses art, design, and creative education. To illustrate the research relevance of these technologies, the contextual background refers to the debate regarding the *Anthropocene* from an ecological, technological, and socio-cultural perspective.

Atmospheric chemist Paul Crutzen and limnologist Eugene Stoermer (2000) proposed the term Anthropocene to mark the current geological epoch in which the central role of human impacts on the Earth's system has been highlighted. In their research, Crutzen and Stoermer (2000) identified a number of human impacts that affect the Earth's system, such as emissions released into the atmosphere, and suggested global research on anthropogenic climate change. To address the complex challenges of unknown dimensions, the scientific community strives to better understand the processes that trigger and drive global change (Mauser, 2006). For this purpose, scientists use a range of sensor technologies that are being used not only to obtain empirical measurements of ecological processes from space and on the Earth but also to observe the environment-dependent behaviour of species (Gabrys, 2016). While some scientific disciplines focus primarily on collecting and analysing quantitative measurements, other disciplines (e.g., the humanities, social sciences, and the arts) strive to heighten the consciousness of the current epoch (Horn, 2020). They understand the Anthropocene as the current state of affairs and as a possibility to describe the complexity of global change. Their holistic perspective also includes a new way of being in the world by considering the interconnectedness of human and non-human species (e.g., animals, plants, and microorganisms; Haraway, 2003, 2016; Tsing, 2012).

Although the collaboration between science and technology is a generally acknowledged interdisciplinary approach for sustainable development, Jäger (2006) noted a deficit in the involvement and knowledge transfer to the broader society. Despite the complex and voluminous datasets that illustrate global climate change in the form of graphs and statistics, the impacts of anthropogenic activities remain abstract for most people in society unless they are directly affected (Horn, 2019). To draw people's attention to environmental issues and involve them in citizen science projects, transdisciplinary research provides an approach that combines academic and non-academic knowledge to achieve a common goal, such as mastering global climate change (Tress et al., 2005).

Along with a variety of approaches and multipliers, artistic and critical design practices offer an alternative to mediate environmental concerns amongst culturally interested people by stimulating individuals' senses in ways that extend beyond numerical datasets and statistics (Anderson, 2015; Davis and Turpin, 2015; Dunne and Raby, 2014; Fowkes and Fowkes, 2022; Reiss, 2019). These positions hence become mediators of environmental concerns while being presented to the society in exhibitions (e.g., in museums, in galleries, and at public sites). According to Horn (2018) and (Randerson, 2018), some of these positions use the air as a *medium* to enable an aesthetic and social encounter with the environment and bring ecological concerns to the foreground of human perception. In line with Gibson (1979) and Horn (2018), the present study understands an aesthetic of air as a perceptual dimension that can be experienced by the human's sensory system (e.g., visual, auditory, touch smell, and taste receptors). Furthermore, a social encounter with the air is interpreted as an emotional and meaningful connection. For example, Randerson (2018, p. xvii) explained that "Weather as an artist's medium can be an input in a process-based meteorological artwork, in the sense of a constitutive 'material,' like clay or paint". While some positions, for instance, use the weather dynamic itself, others utilise technological approaches to represent meteorological processes in the following forms: (a) data-driven sculptures that communicate the state of the air through their aesthetic (e.g., Baraga, 2016; Broscheit et al., 2021b; Khan, 2010); (b) metaphorical representations of species that are sensitive to environmental conditions and thereby engage with humans on an emotional level (e.g., Broscheit et al., 2018a; Fabrizi, 2014; Grade, 2013; Seow et al., 2022); (c) immersive environments that can be explored to reconnect with natural phenomena (e.g., Nakaya, 2022; Random International, 2012); and (d) bodily experiences that augment the human's perception to explore nearby surroundings (e.g., Bentel, 2016; Broscheit, 2020; Molga, 2016). In addition, some artist and design practitioners engage directly with people in society by using participatory interventions for creative environmental knowledge transfer (e.g., Broscheit et al., 2018a; De Greve et al., 2022; Saraceno, 2016; Solomon et al., 2018).

In contrast to conventional measurement methods or technological solutions that operate in the background, these aesthetic and social encounters with the air play an important role in human-computer interaction (HCI) to directly engage with users. These encounters thereby generate knowledge about users experiences and the environment, become antennas for future developments, and provoke discussions within the society (Dunne and Raby, 2014; Horn, 2018; Randerson, 2018). Moreover, these creative practises for environmental awareness have gained special attention in HCI to address broader and more holistic research questions in the Anthropocene epoch (Bendor, 2018; Bendor et al., 2021; Gaikwad, 2020; Key et al., 2022; Rahm-Skågeby and Rahm, 2022). Some of these HCI studies emphasised the important role of artistic, critical, and speculative design practices in the development of technologies to tackle anthropogenic concerns. Rahm-Skågeby and Rahm (2022), for example, explained that design supports the creation of novel technologies through which people experience the world and thereby reshape their beliefs and worldview. Lastly, Bendor et al. (2021) underlined the ability of designers to deal with complexity, activate society, and envision possible futures.

In summary, this section presented the relevance of interactive technologies that aim to raise awareness about the environment in the cultural sector. This included the understanding of the term Anthropocene and its meaning within different disciplines. Overall, it can be assumed that interactive technologies for environmental awareness have become a relevant approach to transcend the boundaries between academic disciplines and the general public, and thereby supporting transdisciplinary sustainable development. The next section introduces the main goal of this study on addressing anthropogenic impacts, such as air pollution, at the intersection of art, design, and technology.

1.2 Research Aim

As previously mentioned, interactive technologies are used both to solve known problems, such as in cities with high air pollution, and to raise awareness regarding environmental issues among the civil society. The present study is particularly interested in addressing environmental issues in the cultural sector to explore interactive technologies beyond known application scenarios and to discuss future directions. The exhibition space is especially appropriate for engaging with the public and presenting speculative scenarios that reflect on anthropogenic concerns to identify new perspectives for HCI research. Although interactive technologies are increasingly being used to raise awareness about the environment, little is known about users' experiences during an interaction. The aim of this study is therefore to design, implement, and evaluate an interactive technology that enables an aesthetic and social encounter with the air. This technology can then be used as a discursive object to engage with the culturally interested society and to understand users' experiences during an interaction. This interactive technology could potentially contribute to transdisciplinary research and heighten awareness of environmental concerns among science and society.

1.2.1 Research Questions

To fulfil the aforementioned aim, the following research questions were formulated:

1. How does one provide an aesthetic and social encounter with the air?

2. How does related knowledge guide the practical development of an interactive technology designed to raise awareness about the atmospheric environment?

3. What do users experience while interacting with a technology that represents the state of the air?

1.2.2 Research Objectives

To accomplish the above research questions, the following theoretical, practice-based, and empirical objectives were defined:

1. To identify research gaps by analysing literature on interactive technologies that aim to raise awareness about the atmospheric environment, especially at the intersection of art, design, and technology.

2. To formulate a conceptual framework that explores the design and interaction space of an aesthetic and social encounter with the air and that can be used to guide the design and implementation process of an interactive technology.

3. To develop an interactive technology that aims to enable an aesthetic and social encounter with a changing atmosphere by drawing on related knowledge and practice-based approaches.

4. To evaluate, through the use of qualitative and quantitative methods, users' experiences while interacting with an interactive technology that represents the state of the air.

1.3 Research Contribution

This study contributes knowledge to the interdisciplinary field of human–computer interaction (HCI), a research area that has evolved from computer science. Hewett et al. (1992, p. 5) defined HCI as "a discipline concerned with the design, evaluation, and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them." HCI research is particularly interested in the study of the relationship between computing systems and human beings. HCI also encompasses disciplines such as social sciences, engineering, and design (Hewett et al., 1992). As computing systems have become increasingly intertwined with people's daily lives, research aspects such as context, experience, and emotions have become central topics (Bødker, 2006; Dourish, 2004; Weiser, 1991). Knowledge in this interdisciplinary research field therefore derives from various types of contributions, such as theories, system development, and empirical findings (Wobbrock and Kientz, 2016). In this respect, the contributions of this study are threefold:

> **1) Theoretical Foundations.** The theoretical contribution of this research encompasses the conceptual framework of atmospheric interfaces, which provides an overview of the design and interaction space for the development of interactive technologies that raise awareness about the environment through an aesthetic and social encounter with the air. This framework consists of (a) inputs and outputs, (b) interface metaphors, and (c) types of interaction. Parts of this contribution have been published in Broscheit et al. (2021a).
>
> **2) Interactive Technologies and Forms of Interactions.** The practice-based contribution involves the design and implementation of expressive interfaces that use the concept of sentinel species – more specifically, the miner's canary – as a metaphorical representation for communicating the state of the air as multisensory eco-feedback. Additionally, this study contributes an approach to simulate a changing atmosphere for an immediate user interaction. Parts of this contribution have been published in Broscheit et al. (2019), Broscheit (2020), and Broscheit et al. (2023).

3) Understanding of Users. The empirical contribution provides a first-hand understanding of the participants' experiences and their relationships to the environment as they explore fields of high particle concentrations in an experimental setting with an sentinel species-mimicking interface worn on their bodies. Parts of this contribution have been published in Broscheit et al. (2023).

This dissertation also includes preliminary studies, conducted by the author, addressing environmental awareness through the use of interactive technologies in the real- and virtual worlds (e.g., Broscheit, 2020; Broscheit et al., 2018b,a, 2021b; Meyer et al., 2019). Taken together, the theoretical, practice-based, and empirical contributions provide important implications for the following topics: (a) expressive interfaces that can be used as discursive objects to raise awareness about the atmospheric environment in the cultural sector, and (b) promising conditions for transdisciplinary knowledge transfer between science and society.

1.4 The Researcher's Role

Creswell (2014) highlighted the importance of clarifying the researcher's role and bias to ensure the trustworthiness and credibility of qualitative research. This section therefore outlines the author's background and motivation for this research project. Overall, this dissertation was written from the perspective of an author, who investigates and practices at the intersection of art, design, and technology. The author was funded through a part-time position at the Hamburg University of Applied Sciences' Faculty of Engineering and Computer Science. There, she worked as a researcher for the Research and Transfer Center Smart Systems[1] and conducted studies in the Creative Space for Technical Innovations[2] and the Living Place lab.[3] The motivation for this research project originated from the author's

[1]https://smsy.haw-hamburg.de
[2]https://csti.haw-hamburg.de
[3]https://livingplace.haw-hamburg.de

personal experience in China, narrated from the first-person perspective below.

In 2013, during my residency as a media artist within the framework of an exchange program of the Robert Bosch Stiftung in cooperation with the International Media Center, I received lectures on China's historical, cultural, and social background at the Tsinghua University in Beijing. Aside from the lectures, I spent three months photographically capturing my impressions of the everyday life in the global city. While exploring the streets of Beijing with my camera, I experienced varying air quality levels. To combine this experience with actual measurements, I documented the daily values in my handwritten data diary through the support of an air quality index app. This field observation sparked my interest in conveying invisible information, such as urban air pollution, through the creation of multisensory and interactive experiences. Since then, I have been interested in environmental sensing with the aim of transforming sensor measurements into interactive material to explore the aesthetic dimension of air and to discuss the interrelation between humans and their changing environment. To accomplish this, I draw on a documented background in communication design, stage performance, and experimental music. Throughout this research I designed, implemented, and documented all interfaces, unless otherwise noted. Despite the challenge of combining research and creative practice, I see significant potential to engage with different communities by presenting my work in exhibitions and at scientific conferences. To date, my work has been peer-reviewed and discussed within a broader research community and presented in exhibition spaces to the civil society. Furthermore, I transfer knowledge through teaching and within participatory interventions (e.g., to children, students, citizens, and people from the cultural, creative, and technology sector).

1.5 Thesis Structure

This dissertation is organised into seven chapters (see Figure 1.1).

Chapter 1) Introduction

The first chapter begins with the contextual background to clarify the relevance of interactive technologies that aim to raise awareness about the environment in the cultural sector by referring to the epoch of the Anthropocene from an ecological, technological, and socio-cultural perspective. Then, the chapter introduces the scope of this research by summarising the aim, questions, objectives, contributions, researcher's role, and thesis structure.

Chapter 2) Literature Review

The second chapter provides a state-of-the-art literature review on interactive technologies that aim to raise awareness about the environment. In regard to the research aim, the literature review focuses in particular on interfaces that provide an aesthetic and social encounter with the air and that have emerged at the intersection of art, design, and technology for engaging with people in the cultural sector. Based on the findings, this chapter identifies research gaps and explains how the contributions of this dissertation build on previous work.

Chapter 3) Methodology

The third chapter outlines the methodology, which includes the philosophy of pragmatism and a case study research design. Furthermore, it details the research methods, such as qualitative and quantitative approaches, and summarises ethical considerations.

Chapter 4) Conceptual Framework

The fourth chapter provides a conceptual framework for creating interactive technologies that aim to enable an aesthetic and social encounter with the environment. Therefore, this study explores the design and interaction space based on meteorological principles, related HCI studies, and practice-based research to formulate the conceptual framework of atmospheric interfaces. This framework consists of (a) inputs and outputs, (b) interface metaphors, and (c) types of interaction.

Chapter 5) IVORY – The Initial Sentinel Species Interface

Informed by the conceptual framework, the fifth chapter involves the design and implementation process of an expressive interface that metaphorically represents the state of the air. For this purpose, the study provides background information about sentinel species – more specifically, the miner's canary – and urban air pollution. Then, the study describes the design and implementation process of the initial interface, provides field notes from exhibition spaces, and discusses the findings.

Chapter 6) ONXY – The Body-Worn, Sentinel Species Interface

By drawing on the findings of the previous Chapters 4–5, the sixth chapter involves the design, implementation, and evaluation of the second interface generation. For this purpose, the study details the implementation process of an interface that can be worn on the human body. Then, the study evaluates the interface within a user experience research by applying qualitative and quantitative research methods, before it discusses the findings.

Chapter 7) Conclusion and Future Work

The final chapter revisits the research objectives and provides a cross-case conclusion by synchronising the findings from Chapters 4–6. In addition, it outlines opportunities for raising awareness through interactive technologies at the intersection of science and society, before the chapter recommendations for further research are presented based on the limitations.

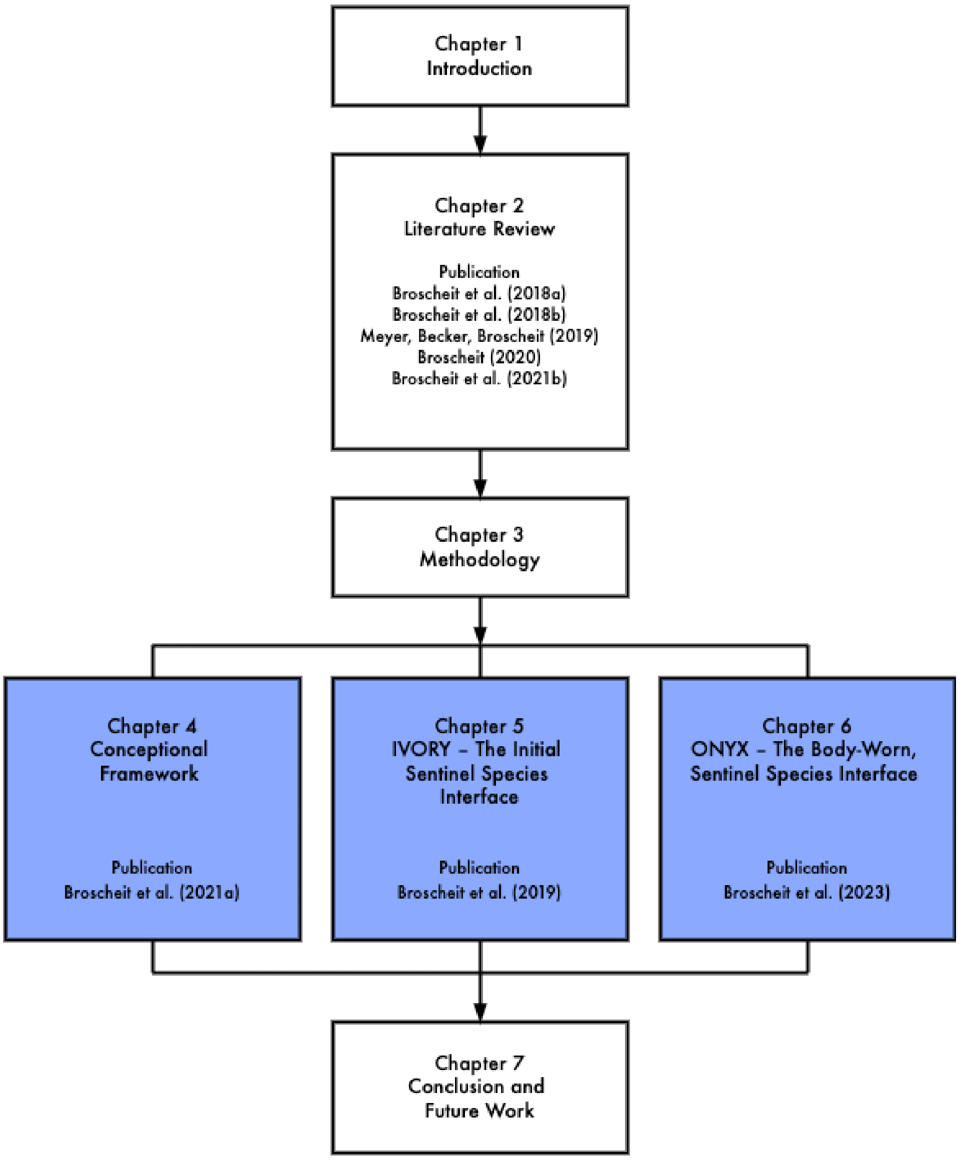


Figure 1.1 Overview of the thesis structure.

Chapter 2

Literature Review

This chapter presents a state-of-the-art literature review on interactive technologies that aim to raise awareness about the atmospheric environment to engage with people in the cultural sector. The primary data sources include conference proceedings from the digital library of the Association for Computing Machinery (ACM) and the Institute of Electrical and Electronics Engineers (IEEE), as well as artworks, which have been partly valued through secondary sources. The following sections describe the findings of the literature review (2.1), the data analysis, and open research issues (2.2), and conclude with a summary (2.3).

2.1 An Introduction to Environmental Awareness Technologies

In recent years, HCI research has introduced a wide range of technologies that aim to raise awareness about the quality of the environment. This study provides a brief introduction to the origins of sustainable interaction technologies. According to Hansson et al. (2021) and Bremer et al. (2022), the starting point for sustainable interaction were two landmark papers presented at the Conference on Human Factors in Computing Systems (CHI) in 2007. In these theoretical papers, Blevis (2007) and Mankoff et al. (2007) argued that interaction must address certain aspects of sustainability and must become a central role in HCI research. Following these arguments, DiSalvo et al. (2010, p. 1977) proposed the broader term sustainable HCI (SHCI) that was illustrated by a landscape of various technological approaches, including “ambient awareness”. While SHCI has become a rapidly growing research area, several researchers have called for a change in perspective – away from the traditional, technologically-oriented way of thinking. Dourish (2010), for example, stated that the cultural and political contexts of environmental practice must also be considered as part of technological solutions. In addition, DiSalvo et al. (2009) and Shi-zhu (2008) argued for the use of environmental art to address people’s consciousness about the environment and to identify new perspectives for HCI research. More recently, Bremer et al. (2022) examined the achievements of SCHI and noted that a vast number of speculative designs raise awareness about the current situation and future developments, which leads to more inclusive and practical outcomes than imposed prescriptions for sustainable behaviour change. Although this present study is particularly interested in interactive technologies developed at the intersection of art, design, and technology, the following sections present a wide range of augmentations designed to raise awareness about the environment.

2.1.1 Environmental Sensing

Early visions in the field of computer science foresaw technologies that would support people in their daily lives. Engelbart (1962), for example, introduced the conceptual framework of "augmenting human intellect" to improve people's ability to solve complex problems, such as by using artifacts, language, methodology, or training that could be organised into networks. Thereafter, Mark Weiser and his team at Xerox Palo Alto Research Center further developed the vision of computer-controlled artifacts in networks. They coined the terms *ubiquitous computing* and *calm technologies* to envision a world of seamlessly integrated and connected computer systems that, on the one hand, perform a specific task and, on the other hand, also consider the relationships between people and technology (Weiser, 1991, 1993; Weiser and Brown, 1997). By drawing on Engelbart's and Weiser's visions, Schmidt (2017) explained that people can now be amplified beyond their abilities through the use of technologies, and he identified two key aspects for amplifying human perception:

> - Enhancing and amplifying existing senses (such as vision, hearing, and touch), and
> - extending perceptual abilities to domains where humans have no perception but technical sensors exist (such as sensors indicating magnetic north or solar radiation). (Schmidt, 2017, p. 8)

Regarding the second aspect, recent studies use various environmental sensing technologies to monitor the Earth's system by collecting, analysing, and predicting sensor readings to understand the complex and permanently changing ecological processes. To this end, a large number of environmental sensors and networks are being developed and installed in urban cities to monitor the air pollution development, such as particulate matter (e.g., Fekih et al., 2021; Kirešová et al., 2022; Singh Katiyar et al., 2022). Likewise, these environmental sensor networks are also being used to detect the air quality indoors, such as in schools, offices, and laboratories (e.g., Al-Okby et al., 2022; Cho and Baek, 2022; Esfahani et al., 2020; Raj and Vijila, 2020). On the basis of sensor measurements, machine learning algorithms are utilised to predict air quality trends and thereby support personal and local healthcare in air-polluted cities (e.g., Cheng et al., 2021; Last et al., 2021; Li et al., 2021; Zhang and Woo, 2019). Zhong et al. (2021), for example, developed a sensor node to measure various environmental information in offices (e.g., temperature, humidity, carbon dioxide [CO_2], particulate matter [PM]). The study then focused on CO_2 concentrations to encourage participants to take preventive actions when the air quality was poor. In addition, Rajalakshmi et al. (2022) presented a sensor node to protect workers in unhealthy environments. Rahman and Elsheikh (2022) embedded environmental sensors into a respiratory mask to support COVID-19 patients to breathe in sufficient oxygen, and Zhao et al. (2021) introduced a sensor node to interpret air quality as soundscape sonification based on data from the near surroundings.

Moreover, environmental sensor technologies are also being used to empower people to measure air quality as part of citizen science projects, participatory research, and activism. Kuznetsov et al. (2011; 2014; 2010), for example, introduced various sensor kits to detect the air quality in public spaces and used them as an instrument of change. Similarly, Diez and Posada (2013) fabricated a sensor kit for citizen science and sustainable city development. Furthermore, Hviid Trier and Jenkins (2020) engaged with citizens of Copenhagen through the use of an air quality sensing bracelet. Fjukstad et al. (2018) developed a sensor kit to motivate students to explore environmental and technological topics in the framework of an education project. Dey et al. (2021) presented a low-cost do-it-yourself CO_2 meter for measuring the air quality in classrooms. In addition, artist and researcher Beatriz da Costa (2006) equipped pigeons with backpacks containing technical sensors to measure the air quality of southern California. While the birds flew through the air, the current readings were published to the internet to inform the general public (Haraway, 2016).

In contrast to technical sensor measurements, Hsu et al. (2019) introduced a citizen science project that utilised humans as sensors. Participants documented the smell of the air to identify pollution patterns. The reported data was then made accessible via the internet to inform the community about the local air quality. Lastly, Liu et al. (2020) developed a strategy to bridge the gap between objective air quality measurements and subjective perception. To this end, they held a participatory workshop to capture people's lived experience, which they used to create cognitive air quality maps.

2.1.2 Augmentations through Screen-based Devices

Aside from various environmental sensing strategies, previous studies have investigated people's needs in terms of receiving and understanding air quality information (Gupta and Eden, 2022; Kim and Li, 2020; Lu and Zheng, 2013). This section outlines different screen-based augmentations that can be used to visualise air quality data, such as graphical user interfaces and augmented and virtual reality.

2.1.2.1 Graphical User Interface

A graphical user interface (GUI) is a visual operating system that allows users to interact with a computer via a screen, such as monitors and touchscreens (Jansen, 1998; Sharp et al., 2019). In a long-term study, Kim and Paulos (2010) and Kim et al. (2013) presented a GUI application that measures and visualises indoor air quality data of households. The results revealed an increased awareness of the air quality, behavioural changes towards environmental sustainability, and social bonding within the community. Smid et al. (2011) introduced an application, entitled *Canary in a Coal Mine*, that visualises air quality datasets on a map based on public tweets from citizens. The information visualisation aims to support citizens to track of their local air quality.

In addition, several studies have presented mobile GUI solutions to monitor the air quality in the near surroundings. Tian et al. (2016), for example, developed a wrist-worn sensor device that visualises airborne particles on a smartphone application for monitoring the outdoor air quality. The application displays both a graphical interpretation of particulate matter and numerical values for comparing various measurements detected by the sensor. Similarly, Maag et al. (2018) introduced a wearable wristband that measures ambient O_3 and CO_2 concentration for personal healthcare. Furthermore, Zhong et al. (2020) presented an application for a smart watch that visualises CO_2 concentrations indoors. The system consists of a sensor node that measures the environment and an app that informs the user to take preventive actions, such as opening the window when the air quality is poor. Yun and Gross (2010) introduced a wall-mounted GUI designed to convey ambient conditions in a home automation system. In addition to numeric information, the application also displays a human face that expresses the conditions through various facial expressions. Depending on the room temperature, the image changes from a person fanning themself when it is too hot to shivering when it is too cold.

Moreover, some studies introduced screen-based approaches for environmental awareness at the intersection of art, design, and technology. González and Salvador (2019), for example, introduced the screen installation *trasTocar* for raising awareness about polluted wetlands in central Mexico. The screen installation was exhibited in a museum to encourage a transdisciplinary discourse. Lastly, artist Andrea Polli (2013), known for her sonification of meteorological data (Polli, 2004), also presented a graphical media installation, entitled *Particle Falls*, in public spaces. The media installation is a real-time visualisation of particulate matter data (PM-2.5) projected on buildings in public spaces.

2.1.2.2 Augmented and Virtual Reality

An augmented reality (AR) is an advanced development of GUIs that merges the real world with the virtual environment through the use of mobile devices such as smartphones, tablets, and special headsets (Sharp et al., 2019). To combine the

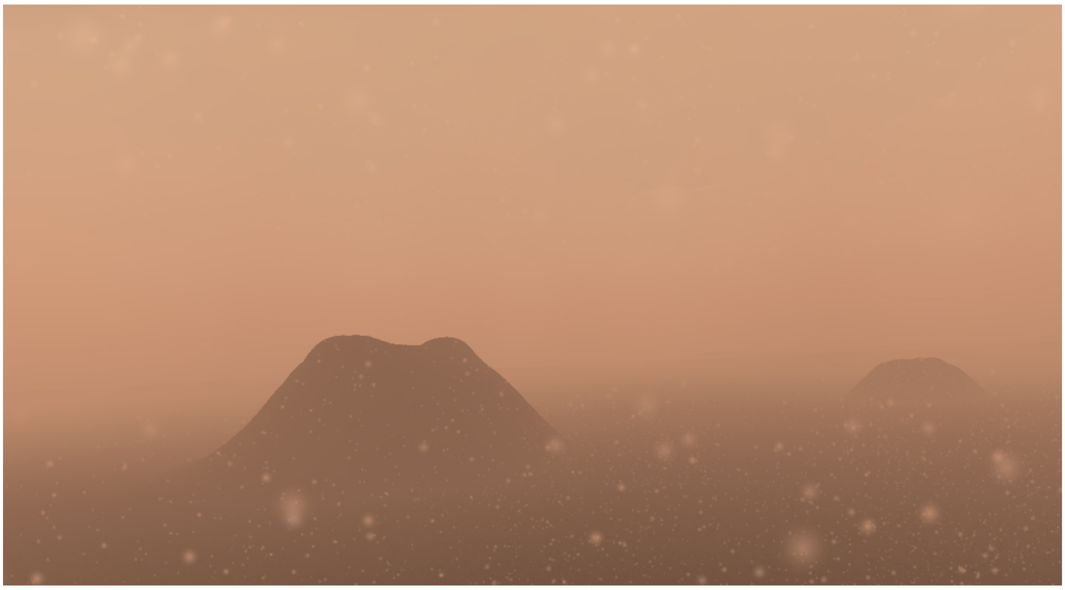


Figure 2.1 An interactive VR environment of real-time particulate matter sensor data developed as part of a collaboration between Meyer, Becker, and the author (2019). Image: Uli Meyer.

real world with air quality information, Torres and Campbell (2019), for example, introduced an interactive experience that enhances images of the real world with both graphical animations and information about various air pollutants. In addition, Perry-James Sugden and Daria Jelonek from Studio Above&Below (2020) presented the installation *Digital Atmosphere* to experience the air quality in an augmented reality at the intersection of art, science, and technology. With a headset, users could observe changes in air quality through a graphical simulation created on the basis of sensor measurements.

Furthermore, air pollution can also be simulated in a virtual reality (VR). A virtual reality is a fully computer-generated graphical environment that users can experience through the use of a head-mounted display (Earnshaw et al., 1993; Sharp et al., 2019). A recent study by Meyer et al. (2019), for example, introduced an interactive VR environment visualising particulate matter concentrations according to real-time sensor measurements. The air pollution data was translated into visual characteristics, such as size and density, and animated by the engine physics in terms of collision, gravity, and wind. This VR environment can be used as a magnifying glass to provide users with an immersive experience, where they see and explore proportionally enlarged particles from the nearby surroundings (see Figure 2.1).

2.2 Tangible and Embodied Interactions

In contrast to the screen-based augmentations mentioned above (e.g., GUI, AR, and VR), the umbrella term *tangible and embodied interaction* (TEI) aims to augment the real world by taking into account technological, artistic, and design practices that consider the materiality and physicality of objects, the embodiment of data, bodies, and spaces (Hornecker, 2005, 2011; Hornecker and Buur, 2006; Ishii et al., 2012; Ishii and Ullmer, 1997; Shaer and Hornecker, 2009). This section presents a brief introduction to the origins of TEI, followed by related studies that aim to provide an aesthetic encounter with the environment through the use of augmentations in the real world (2.2.1), augmentations for the human body (2.2.2), and creative environmental education (2.2.3).

2.2.1 Augmentations in the Real World

Following Weiser's vision of ubiquitous computing (1991), Ishii and Ullmer (1997, p. 235) introduced their concept of a *tangible user interface* (TUI) as an approach to "augment the real physical world by coupling digital information to everyday physical objects and environments." Rather than interacting with screen-based devices, such as computer screens, mobile phones, and headsets, TUIs allow users to literally grasp and manipulate digital information. To complement TUIs, Ishii et al. (2012) also introduced the term *radical atoms* to establish an interaction with materials. In contrast to TUIs that integrate actuators (e.g., servo motors or electromagnets), radical atoms provide an interaction with transformable materials on a molecular level (e.g., electroactive polymers and thermochromic materials). While studies on tangible user interfaces and radical atoms have focused on the interface itself, Hornecker and Buur (2006) proposed the related term *tangible interaction* with the purpose of broadening the research area for an interdisciplinary community. Today, TEI is an established research field with its own ACM conference that investigates at the intersection of art, design, and technology (Hornecker, 2011). Since the concept of tangibles originally focused on augmentations that aimed to provide a seamless interaction for people in their natural habitat (Ishii and Ullmer, 1997), related interactive technologies that are intended to raise awareness about the environment in the real world are presented below.

Ishii (2004), for example, introduced the *Weather Forecast Bottle* to convey weather information though tangible interaction. When users open the lid of the bottle, they hear audio recordings that correspond to weather forecast data (e.g., singing birds forecasting a clear day). The aim of the bottle is to provide an intuitive and everyday interaction that could be integrated into a household. Similarly, Wu (2010) developed the *Weather Lamp* comprising three tangible visualisation modules that represent weather information from the internet through the use of colour, shape, and size. The interface also accepts tangible inputs from users and was designed for home environments. Airaud et al. (2016) introduced the art installation *Weather Traveler*. The installation consists of a three-dimensional and handcrafted surface, augmented through video projections and sound. The aim of the installation is to create an immersive user experience with freely interpreted weather phenomena. In addition, Hsu (2005) introduced the *Tangible Weather Channel* with the intention of evoking emotional attachments. The sculptural interface encodes real-time weather data represented through the use of natural elements such as water, air, and sound. Users can choose a specific city on a touch screen and have a multisensory experience with the weather.

According to Chang et al. (2022), various studies have used plants to raise awareness about the environment, thereby providing a relationship with nature. Seow et al. (2022), for example, introduced *Mimosa Pudica* as a natural plant interface with the aim of creating an emotional bond with plants to address global climate change. When a user touches the plant, the leaves open and close according to online air quality data. In contrast to this natural plant interface, Hsu et al. (2018) developed the *Botanical Printer* for reflecting on both the natural and technological climate. Their plant-inspired interface measures both CO_2 concentration and Wi-Fi signal strength and then communicates the information via an integrated thermal printer. In addition, Sabinson et al. (2021) developed the therapeutic *Plant-Human Embodied Biofeedback* interface that aims to foster the user's relationship with nature and hence support the well-being of people in homes.

Other interactive technologies aim to control the environmental condition in buildings. Khan (2010), for example, implemented a deployable architecture, entitled *Open Columns*, constructed from urethane elastomers that responds to CO_2 sensor values. When the CO_2 concentration rises, the columns move downwards to reduce the space for people. The space reduction has consequently contributed to the improvement of the indoor climate. Similarly, Coelho and Maes (2009) presented shape-changing shutters for indoor architecture. Shutters are kinetic textiles built with shape-memory mechanisms to control the airflow and daylight in buildings in terms of environmental conditions. Furthermore, Stamhuis et al. (2021) implemented the *Office Agents* with the aim of debating about healthier working conditions with office employees. The interface consists of a set of objects that were placed onto a desk to measure the employees' environment, productivity, and physical activity. The object that measures the air quality provides an user with feedback through the use of haptic air flow. Unlike these interactive interiors that respond to the indoor climate, Stegers et al. (2022) introduced *Ecorbis* a physical data representation of the personal environmental behaviour in homes. The data-driven, shape-changing interior translates everyday activities (e.g., the use of transport, electricity, and water) into climate impacts.

Some interactive technologies have been designed to become a discursive object in exhibition spaces. Artist John Grade (2013), for example, exhibited the shape-changing installation *Capacitor* that opens and closes according to environ-

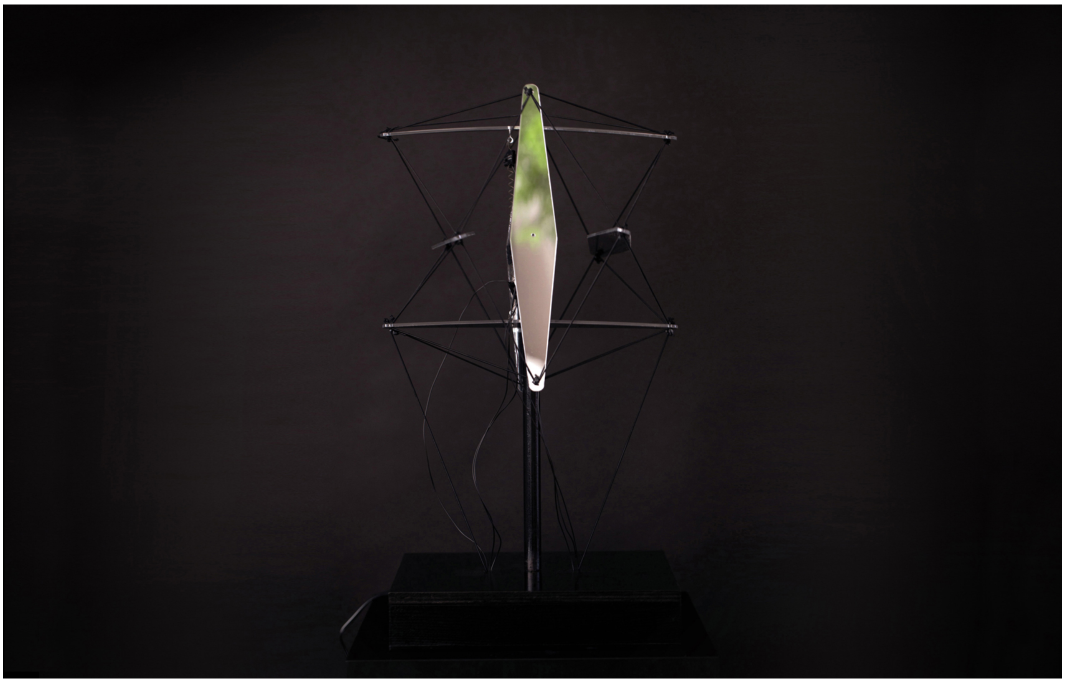


Figure 2.2 *Reflections on Air*, a shape-changing, mirrored interface that is enriched by sound to provide a multisensory experience that responds to CO_2 concentrations (Broscheit et al., 2021b).

mental data. The shape was inspired by a single-celled organism that supports the cooling of the earth by extracting CO_2 from the environment. In addition, Broscheit et al. (2021b) introduced the interactive, mirrored sculpture, entitled *Reflection on Air*, to foster discussion around increasing CO_2 concentrations caused by human activities (see Figure 2.2). To this end, the interface uses an SMA spring for the kinetic behaviour and FM synthesis to sonify the incoming data. When a user exhales on the mirror, the interface responds to the increased CO_2 concentrations with movement and sound. Furthermore, Baraga (2016) exhibited the *Cyanometer* monument to the public. The monument was inspired by the work of meteorologist Horace-Bénédict de Saussure, who invented the cyanometer to determine the state of the air according to the blueness of the sky. Likewise, the digital cyanometer analyses images of the sky and displays the air quality on the monument to inform citizens. Moreover, Kaufmann et al. (2021) presented the environmental art installation *Ripple Effect* that visualises water quality data as vibration and sound. The installation consists of various water-sound stations to represent different levels of pollution as individual patterns and waves.

In contrast to augmentations that represent the state of the environment, some studies have allowed for a direct interaction with natural phenomena (e.g., rain and fog). Random International (2012), for example, developed the *Rain Room* as an immersive environment that has been exhibited in various museums (e.g., MoMA). The installation offers visitors the experience of controlling the rain. When people enter the rainy installation, their presence stops the rain from falling. Although visitors can perceive the sound and smell of the rain, they do not get wet. Furthermore, the Japanese artist Fujiko Nakaya was part of the collective *Experiments in Art and Technology* (E.A.T.) in the 1960s (Randerson, 2018). In one of his recent exhibitions, at the Haus der Kunst in Munich, Nakaya (2022) presented an immersive fog sculpture to address the entanglement of human beings and nature. Visitors could explore the nebulous landscape sculptures made of evaporated water. Lastly, Sylvester et al. (2010) and Döring et al. (2013*a*,*b*) introduced their research on *Ephemeral User Interfaces* that include interactions with physical matter. These interfaces enable aesthetic experiences with natural environmental phenomena that do not last, such as water drops, ice, bubbles, and fog.

2.2.2 Augmentations for the Human Body

At the beginning of TUI research, Ishii and Ullmer (1997) distinguished between two directions for augmentations in ubiquitous computing environments. The authors stated,

> We see the locus of computation is now shifting from the desktop in two major directions: (i) onto our skins/bodies and (ii) into the physical environments we inhabit. The transition to our bodies is represented by recent activities in the new field of wearable computers.
>
> (Ishii and Ullmer, 1997, p. 235)

Following the second direction, in 1996 another group of researchers from the Massachusetts Institute of Technology (MIT) introduced *wearable computers* through early studies; these researchers were particularly interested in improving human capabilities through technology on th human body (Mann, 1996, 1997; Rhodes, 1997; Starner et al., 1997). According to Rhodes (1997, p. 218), a wearable computer can be defined by the following characteristics: (a) it is "portable while operational"; (b) it enables "hands-free use"; (c) it has "sensors", (d) it is "proactive", and (e) it is"always running". Unfortunately, the first experiments with wearable computers appeared as cyborg-like technologies and were rejected by society. Mann (1996, p. 23) reported that "people were shocked by the visceral combination of human and machine." However, with the miniaturisation of technologies and studies on interactive and aesthetic materials, body-worn augmentations have been progressing in the field of TEI. Thus, related studies on environmental awareness for the human body are outlined below.

Kim et al. (2010), for example, developed the illuminating t-shirt *WearAir* that measures the air quality of the user's surroundings. The t-shirt contains a sensor that measures volatile organic compounds (VOCs) and interprets different air quality levels by illuminating patterns on the shirt. Similarly, Hanne-Louise Johannesen and Michel Guglielmi, the founders of Diffus (2009), presented the interactive *Climate Dress*, which was cited by Kao et al. (2017). The dress consists of conductive embroidery and LEDs to visualise different CO_2 concentrations. Furthermore, artist Kasia Molga (2016) presented the artwork *The Human Sensor*, for which Molga and her team developed wearable costumes to explore urban air pollution through a public dance performance in the streets of London. The costumes are illuminated in different colours in response to real-time air pollution levels (Leopoldseder et al., 2018). Likewise, Broscheit (2020) introduced the speculative design *Air Mask* to monitor the environment and inform other citizens about the state of the air. The aim of the mask is to detect the near surroundings to communicate the air quality as a three-colour warning system through the use of an

Figure 2.3 The *Air Mask*, a speculative design to monitor urban air pollution and to inform other citizens about the state of the air (Broscheit, 2020). The author developed the mask as part of a collaborative project at the Hamburg University of Applied Sciences in 2015.

illuminated filter cap on the mask (see Figure 2.3).

Unlike illuminated fabrics as mentioned above, thermochromic pigments offer a colour change on a molecular level. In this regard, Kao et al. (2017) introduced a cosmetic eye shadows that senses atmospheric hazards. The powder consists of thermochromic pigments that change colour when elevated levels of carbon monoxide (CO), ultraviolet (UV) rays, and ozone (O_3) are present. The chemical body powder functions as a sensor and an actuator on a molecular level without utilising electronic components. The artist Bentel (2016), as cited by Kao et al. (2017), also used reactive colours for sweaters, which changes their pattern according to the condition of the atmosphere: when the air quality is poor, the graphical pattern of the clothing appears. In addition, Mariakakis et al. (2020) presented the study *EcoPatches* with the aim of addressing the relationship between human beings and their environment. The chemical sensor patches interpret UV exposures as a colour-changing image. Moreover, Adhitya et al. (2016) created the garment *BIOdress* that reflects the air quality via thermochromic colours to motivate people towards sustainable development. The thermochromic fabric of the dress changes its color according to particulate levels. When the air quality is healthy, the dress appears in green and brown, otherwise the dress displays a magenta pattern.

Unlike these colour-changing materials, other interactive technologies utilise dynamic behaviour. Fabrizi (2014), for example, presented the textile flower *Fiori in Aria* for communicating the air quality in a home automation environment. The shape-changing interface opens and closes its flower petals to indicate healthy or poor air quality and can be worn on the human body. To this end, the interface utilises an indoor air quality sensor that monitors the climate and shape-memory alloy for the dynamic movement. In addition, Yu (2020) developed the facial mask *AirMorphologies* to improve social interaction in polluted air environments. The design of the mask consists of pneumatic modules inspired by the skin of a pufferfish. Schulte et al. (2018) developed a wearable mask that opens and closes autonomously according to air pollution levels. Through the use of a "wizard of oz" approach, spectators select an air pollution value from a graphical user interface to observe the functionality of the mask on a mannequin. Finally, Roinesalo et al. (2016) developed the *Solar Shirt* to detect noise pollution in urban areas. The garment consists of integrated sensors and an electrochromic pattern that changes its shape according to the detected noise levels in the near surroundings.

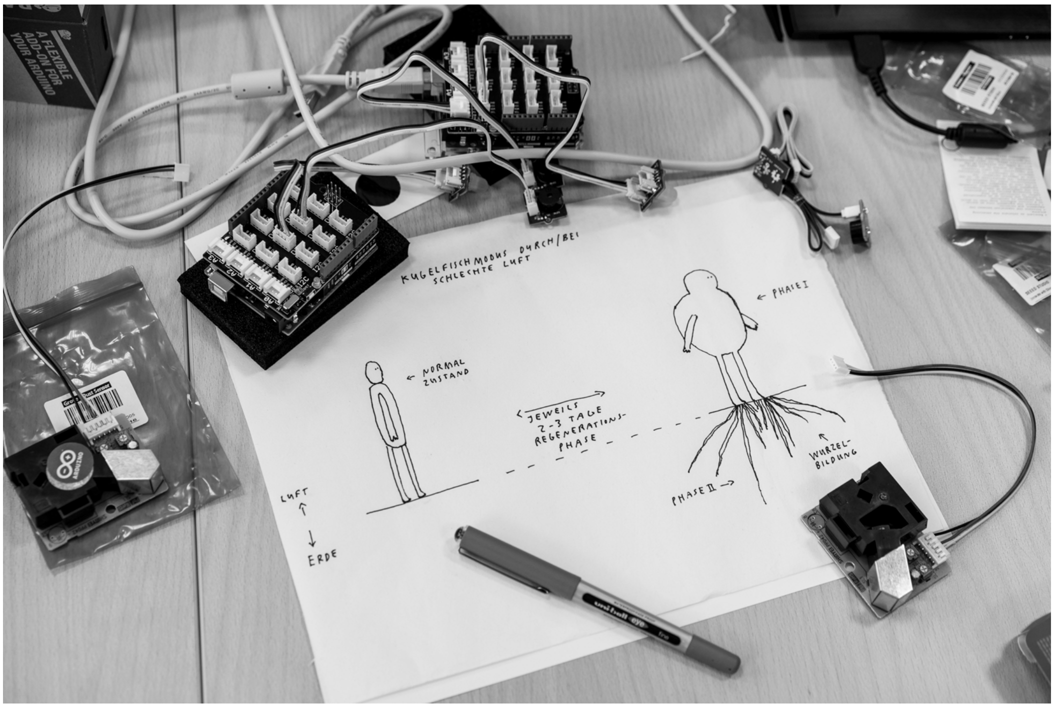
As a speculative design, Biggs and Desjardins (2020) introduced *High Water Pants*, a wearable to thematise rising sea-levels caused by climate change. For this, the researchers employed shape-changing pants, whose length shorten according to future sea levels. In addition, Wilkens (2010) proposed a *Weather Camera* to capture personal memories with the environment. Wilkens envisioned that the camera would capture light, temperature, humidity, wind, and air quality information at a specific time and location to create a personal and emotional memory of data. Moreover, Flanagan and Frankjaer (2018) created wearable interfaces, entitled *Cyborganic*, to explore the post-human condition in rewilded environments. The interactive headpieces were used as a tool to promote an empathetic experience with non-human beings, especially insects, and to convey a holistic and biodiverse ecology.

In contrast to the visual sensations of colour changes and dynamic movement, *The Intimate Earthquake Archive* by Sissel Marie Tonn and Jonathan Reus provides a tactical sensation. Reus and Tonn (2020) created a multimodal experience of man-made earthquakes from digital data provided by the Royal Dutch Meteorological Institute. To create a bodily experience, the duo created a vest that translates the environmental data into a vibro-tactile output. In addition, they presented the project *Sensory Cartography* that explores the relationships between body, cognition, and environment. For this, the duo developed a wearable that refers to the origins of colonial botany and collects data to amplify human senses. Moreover, Pakanen et al. (2021) introduced a small, tangible, leather self-tracking device for pollen allergies. The device is connected to an application on the user's mobile phone and can track their allergy symptoms and medicine intakes. Users interact with the interface through haptic inputs and outputs. The device can be used as a keyring or a necklace, or it can be worn on a belt or carried in one's bag for daily use.

2.2.3 Creative Environmental Education

Tangible and embodied interaction has also become a recognised area for supporting playful and creative learning through the use of prototyping methods (Hornecker and Buur, 2006; Shaer and Hornecker, 2009; Sharp et al., 2019). This section outlines various participatory projects that address environmental awareness through creative eduction. Guler (2013), for example, conducted a participatory sensing project with citizens to measure the air quality in Beijing through sensor-equipped kites. Participants learned the basics about electronics and mounted the air quality sensing kit onto a handmade kite. Similarly, the *Aerocene* backpack is a floating, sensing kit that allows people to measure environmental data, such as temperature, humidity, and pressure. The Aerocene, a collaborative, initiated by

(a)

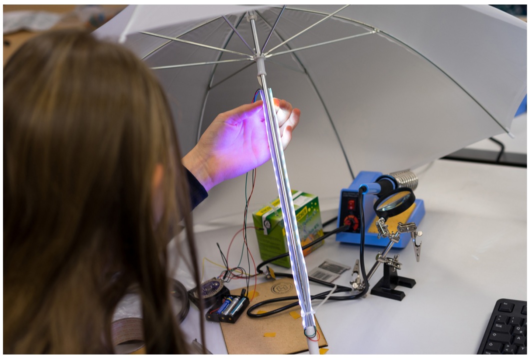


(b)

Figure 2.4 Impressions from the workshop *How will we breathe tomorrow?* conducted by Broscheit et al. (2018a): (a) the programming of the prototyping kit and (b) the creative design process. Photos: André Jeworutzki.

Saraceno (2016), has developed various projects to promote environmental awareness (Fowkes and Fowkes, 2022). Furthermore, Kuznetsov, Davis, Paulos, Gross and Cheung (2011) conducted a workshop with illuminating sensing balloons that change their colour according to different air quality levels. The aim of the illuminating balloons was to spark an environmental debate in the public space. In addition, Kuznetsov et al. (2014) introduced a low-cost paper sensing system for citizens to collect particulate matter samples in the neighbourhood. After participants have collected the samples in the field, the data was visualised via high-precision microscopes to present the results to a broader audience. Within the framework of an urban artist, research, and mediation project, Broscheit et al. (2018a) explored the question, "How will we breathe tomorrow?". The intention of this participatory workshop was to augment the human senses through sensor technologies and to make particulate matter levels perceptible. The participants learned how to program a sensor node and created species-inspired prototypes, which were then exhibited to the public (see Figure 2.4). Moreover, Broscheit et al. (2018b) developed a prototyping kit for an environmental sensing umbrella (see Figure 2.5). The main goal of this workshop was to inspire young women to enter a STEM profession and to address environmental topics through the practice-oriented experience. In addition, Solomon et al. (2018) presented the participatory project *VisualLife* to visualise air pollution in the form of a t-shirt. To this end, participants collected sensor measurements and tracked their location throughout the day. They then expressed the sensor logging values with black pigments, made from carbon emissions, on a white shirt to raise awareness of air pollutants. De Greve et al. (2022) developed the *Air Quality Lens*, which translates real-time air quality data into colour and intensity. The lens can be placed in front of a camera to take photos that are shaped by environmental data from the near surroundings with the aim of encouraging young participants to engage in climate storytelling. Furthermore, Beça and Aresta (2022) conducted a co-design workshop with young students to create a digital game for promoting environmental awareness through gamifica-

(a)



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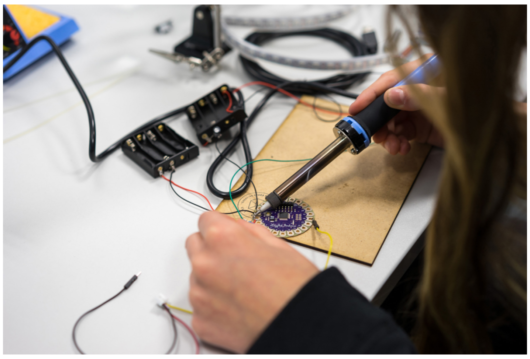


(c)

Figure 2.5 Broscheit et al. (2018b) prototyping kit for experiencing environmental data in the form of an illuminating umbrella. (a) The coding process, (b) the assembly of the umbrella with the prototyping kit, and (c) the soldering of the electronic components. Photos: André Jeworutzki.

tion strategies. A *Gamers4Nature* toolkit was developed that consists of thematic cards to support the students in creating game narratives. Lastly, Mann (2012) exhibited *Hydraulikos* as an immersive educational installation to the public. People were allowed to interact with different water-based instruments to explore the relationship between technology and nature in a live art experience.

2.3 Discussion

This section discusses the findings of the literature review and outlines the process of the data collection to determine open research issues.

2.3.1 Identifying Open Research Gaps

The aim of the literature review was to investigate interactive technologies raising awareness about the environment by offering people in the cultural sector an aesthetic and social encounter with the air. To this end, conference proceedings from the ACM and IEEE digital libraries, as well as artworks, which have been partly valued through secondary sources, served as primary sources for the data collection (see Figure 2.6). The review process began with a keyword search that was carried out from 2019 to 2022. Then, the latest search results were manually checked in terms of their relevance to this research. In addition, the data was filtered according to the most relevant HCI conferences that are situated in the realm of the ACM Special Interest Group on Computer–Human Interaction (SIGCHI), such as (a) the flagship Conference on Human Factors in Computing Systems (CHI); (b) the Conference on Tangible, Embedded, and Embodied Interaction (TEI); and (c) the Conference on Designing Interactive Systems (DIS). Once the filters were applied, the studies were manually selected based on title and abstract. Then, a reference search was conducted, and recommendations were considered. The database (n = 85) included different technologies for environmental awareness, such as sensor node, GUI, AR/VR, and TEI (see Table 2.1).

However, to address the main goal of this study and to offer people in the cultural sector an aesthetic and social encounter with the air, the database on technologies for environmental awareness was analysed in terms of the main motivational criteria. Studies on graphical user interfaces, virtual and augmented realities, weather interfaces, living organisms, chemical sensing, participatory designs, and conceptual designs without a functional prototype were excluded from the

Table 2.1 Overview of the included technology database.

Technology	Count	Database
Sensor Nodes	$n = 26$	Al-Okby et al. (2022); Cheng et al. (2021); Cho and Baek (2022); da Costa (2006); Dey et al. (2021); Diez and Posada (2013); Esfahani et al. (2020); Fekih et al. (2021); Fjukstad et al. (2018); Hsu et al. (2019); Hviid Trier and Jenkins (2020); Kim and Li (2020); Kirešová et al. (2022); Kuznetsov, Davis, Cheung and Paulos (2011); Kuznetsov and Paulos (2010); Last et al. (2021); Li et al. (2021); Liu et al. (2020); Rahman and Elsheikh (2022); Raj and Vijila (2020); Rajalakshmi et al. (2022); Singh Katiyar et al. (2022); Zaidan et al. (2022); Zhang and Woo (2019); Zhao et al. (2021); Zhong et al. (2021).
GUI	$n = 9$	González and Salvador (2019); Kim and Paulos (2010); Kim et al. (2013); Maag et al. (2018); Polli (2013); Smid et al. (2011); Tian et al. (2016); Yun and Gross (2010); Zhong et al. (2020).
AR/VR	$n = 3$	Meyer et al. (2019); Studio Above & Below (2020); Torres and Campbell (2019).
TEI	$n = 47$	Adhitya et al. (2016); Airaud et al. (2016); Baraga (2016); Beça and Aresta (2022); Bentel (2016); Biggs and Desjardins (2020); Broscheit (2020); Broscheit et al. (2018b,a, 2021b); Chang et al. (2022); Coelho and Maes (2009); De Greve et al. (2022); Diffus (2009); Döring et al. (2013*a*); Fabrizi (2014); Flanagan and Frankjaer (2018); Grade (2013); Guler (2013); Hsu (2005); Hsu et al. (2018); Ishii (2004); Kao et al. (2017); Kaufmann et al. (2021); Khan (2010); Kim et al. (2010); Kuznetsov, Davis, Paulos, Gross and Cheung (2011); Kuznetsov et al. (2014); Liu et al. (2018); Mann (2012); Mariakakis et al. (2020); Molga (2016); Nakaya (2022); Pakanen et al. (2021); Random International (2012); Reus and Tonn (2020); Roinesalo et al. (2016); Sabinson et al. (2021); Saraceno (2016); Schulte et al. (2018); Solomon et al. (2018); Stamhuis et al. (2021); Stegers et al. (2022); Sylvester et al. (2010); Wilkens (2010); Wu (2010); Yu (2020).

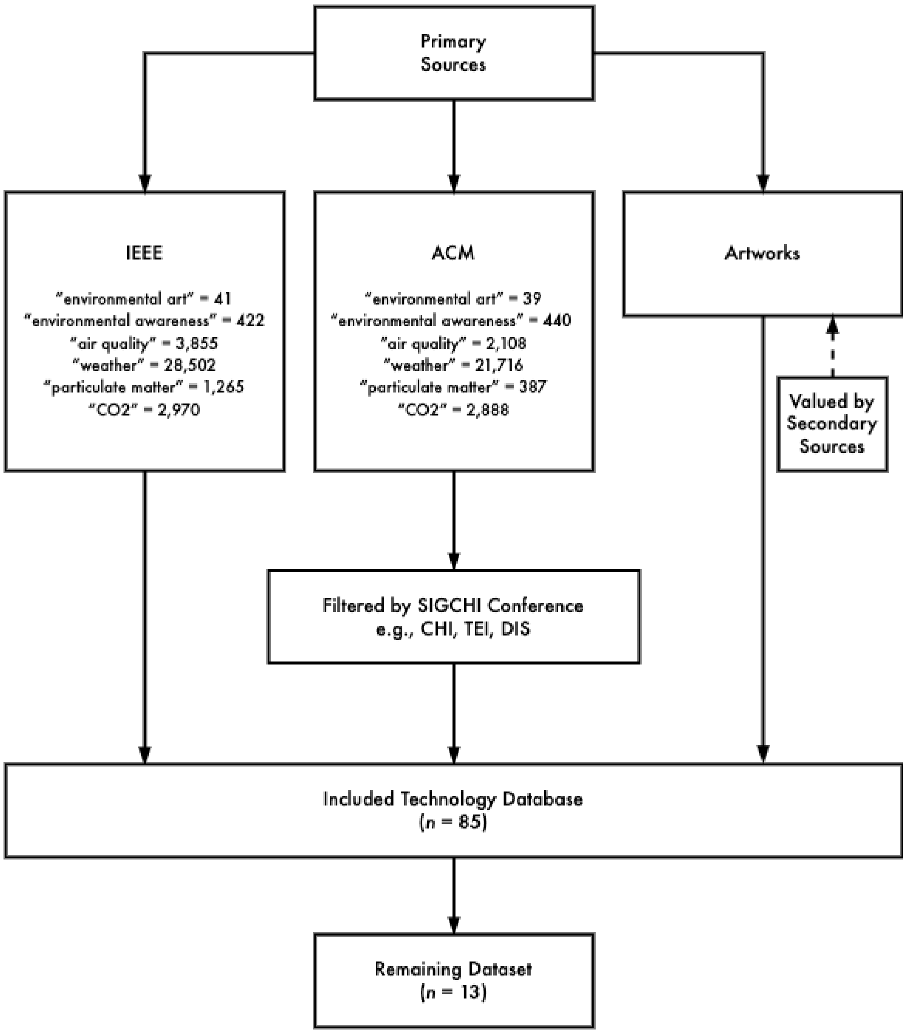


Figure 2.6 Flow diagram of the literature review.

database. The remainder of the database includes studies (n = 13) expressing the air quality as physical data representations. To make the remaining database comparable, the data was classified according to the categories following: (a) discipline, (b) input, (c) output, (d) interface metaphor, (e) iterations, and (f) user experience research (see Table 2.2), as described below.

- **Discipline.** As the literature review includes conference proceedings and artworks as primary sources, this category distinguishes between the disciplines of HCI and the arts.

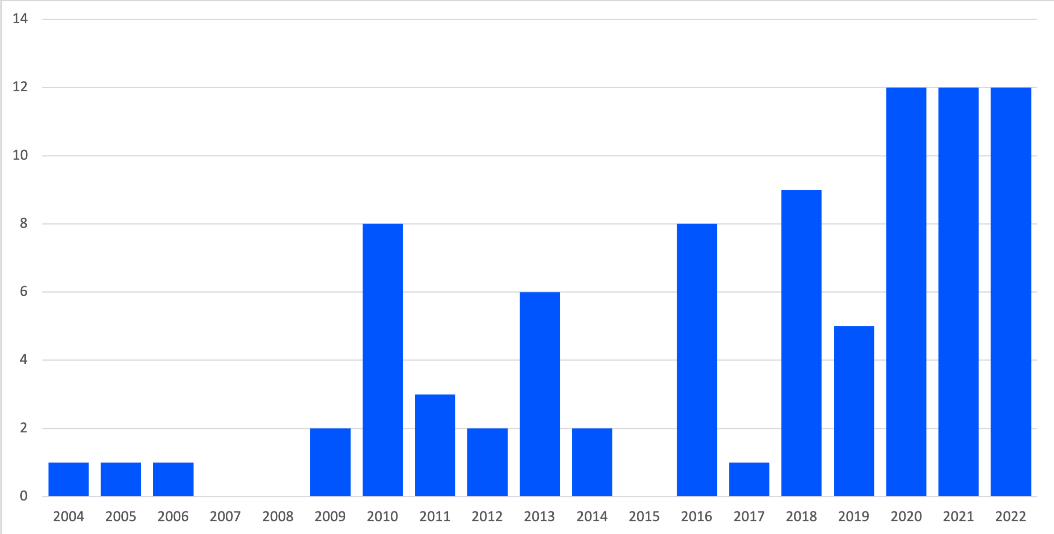


Figure 2.7 Histogram of the included technology database.

- **Input.** Technical sensors can augment human beings' perceptual abilities (Schmidt, 2017). Therefore, this category evaluates whether interfaces monitor the atmosphere with technical sensors to convey air quality information.

- **Output.** While human perception is a multisensory phenomenon (Gibson, 1966), the analysis emphasises expressive interfaces that translate air quality information into an aesthetic output that can be experienced through the sensory modalities of humans (e.g., visual, haptic, olfactory, gustatory, and auditory feedback).

- **Interface Metaphor.** Designing an intuitive interface often includes a designer's model that draws on an analogy or metaphor for communicating how to use and understand an interactive technology (Carroll et al., 1988; Sharp et al., 2019). For this reason, this category identifies whether the interface embodies an analogy or metaphor for user interaction.

- **Iterations.** In line with Bremer et al. (2022), iterative studies could better support sustainable development than non-iterative studies. This category therefore assesses the depth of a study by considering the iterations of an outcome.

- **User Experience (UX).** Empirical research, such as the analysis of user studies, is the main contributions to HCI research (Hewett et al., 1992; Wobbrock and Kientz, 2016). This category thus determines interfaces that have been evaluated through a user experience research. In addition, the number of participants is highlighted.

2.3.2 Resulting Research Gaps

Overall, the findings of the literature review indicate that interactive technologies representing air quality information as aesthetic and expressive material engaging with people in the cultural sector are limited in HCI research. Furthermore, it has been found that research gaps exist in the following areas: (a) theoretical foundations, (b) interface development, and (c) an evaluation of the user's experience during an interaction. The identified research gaps are detailed below.

Gap 1) Theoretical Foundations

Although extensive research has been conducted on interactive technologies for environmental awareness (see Table 2.1), the HCI community has shortcomings in theoretical foundations. The present study addresses this gap by exploring the design and interaction space of interactive technologies that enable an aesthetic and social encounter with the air to provide a conceptual framework that can be used as a tool for conducting systematic and transdisciplinary research.

Gap 2) Interface Development

Based on the remaining dataset (see Table 2.2), various expressive interfaces represent the air quality as unisensory output (e.g., visual, haptic, and odour). Shortcomings exist, for example, in the development of expressive interfaces that consider (a) multisensory experiences, (b) interface metaphors, (c) iterative studies, and (d) transdisciplinary discourse. More specifically, a research gap exists in the form of

Table 2.2 Remaining dataset of expressive interfaces that represent air quality information as aesthetic augmentation.

Author	**Discipline**	**Input**	**Output**	**Metaphor**	**Iteration**	**UX**
Diffus (2009)	Art	air quality	unisensory, visual	–	–	–
Kim et al. (2010)	HCI	air quality	unisensory, visual	car	–	field (n =1)
Khan (2010)	HCI	air quality	unisensory, visual	–	–	–
Fabrizi (2014)	HCI	air quality	unisensory, visual	plant	–	–
Amores et al. (2015)	HCI	air quality	unisensory, odor	–	–	–
Bentel (2016)	Art	air quality	unisensory, visual	–	–	–
Molga (2016)	Art	air quality	unisensory, visual	–	–	–
Adhitya et al. (2016)	HCI	air quality	unisensory, visual	–	–	–
Schulte et al. (2018)	HCI	air quality	unisensory, visual	–	–	–
Hsu et al. (2018)	HCI	air quality	unisensory, visual	plant	–	field (n = 2)
Pakanen et al. (2021)	HCI	air quality	unisensory, haptic	–	–	–
Stamhuis et al. (2021)	HCI	air quality	unisensory, haptic	–	–	–
Broscheit et al. (2021b)	HCI	air quality	multisensory, audio-visual	mirror	–	–
Dissertation						
Broscheit et al. (2020; 2019; 2023)	Art/HCI	air quality	multisensory, audio-visual	bird	multiple	lab (n = 14)

an expressive interface that draws on a metaphorical representation of a species to convey the air quality as a multisensory experience. The goal of this study is therefore to design and implement iterative and high-fidelity prototypes that build on the findings of the conceptual framework and can be used as a discursive object in the cultural sector as well as a research tool in HCI.

Gap 3) Understanding the User's Experience

The most significant finding was the lack of user experience research (see Table 2.2). Related studies have generally focused on the interface implementation and have not evaluated the participants' experiences while interacting with the technology. Kim et al. (2010), for example, have worn their prototype in public but reported only a few comments they received from spectators. In addition, Hsu et al. (2018) conducted a participatory workshop to design a functional prototype, but little was reported about the user's felt experience during an interaction with the final prototype. The present study hence aims to explore the experience of a sufficient number of participants interacting with an interactive technology that represents the state of the air.

2.4 Summary

This chapter provided a state-of-the-art literature review on related studies that have focused on interactive technologies raising awareness about the environment. Specifically, interfaces that represent air quality data as expressive and interactive material have been of particular interest to convey anthropogenic concerns to people in the cultural sector. Overall, the literature review presented a wide range of technologies (e.g., sensors, graphical user interfaces, augmented and virtual realities, and tangible and embodied interactions) that can be used for raising awareness about the environment. However, analysis of the data revealed shortcomings in (a) theoretical foundations, (b) interface development, and (c) understanding of the user's experience. To the best of the author's knowledge, no previous work has addressed the above gaps in HCI research. On this basis, the Chapter 3 outlines the methodology for addressing these research gaps. In summary, this chapter provided the following contributions:

- A state of knowledge on interactive technologies raising awareness about the environment
- An analysis of resulting research gaps.

Chapter 3

Methodology

This chapter presents the research methodology adapted from Saunders et al.'s theoretical model, namely the *research onion* (see Figure 3.1). Saunders et al. (2019) explained that the general purpose of the model is to aid in understanding how the different layers of a research methodology relate to one another and how knowledge will be achieved. The first two layers of the model include the research philosophy and the approach that generates knowledge. The other layers provide information about the research design, including the methodological choice, strategy, time horizon, techniques, and procedures (see Figure 3.1). The following sections outline the research philosophy (3.1), the research design (3.2), and conclude with a summary (3.4).

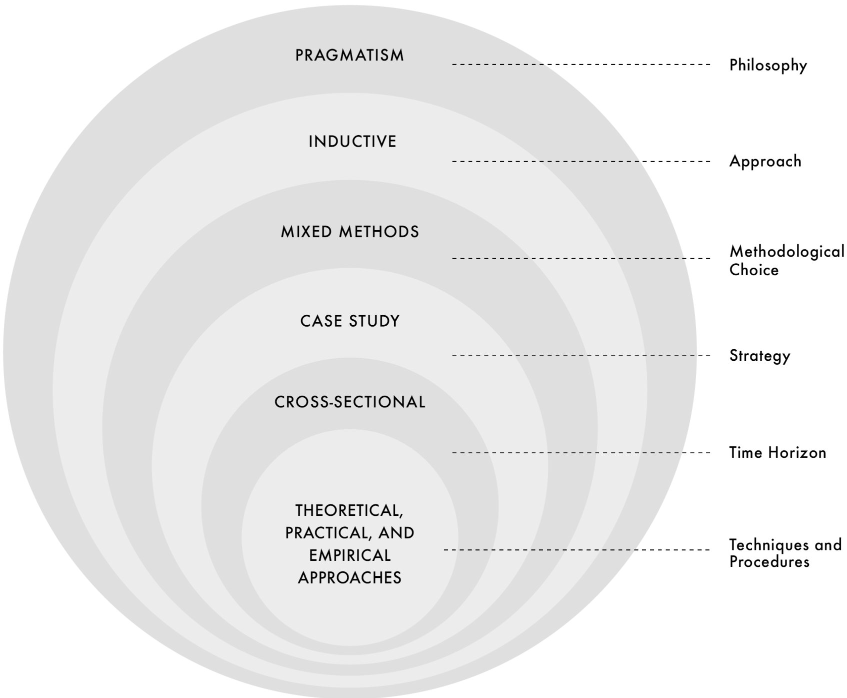


Figure 3.1 Overview of the methodology adapted from Saunders et al.'s research onion (2019, p. 130), redrawn by the author.

3.1 Research Philosophy

Saunders et al. (2019) highlighted that the philosophical perspective is essential for the development of new knowledge. This section outlines the philosophical perspective that underpins the research design to explore a little-known case of individuals who encounter the state of the air through the use of interactive technologies. Although this study is highly inspired by the philosophy of phenomenology and its implications for tangible and embodied interaction (e.g., Dourish, 2001; Hornecker and Buur, 2006), the research philosophy of pragmatism was chosen to generate knowledge through inductive reasoning. Section 3.1.1 introduces pragmatism, while Section 3.2.2 describes the relevance of pragmatism in HCI, and Section 3.2.3 summarises the rationale for choosing pragmatism in this research project.

3.1.1 An Introduction to Pragmatism

Pragmatism began in the early 1870s in the United States and has been characterised in the work of early pragmatists, such as Charles Sanders Peirce, William James, John Dewey, and Jane Addams (de Waal, 2022). While Peirce (1878) first introduced his pragmatic maxim into philosophy, James (1907) popularised the philosophical theory under the name of pragmatism. According to James (1907, p. 46), the term pragmatism originated from the Greek *prâgma*, which he interpreted in the sense of “action” and associated it with the notions “practice” and “practical”. In this way, pragmatism can be seen as a practice-oriented philosophy that does not consider the world as an absolute unit and in which knowledge derives from experience, practice, and consequences rather than only from theoretical thinking. Since pragmatism has been established as a philosophy through various contributions such as Dewey’s logical principles and Addam’s experience based research, pragmatism has evolved into a research philosophy that engages with concrete problems to contribute practical solutions for determining truth that also informs future research (de Waal, 2022). Furthermore, pragmatists value practical results by applying the most appropriate methods and the use of deductive, inductive, or abductive reasoning for their investigations (Creswell, 2014; de Waal, 2022; Saunders et al., 2019). Since experiences are central aspects of this philosophy, pragmatism also offers a perspective on aesthetic qualities. According to Cherryholmes (1992), Dewey considered the aesthetics of everyday life to be an essential component of pragmatism. In his book *Art as Experience*, Dewey (1934) stated that the aesthetic can be experienced in events or scenes that affect humans in their personal lives:

> Experience occurs continuously, because the interaction of live creature and environing conditions is involved in the very process of living. Under conditions of resistance and conflict, aspects and elements of the self and the world that are implicated in this interaction qualify

> experience with emotions and ideas so that conscious intent emerges.
> (Dewey, 1934, p. 36)

Aside from this holistic view on experience that can occur in everyday situations, Dewey (1934, p. 83) also introduced the theory on the *expressive object* as a result of an act of expression that aims to provide an experience to the observer. Although the expressive object is informed by the creator's experience, it has its own meaning, which can be interpreted individually by the observer. Thus, Dewey provided a perspective not only on the experience itself but also on how experiences relate to objects that engage or stimulate one's senses. Inspired by Dewey's philosophy, Richard Shusterman (2008) introduced the term *somaesthetics* as a philosophical framework that focuses on the role of the living body in regard to human experiences. Shusterman (2008, p. 1) described somaesthetics as a discipline concerning "how we experience and use the living body (soma) as a site of sensory appreciation (aesthetics) and creative self-fashioning". He further explained that

> The complementary route offered by somaestetics is to correct the actual performance of our senses by an improved direction of one's body, since the senses belong to and are conditioned by the soma. If the body is our primordial instrument in grasping the world, then we learn more of the world by improving the conditions and use of this instrument. (Shusterman, 2008, p. 19)

Thus, somaesthetics emphasises the sentient body as a medium for perception to cultivate the sensibility of awareness and to improve one's thinking through the body. Furthermore, somaesthetics highlights the sensuality of art as well, which is capable of holding people's attention and being grasped through the bodily senses and emotional values (Shusterman, 2012).

3.1.2 Relevance of Pragmatism in Human–Computer Interaction

In particular, Dewey's (1934) and Shusterman's (2008) philosophy on experiences and aesthetics has demonstrated the relevance of pragmatism for HCI research, supported by the following studies. Although Dewey's philosophy is often overlooked by Merle-Ponty's *Phenomenology of Perception* (1962), Candau and Schiphorst (2020) stated that Dewey's thoughts on experiences are reflected in contemporary perspectives of HCI research. For example, McCarthy and Wright (2004, p. 120) explained that Dewey's characterisation of having "*an* experience" provides a useful approach for analysing the aesthetic quality of individuals' felt experience. In addition, Candy and Ferguson (2014) highlighted that Dewey's philosophy contributes to the development of interactive technologies that offer an intense and immersive experience by bringing together the artist, the object, and the audience. However, Shusterman has gained special attention through his thoughts and practices on the bodily experience. According to Höök et al. (2015), somaesthetics contributes to the understanding of how people perceive themselves and the real world, as novel interactive technologies are used to augment their sensory perception. For this reason, practice-orientated somaesthetics could increase one's awareness of their body and their way of living and acting through the use of different forms of trainings and practices.

3.1.3 Rationale for Pragmatism

As analysed in the literature review (see Chapter 2), the research gaps include theoretical, practice-oriented, and empirical challenges for addressing awareness about a changing environment through the use of interactive technologies that aim to engage with people in the cultural sector. To attain knowledge through the use of practical solutions and lived experiences in a rapidly changing world, pragmatism seems to be the most compelling and open-minded research philosophy. Aside from the choice to select the most appropriate technique and procedure for conducting research, the motivation for choosing pragmatism was also influenced by Dewey's theory on expressive objects (1934) to develop an interactive technology and Shusterman's thoughts on the perceptual capacity of the human body (2008) to explore participants' experiences during an interaction. In summary, expressive objects that aim to augment human senses to experience an invisible dimension, such as the state of the air, make pragmatism an attractive philosophy for underpinning this theoretical-, practice-, and experience-orientated research project.

3.2 Research Design

Regarding Saunders et al.'s research onion (2019, p. 130; see Figure 3.1), this section outlines the research design, including the methodological choice, strategy, time horizon, techniques, and procedures. To accomplish the objectives outlined in the introductory chapter, the research design follows the strategy of a case study. Social scientist Yin (2009, p. 18) defines a case study as "an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident." A case study is used to contribute knowledge about individuals, groups, and related phenomena. However, case studies are used not only in social sciences but also in HCI research to study the development and use of interactive technologies in the field or in an experimental setting (Hewett et al., 1992; Sharp et al., 2019; Wobbrock and Kientz, 2016). In the present study, a single case design was chosen to create an interactive technology that aims to raise awareness about the environment and that can be used to provoke users' experiences during an interaction. To this end, the research design includes theoretical, practice-based, and empirical research methods that were applied in a cross-sectional time dimension to gather quantitative (closed-ended) and qualitative (open-ended) data. Sections 3.2.1–3.2.3 describe the methods of the research design, which were organised into: (a) ex-

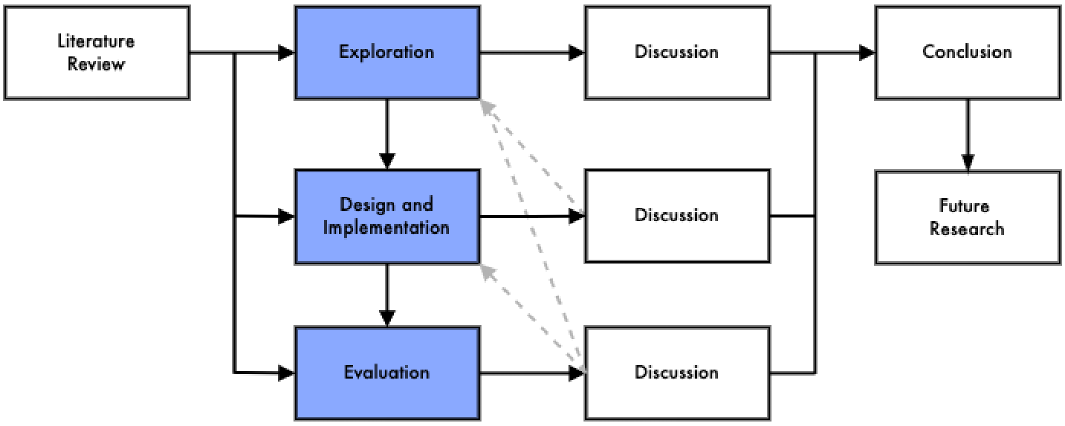


Figure 3.2 Overview of the research design.

ploration, (b) design and implementation, and (c) evaluation (see Figure 3.2). In addition, an overview of the methods is provided in Table 3.1.

3.2.1 Exploration

The research methods discussed in this section aim to formulate a conceptual framework by exploring the design and interaction space of technologies that offer an aesthetic and social encounter with the air. A conceptual framework is an analytical approach to specify the scope of an HCI research project (Sharp et al., 2019). To formulate a conceptual framework that can be used to guide the design and implementation process of an interactive technology, this study synthesises literature on meteorological principles and HCI studies. In doing so, this study thereby provides a basic understanding of the air and grounds related works into major research streams. In addition to the content analysis, the development of this framework also involves practice-based research to underpin the theory through practice, such as participatory interventions on environmental sensing, material research, and preliminary prototypes (e.g., Broscheit, 2020; Broscheit et al., 2018b,a, 2021b).

Table 3.1 Overview of the research methods.

Research Methods	**Description**
Exploration	
Conceptual Framework	to explore and scope the design and interaction space through theoretical and practice-based research
Design and Implementation	
Research through Design	to design interfaces that enable an aesthetic and social encounter with the air
Physical Computing	to implement a functional interface to explore human–atmosphere interactions
Interaction Logs	to record sensor readings of the interaction
Audio-Visual Material	to document the system and the implementation process
Evaluation	
User Experience Research	to explore interfaces used by participants
Pilot Study	to test and refine the procedure of the user study
Think-aloud Technique	to collect verbal data regarding participant's thoughts
Interview	to explore the participant's felt experience
Questionnaire	to gather closed-ended data after the user experience
Data Triangulation	to ensure internal validity by collecting audio-visual materials and interaction loggings for data triangulation
Ethics Approval	to ensure ethical research practice

3.2.2 Design and Implementation

The research methods discussed in this section involve the design and implementation of an interactive technology that can be used as a discursive object in the cultural sector through the use of research through design (RtD) approaches along with software and electrical engineering.

According to Zimmerman and Forlizzi (2014), RtD originated from Frayling's conceptional framework (1993) on generating new knowledge through the use of art and design practices. Over the years, RtD has evolved and has become a relevant research practice in the HCI community. Zimmerman et al. (2007) explained that in traditional HCI research, *design* was mainly used for usability engineering, whereas current interface development also considers design aspects, such as speculative and critical design. To take a critical stand on environmental issues, speculative and critical design offers the possibility of fabricating physical and crafted artifacts that can be used as discursive objects to reflect the current situation and future directions (Dunne and Raby, 2014).

In addition, in the present study, high-fidelity prototypes were developed for user interaction by building on physical computing and material swatches. Fundamentally, prototypes serve as a concrete manifestation of an idea or design and range from low-fidelity prototypes (e.g., sketches) to high-fidelity prototypes (e.g., functional systems). For the development of a high-fidelity prototype, this research applied physical computing. According to O'Sullivan and Igoe (2004), physical computing is the coding and making of high-fidelity prototypes by combining programming, materials, and electronic components (e.g., microcontrollers, sensors, and actuators). Furthermore, the present study fabricated swatches to explore and test expressive materials, techniques, and designs as preliminary studies. According to Perner-Wilson and Posch (2022), material swatches originated from the e-textile community with the idea of creating and sharing physical work.

To access functional prototypes, in this study, interaction logs were gathered to understand the performance of the interactive technology. Sharp et al. (2019) explained that interaction logs derive from various types of actions and are used to analyse data both quantitatively and qualitatively. In the present study, numeric data was recorded from environmental sensors to capture the user's interaction with high particle concentrations and to evaluate the functional prototypes.

Lastly, this study used audio and visual materials (e.g., photographs, videos, and sounds) to cross-reference the findings. According to Creswell (2014), the collection of audio and visual materials is considered as a qualitative method to capture useful information. In the present study, audio and visual materials were collected for the following reasons: (a) to document the design practices and the outcome of the prototype, (b) to analyse archival materials and observations from the field, and (c) to compare the audio and visual material with other types of data.

3.2.3 Evaluation

The research methods discussed in this section aid in understanding of participants while they interact with a technology through the collection of empirical data within a user experience (UX) research. UX research is commonly used in HCI research for evaluating how a technology is experienced by a user. Unlike traditional usability goals that focus on the effectiveness of a technology, UX also assesses the sensual aspects, meaning, and value of an interaction (Hassenzahl, 2008; Law et al., 2009; Sharp et al., 2019). In addition, a pilot study was conducted to ensure the validity of the procedure. A pilot study is a trial run to test methods and the procedure before conducting the main study (Sharp et al., 2019). The methods employed in the present study to conduct UX research are outlined below.

First, the think-aloud technique was used to gather data about the participants' first impressions of using the interface. According to Ericsson and Simon (1993), the think-aloud technique is a qualitative method to collect verbal data about participant's cognitive processes during a given task. Verbal thinking-aloud protocols were initially used in areas of psychology, cognitive science, and education, but they are now a useful method for understanding users who participate in a study (Boren and Ramey, 2000).

Second, semi-structured interviews were applied directly after the think-aloud technique to explore participants' experiences within a conversation. According to Sharp et al. (2019), interviews are types of conversation used to collect verbal data via different kind of forms (e.g., open-ended or unstructured, structured, semi-structured, and group interviews). In semi-structured interviews, the investigator can start the interview with a pre-prepared script that combines closed and open questions to obtain relevant information through follow-up questions.

Third, questionnaires were utilised to collect measurable results directly after participants interacted with the technology. The format of questionnaires can differ (e.g., Likert scales) depending on whether closed or open questions are used, and questionnaires can also be distributed to large groups of participants in remote locations (Sharp et al., 2019).

Forth, data triangulation was applied to compare the participants' statements with their activities based on audio-visual materials and interaction logs that were collected during the user study. According to Creswell (2014), researchers collect data from multiple sources for triangulation (e.g., photo, video, and audio recordings) to ensure internal validity and to strengthen the reliability of a study.

Lastly, this research project was reviewed and approved by the Computing, Engineering, and Physical Sciences School Ethics Committee (SEC) at the University of the West of Scotland to ensure strong ethical research practice and to avoid activities that could harm vulnerable groups. On January 30th, 2021, the submission, with the reference number 12,199, was classified as a research project with low risk to participants. As part of the approval, this research guaranteed that all participant data collected during the user study would be kept confidential and anonymous and securely stored.

3.3 Summary

This chapter presented the methodology of this dissertation, adapted from Saunders et al.'s theoretical model (2019). The research philosophy of pragmatism was described with a focus on the theories of John Dewey (1934) and Richard Shusterman (2008) and their relevance in HCI research. Then, the research design, including methods and ethical approval, was outlined to derive theoretical, practice-based, and empirical knowledge in the following chapters.

Chapter 4

Conceptual Framework

This chapter explores the design and interaction space by drawing on meteorological principles, related HCI studies, and practice-based research to formulate a conceptual framework for the development of interactive technologies that raise awareness about the environment. The following sections outline the conceptual framework of atmospheric interfaces characterised by three key aspects (4.1), discuss the findings (4.2), and conclude with a summary (4.3). To date, the work described in this chapter has been published within the ACM TEI research community (Broscheit et al., 2021a). In addition, the conceptual framework has been informed by previous studies conducted by the author (Broscheit, 2020; Broscheit et al., 2018a, 2019, 2021b).

4.1 An Introduction to Atmospheric Interfaces

Although human-induced impacts change the Earth's atmosphere (Crutzen and Stoermer, 2000), humans are often unaware of the state of the air (Horn, 2018). In general, humans can perceive elements of the weather, such as the wind, which moves the leaves of a tree, or the fog, which limits visibility, but cannot determine the air quality that surrounds them (Ahrens, 2015). Motivated to augment humans' sensibility towards the state of the environment, this section introduces the conceptual framework of *atmospheric interfaces* to enable an aesthetic and social encounter with air (see Figure 4.1).

The term atmospheric interfaces describes sensor-based computing systems that measure and translate environmental information into the form of interactive material for augmenting human senses, such as sight, touch, smell, taste, and hearing (Broscheit et al., 2021a). Situated in the realm of tangible and embodied interaction (Hornecker, 2011; Hornecker and Buur, 2006; Ishii, 2008; Ishii et al., 2012; Ishii and Ullmer, 1997), atmospheric interfaces use the air as a medium to create expressive interfaces that can be either embedded into the real world or worn on the human body.

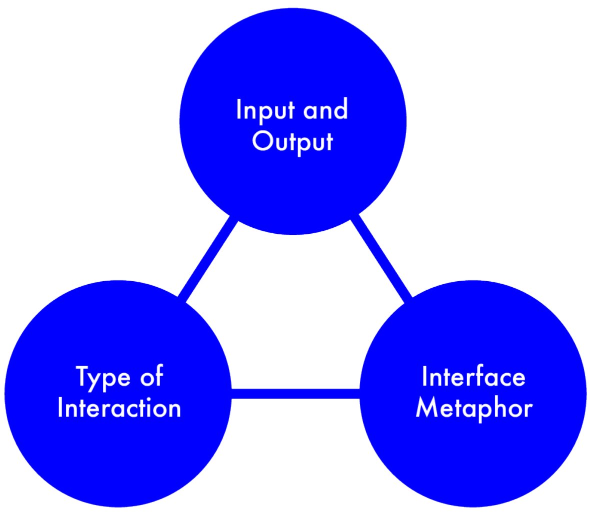


Figure 4.1 Conceptual framework of atmospheric interfaces, which includes three key aspects: (a) input and outputs, (b) interface metaphor, and (c) type of interaction.

In general, atmospheric interfaces refer to the meteorological perspective of the Earth's atmosphere, in which the notion *atmosphere* derives from the Greek *atmós* (vapour) and *sphaîra* (sphere). According to Ahrens (2015), the atmosphere is a thin envelope that consists of different gases and surrounds the Earth in vertical layers. Atmospheric interfaces focus in particular on the lowest layer, the troposphere, to convey the state of the air for human beings.

The composition of the early Earth's atmosphere was different from the air humans breathe today, and it has changed over the past billion of years through chemical, physical, and biological processes (Ahrens, 2015). As a basis of existence, human are in contact with the air from their first to their last breath. The air, for example, fills lungs with oxygen, absorbs ultraviolet radiation from sunlight, and influences the way humans perceive their environment. Although, the air is "tasteless, odorless, and (most of the time) invisible" from a meteorological point of view (Ahrens, 2015, p. 4), humans can perceive different kinds of stimuli events occurring in the air. The American psychologist Gibson (1979, p. 130), for example, stated that the "affordance" of air includes the visual perception of fog, vibrations in the form of sounds, olfactory events of scented fields, and respiration. In addition, social and cultural scientist Horn (2018, p. 22) explained that "an aesthesis of air means exploring it in all its sensory qualities—from its (in)visibility and its tactile states (e.g., temperature, humidity), to its inner dynamics (e.g., winds, drafts, updraft, density) and maybe even the affective qualities of certain weather conditions."

However, to bring the air into the forefront of human perception, the present study argues that meteorological processes must be measured and expressed as physical data representations. Unlike interfaces that enable an experience with environmental events, such as Döring et al.'s *Ephemeral User Interfaces* (2013*b*) or Random International's *Rain Room* (2012), atmospheric interfaces aim to measure the processes in the air for translation of the gathered information into interactive materiality and physicality. In contrast to precise data measurements, these physical data representations provide knowledge through a sensory and emotional interaction that aims to convey meaning on a human level (Lupton, 2017). Therefore, the concept of atmospheric interfaces differs from the aforementioned studies by focusing on an expressive data interpretation of the state of the air rather than working with the weather dynamics themselves. For this reason, atmospheric interfaces consist of an input for sensing the environment and an expressive output for physical data representation. Although sensor nodes can sense the environment in urban cities and buildings (e.g., Dang et al., 2018; Fekih et al., 2021; Kirešová et al., 2022; Kuznetsov, Davis, Cheung and Paulos, 2011; Singh Katiyar et al., 2022), they are not considered to be atmospheric interfaces, as the representation of the environmental data must extend beyond the visualisation of numeric measurements to engage with people's senses.

Since the notion *atmosphere* has also become a commonly used expression for something that affects human feelings, this study pays special attention to Böhme's theory on *The Aesthetic of Atmospheres*. In his research, Böhme (2018, p. 1) stated that "atmosphere is what relates objective factors and constellations of the environment with my bodily feeling in the environment. This means: atmosphere is what is *in between*, what mediates the two sides." Böhme emphasised the atmosphere as an ambient quality for a so-called "between"-phenomenon that the perceiver shares with the perceived. By contrast, in atmospheric interfaces, the term atmosphere is, first and foremost, understood as an interpretation of meteorological processes, which are, however, are also capable of creating an ambient atmosphere, in the sense of Böhme's theory.

To provide an aesthetic and social encounter with the air, the conceptual framework of atmospheric interfaces includes three key aspects: (a) inputs and outputs to develop a functional interface, (b) an interface metaphor to interpret the displayed information, and (c) types of interactions to experience environmental information. Sections 4.1.1–4.1.3 detail these key aspects.

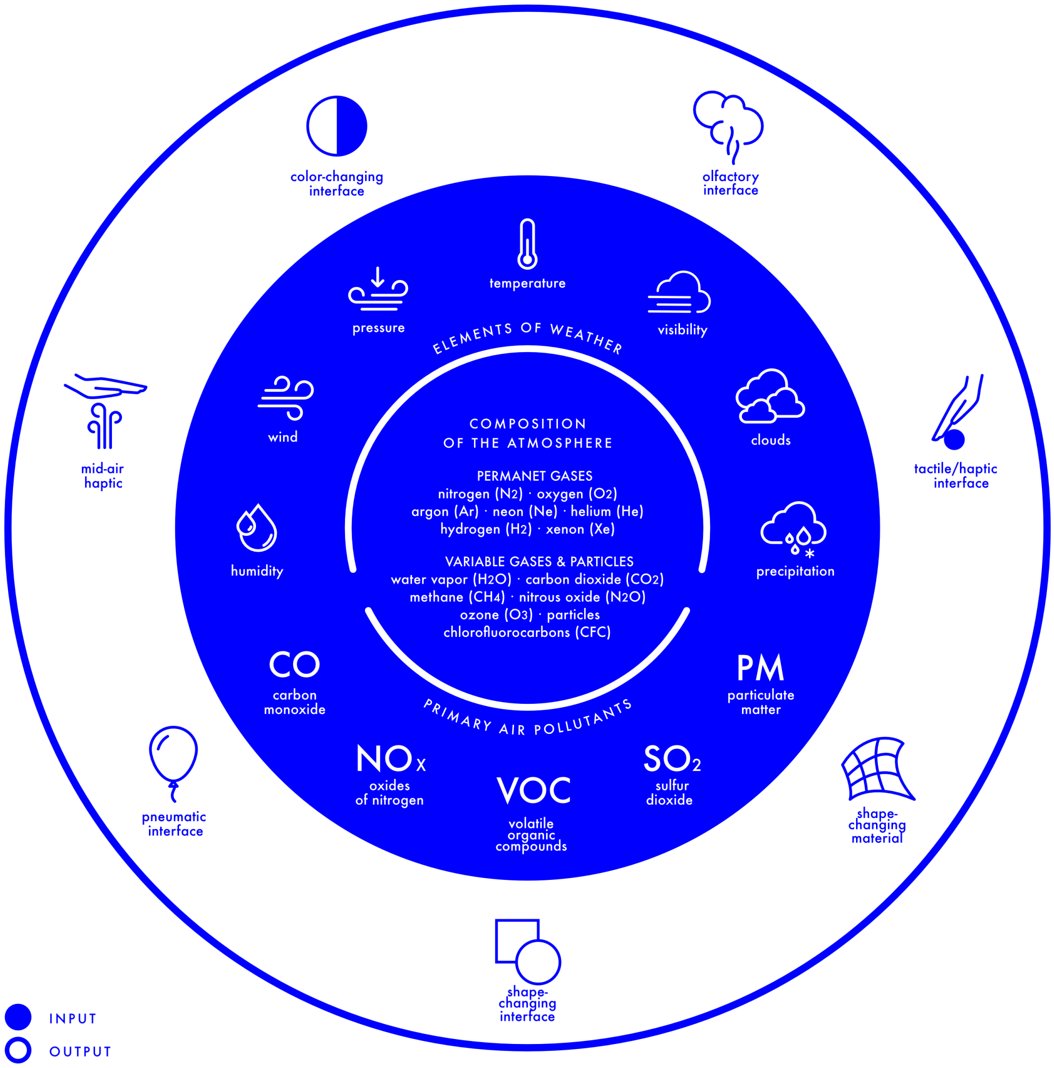


Figure 4.2 Preliminary taxonomy illustrating the design space for the creation of an atmospheric interface. The blue section encompasses environmental inputs, and the white section presents major research streams of physical data representations that can be considered as outputs.

4.1.1 Input and Output

The first key aspect of the conceptual framework comprises inputs and outputs to develop a functional interface. According to El-Ghazawi and Frieder (2003), an input/output (I/O) device transfers data between the computer and the world. This study considers (a) an input that measures the state of the environment and (b) an output that expresses the state of the environment as interactive material and physicality. The following subsections provide a preliminary taxonomy that classifies different inputs and outputs (see Figure 4.2).

4.1.1.1 Input

The aim of the input classification is to provide a basic understanding of the nature of air. This study draws on Ahrens's *Essentials of Meteorology* (2015) to summarise environmental information that can be used for the creation of expressive interfaces representing environmental information. A distinction is made between (a) the composition of the atmosphere, (b) principal air pollutants, and (c) the elements of weather.

The centre of the taxonomy (see Figure 4.2) illustrates the composition of the atmosphere near the Earth's surface, including permanent gases, variable gases, and particles. However, with every inhaled breath, humans intake not only life-sustaining oxygen but also other airborne substances, such as air pollutants. Ahrens

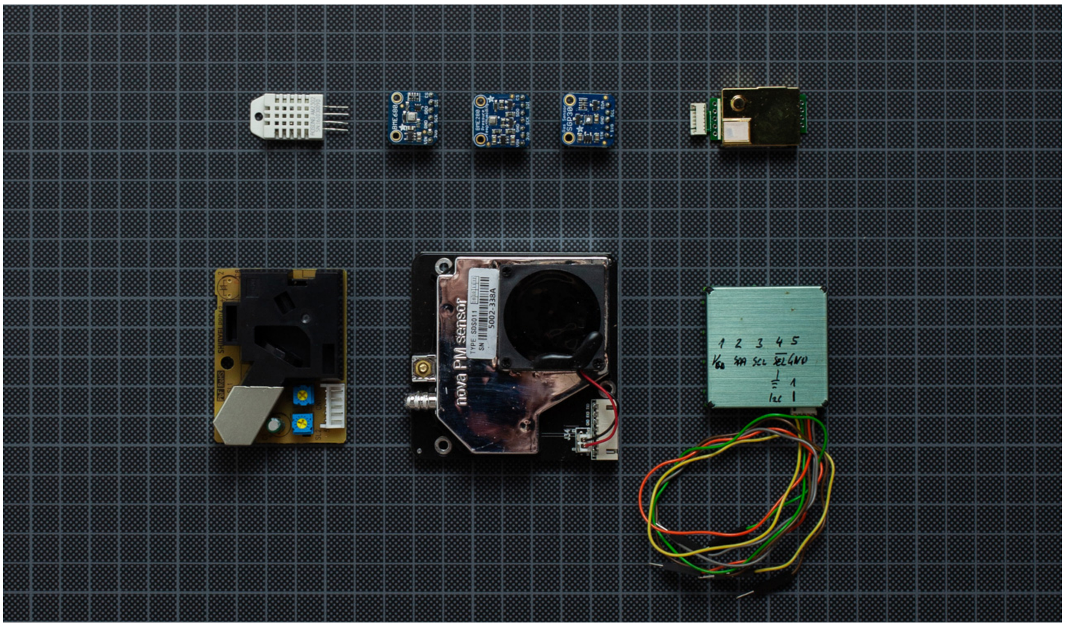


Figure 4.3 Overview of environmental sensors that can be used for physical prototyping to measure meteorological processes in the near surroundings. Top row (left to right): the environmental sensors DHT22, BME680, and BME280; as well as the CO_2 sensors SGP30 and MH-Z19C-PH. Bottom row: the particle sensors PPD42NS, SDS011, and SPS30.

(2015, p. 433) explained that, "air pollutants are airborne substances (either solids, liquids, or gases) that occur in concentrations high enough to threaten the health of people and animals, to harm vegetation and structures, or to toxify a given environment". Anthropogenic pollutants, for example, can result from motor vehicle exhaust fumes and the combustions of oil, gas, and coal, while natural pollutants can result from forest fires and volcanic ash. The taxonomy depicts principal air pollutants, such as carbon monoxide (CO), volatile organic compounds (VOC), sulphur dioxide (SO2), nitrogen oxides (NOx), and particulate matter (PM), that can enter the atmosphere directly and that are produced by natural sources and anthropogenic activities. In addition, various weather events can affect the state of the atmosphere. Wind, for example, can influence the concentrations of particulate matter pollution and carry it over long distances before it settles on the Earth's surface. The taxonomy thus also provides an overview of the elements of weather that are responsible for the temporal dynamics of the air, including air temperature, humidity, air pressure, clouds, wind, visibility, and precipitation (e.g., snow and rain).

To measure the state of the air, various data gathering approaches can be utilised. For instance, users of the taxonomy can employ different types of sensors to measure chemical, mechanical, and optical factors in the near surroundings (see Figure 4.3). In addition, open data services can be used that provide historical, current, and predictive global information (e.g., OK Lab Stuttgart, 2016; OpenWeather, 2012; Sensio Air Inc, 2021). The gathered environmental data can then be used as input for interpreting an expressive output.

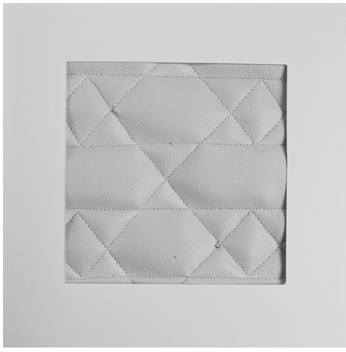
4.1.1.2 Output

The aim of the output classification is to provide an overview of different forms of physical data representations that can be used to create an atmospheric interfaces. The classification was informed by the literature review of related works (see Chapter 2). The reviewed literature yielded interfaces that allow users to experience environmental information via interactive matter that can be encoded by humans' various sensory receptors. According to Gibson (1966), the human sensory system includes visual, auditory, touch, smell, and taste receptors that respond to the environment. In this respect, related works were classified into various forms of physical data representations that can be encoded by sensory receptors. Users of the taxonomy can build on basic research and gain inspiration for interpreting environmental data as interactive material. In addition, some of these approaches were explored and tested in the form of swatches, which served as preliminary material research to explore the different approaches in a practice-oriented manner (see Figure 4.4 and 4.5). What follows is an overview of various outputs that were structured into five major research streams: (a) colour-changing interfaces, (b) tactile/haptic Interfaces, (c) shape-changing interfaces, (d) mid-air haptics, and (e) olfactory interfaces.

a) Colour-Changing Interfaces

Studies involving colour-changing interfaces visualise air qualities levels through the use of thermochromic pigments and illuminated fabrication (e.g., Adhitya et al., 2016; Bentel, 2016; Broscheit, 2020; Diffus, 2009; Kim et al., 2010; Molga, 2016). These interfaces are grounded within basic research on electronic textiles. Electronic textiles have been introduced by researchers of the MIT Media Lab's and encompass a wide range of fabrication techniques, including capacitive yarn for sewn circuits, embroidered LEDs, and fabric sensors (Orth et al., 1998; Post and Orth, 1997); as well as novel crafting tools (e.g., Posch, 2017; Posch and Fitzpatrick, 2018). Over the years, the manufacture of electronic textiles has evolved, and colour-changing interfaces have been produced through the use of thermochromic pigments (e.g., Berzowska, 2004, 2005; Song and Vega, 2018) and the integration of polymeric optical fibres (e.g., Chen et al., 2020; Tao, 2000) that can be used to visualise environmental data.

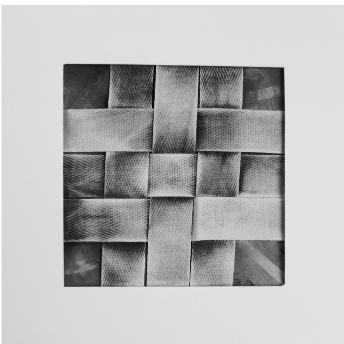
(a)



(b)

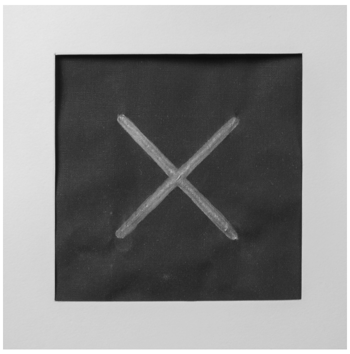
(c)

(d)



(e)

(f)



(g)

Figure 4.4 (a) Swatchbox with taxonomy and material experiments. Swatches for shape-changing interfaces: (b) a sewn structure on fabric, (c) a heat-manipulated structure, and (d) an auxetic structure. Swatches for colour-changing interfaces: (e) a thermochromic woven surface, (f) a thermochromic heat-manipulated surface, and (g) a thermochromic thread.

b) Tactile/Haptic Interfaces

Works related to tactile/haptic interfaces involve physical activities as well as tactile feedback to experience environmental conditions (e.g., Ishii, 2004; Pakanen et al., 2021; Seow et al., 2022; Wu, 2010). These interfaces are grounded in the realm of computer systems that reproduce tactile parameters (Benali-Khoudja et al., 2004) or require a haptic tangibility (Ishii and Ullmer, 1997). Additionally, tangibles can be augmented through media environments that enable users to transform an illuminated physical representation (e.g., Piper et al., 2002) and to present additional visualisations on table-tops, projections, and fog screens (e.g., Jofre et al., 2015; Kaltenbrunner and Bencina, 2007; Martinez Plasencia et al., 2014).

c) Shape-Changing Interfaces

Works involving shape-changing interfaces present environmental information through the use of dynamic behaviour (e.g., Broscheit et al., 2019, 2021b; Coelho and Maes, 2009; Daniel et al., 2019; Fabrizi, 2014; Grade, 2013; Khan, 2010; Yu, 2020). These interfaces are grounded into the major research stream of shape-changing interfaces that utilises various actuators (e.g., motors, electromagnetic actuators, pneumatic, or shape-changing materials) to animate a changing surface (Rasmussen et al., 2012). Transformable materials, for example, can be controlled by direct or electrical stimuli (e.g., Berzowska and Coelho, 2005; Coelho et al., 2008; Coelho and Zigelbaum, 2011; Follmer et al., 2013; Muthukumarana et al., 2021; Ou et al., 2016; Tahouni et al., 2020), and pneumatic devices can change their shape through the use of inflation (e.g., Gohlke et al., 2016; Ou et al., 2016; Webb et al., 2019; Yao et al., 2013).

d) Mid-Air Haptics

Works involving mid-air haptics present environmental information as haptic feedback in mid-air (e.g., Stamhuis et al., 2021; Tolley et al., 2019). These interfaces are grounded into the major research stream of mid-air haptics. Mid-air haptics provide a tactile sensations via air vibrations and without direct physical contact (Rakkolainen et al., 2020). Interfaces could generate haptic stimuli on the user's hand through ultrasonic transducers (e.g., Carter et al., 2013; Paneva et al., 2020; Wilson et al., 2014) or use compressed air pressure to simulate a sensation (e.g., Sodhi et al., 2013).

e) Olfactory Interfaces

Studies involving olfactory interfaces transfer information about the state of the air through the use of odour (e.g., Amores et al., 2015). These interfaces are part of the major research stream of *olfactory displays* that provide a user with a computer–controlled smell. Takamichi Nakamoto (2012, p. xviii) explained, that "a human interface for olfaction is composed of an olfactory display and an odor sensing system called an electric nose. An olfactory display is an output of a machine, whereas the odor sensing system is its input". These interfaces can provide an experience with odour in the ambient setting (e.g., Cao and Okude, 2015; Kao et al., 2015; Seah et al., 2014) and on the human body in the form of accessories (e.g., Wang et al., 2020).

4.1.2 Interface Metaphor

The second key aspect of the conceptual framework considers an interface metaphor to enable a social encounter with the air and to draw special attention to air components that are not easily recognisable (e.g., air pollution). In HCI research, *metaphors* play an important role in the design of user interfaces (Carroll et al., 1988; Hamilton, 2000; Neale and Carroll, 1997; Sharp et al., 2019). In general, the term metaphor is associated with figurative speech used as a rhetorical approach (Hamilton, 2000). According to Lakoff and Johnson (1980, p. 5), "The essence of metaphor is understanding and experiencing one kind of thing in terms of another." Metaphors are commonly used in HCI research to support the understand-

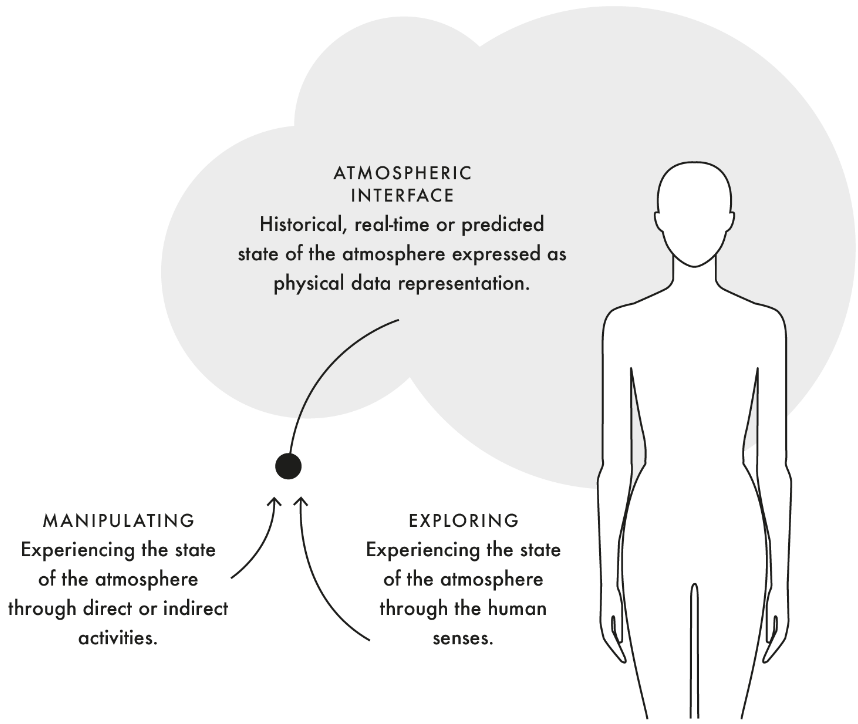


Figure 4.5 Two different interaction types that encompass (a) the exploration and (b) the manipulation of atmospheric interfaces to experience the state of the environment.

ing of complex and abstract information through the embodiment of an interface metaphor (Carroll et al., 1988; Neale and Carroll, 1997). On this basis, the conceptual framework recommends the use of an metaphorical representation to convey hardly recognisable environmental information, such as air pollution. In this way, metaphors could support the communication of non-obvious atmospheric characteristics of the atmosphere (e.g., chemical processes) and engage with the user on a cognitive level. Related works have employed promising metaphors as mental models for communicating the state of the environment by drawing on (a) animals (e.g., Broscheit et al., 2018a, 2019; da Costa, 2006; Yu, 2020), (b) plants (e.g., Fabrizi, 2014; Grade, 2013; Hsu et al., 2018; Seow et al., 2022), and (c) objects (e.g., Broscheit, 2020; Broscheit et al., 2021b; Ishii, 2004; Kim et al., 2010; Schulte et al., 2018).

(a) (b) (c) (d)

Figure 4.6 Preliminary studies conducted by the author to illustrate different types of interactions with the state of the air. Top: interactions through the use of (a) an illuminated mask that demonstrates the air quality of the near surroundings to other individuals in a public space and (b) a bag with a thermochromic symbol for air visualising two levels of air quality. Bottom: interactions involving manipulation of the atmospheric condition through the use of (c) vapour from an e-cigarette to impact the state of the air through particle concentrations and (d) exhalation to affect CO_2concentrations.

4.1.3 Type of Interaction

The third key aspect of the conceptual framework illustrates various types of interactions with the air. With reference to Sharp et al. (2019, p. 81), this study distinguishes between an exploratory and manipulatory type of interaction. In an exploratory interaction, users move through the real world to achieve knowledge from sensor-based technologies (Sharp et al., 2019). In this respect, studies were analysed in which the state of the atmosphere can be experienced through interfaces that represent historical, real-time, or predicted information. This information is expressed via physical data representations that can be perceived by the human senses either indoors or outdoors (e.g., Adhitya et al., 2016; Amores et al., 2015; Broscheit, 2020; Coelho and Maes, 2009; Fabrizi, 2014; Kao et al., 2017; Khan, 2010; Kim et al., 2010; Molga, 2016).

In a manipulatory interaction, users interact with objects in the real world to enhance their knowledge through their physical activity (Sharp et al., 2019). In regard to this category, studies were analysed in which the state of the atmosphere can be experienced through interactions that manipulate an object directly, such as grasping the lit of a bottle to hear the weather forecast (e.g., Ishii, 2004). In addition, humans themselves can impact the atmosphere through their anthropogenic activities (see Figure 4.7c-d). To cause this impact, tools such as a vaporiser that manipulates particle concentrations in the near surroundings (e.g., Broscheit et al., 2018a) and the exhalation of a human breath for increasing CO_2 values can be used (e.g., Broscheit et al., 2021b).

4.2 Discussion

This section presents a discussion of the research implications, further recommendations, and study limitations.

4.2.1 Implications

By drawing on related knowledge and practice-based studies that have been used to explore the design and interaction space, this study formulated the conceptual framework of atmospheric interfaces for developing expressive interfaces designed to enable an aesthetic and social encounter with the air. For this purpose, the term atmospheric interfaces was introduced and differentiated by referring to related studies. Moreover, the term was defined by three key aspects: (a) input and output, (b) interface metaphor, and (c) type of interaction.

The first key characteristic, namely input and output, describes a preliminary taxonomy for the creation of a functional interface that enables an aesthetic interaction with the state of the air. With reference to Ahrens (2015), the input classification provides an basic overview of the nature of air, including the composition of the atmosphere near the Earth's surface, primary air pollutants, and elements of weather. The output classification draws on various major research streams to express environmental data through aesthetic and crafted material as a way to engage with the human senses through non-verbal communication, and thus contributing to the realm of tangible and embodied interaction (Hornecker, 2011; Ishii et al., 2012). With reference to Gibson (1966), the preliminary taxonomy provided an overview of expressive interface outputs that can engage with the human senses through sight, touch, and smell. Although the present study identified interfaces for digital and electric taste (e.g., Nakamura and Miyashita, 2011), a gustatory interface that interprets the state of the air constitutes a research gap. Further research could therefore investigate how environmental information can be translated into a gustatory sensation. The preliminary taxonomy could therefore support the development of atmospheric interfaces by providing a general understanding of the nature of air and offering inspiration for interpreting environmental data as interactive material. In this way, the preliminary taxonomy provides promising implications for conducting systematic research and expanding material-based research.

The second key characteristic, namely interface metaphor, draws on metaphors to enable a social encounter with the air. Although the taxonomy's outputs provide a sensational quality, it was found that metaphorical representation could contribute increased sociality and meaning to the interaction with the air. As shown in a recent study (Seow et al., 2022), this could have promising implications for user connectedness. For example, interface metaphors that embody a non-human species (e.g., an animal, a plant, or a microorganism; Broscheit et al., 2018a; Fabrizi, 2014; Grade, 2013; Seow et al., 2022) have been observed to be the most promising mental models for building a social connection with another living being to address environmental concerns.

The third key characteristic, namely type of interaction, outlines two types of interactions with the air: exploriatory and manipulatory. While exploring the atmospheric environment in the wild (e.g., Kim et al., 2010; Molga, 2016) depends on various factors that are difficult to control, manipulating the state of the air could have a positive impact on an immediate interaction to test the performance of an interface and provoke a user experience. In this context, the studies by Broscheit et al. (2021b) and Broscheit et al. (2018a) demonstrate promising opportunities for staging an interaction with particle and CO_2 concentrations, and they could hence provide an approach to overcome the shortcomings of user experience research (see Chapter 2). Moreover, this approach could be of particularly interest for regions that are not affected by high pollution levels, such that citizens can be sensitised to this global environmental concern within a speculative installation.

In summary, the conceptual framework of atmospheric interfaces has great implications for the development of expressive interfaces aiming to raise awareness about the environment through aesthetic and social encounters with the air that could also provoke users' immediate reaction in various application domains. Based on the findings, this study envisions that atmospheric interfaces could impact peoples cultural lives within the following application domains: (a) the environmental arts (Randerson, 2018), to engage with the society in the cultural sector (e.g., Baraga, 2016; Bentel, 2016; Grade, 2013; Molga, 2016); (b) participatory design (Sharp et al., 2019), to involve citizens in the development of technologies that foster social change, transformation, and education (e.g., Broscheit et al., 2018a; Guler, 2013; Liu et al., 2020; Solomon et al., 2018); (c) personal healthcare (Lupton, 2016, 2017), to achieve self-knowledge from personal data representations through quantified self methods (e.g., Kim et al., 2010; Pakanen et al., 2021); and (d) interactive interiors (Nabil and Kirk, 2019), to allow for aesthetic fulfilment and to enhance quality of life and sustainable living while representing or controlling the indoor climate within public or private spaces (e.g., Amores et al., 2015; Khan, 2010).

4.2.2 Recommendations

Regarding the second research question (see Section 1.2.1), the conceptual framework can be used to develop an interactive technology that aims to enable an aesthetic and social encounter with a changing atmosphere. Users of the conceptual framework first need to investigate a suitable interface metaphor to communicate the state of the air (see Section 4.1.2). Based on the findings, the present study recommends choosing a metaphorical representation of a non-human species (e.g., an animal, a plant, or a microorganism) to provide a meaningful and emotional experience. Following this, users must identify characteristics of the interface metaphor to specify the input and output (see Section 4.1.1). When specifying the input, users can choose between different air components. For example, to address primary air pollutants, the present study recommends PM as an input based on the promising results of a previous study conducted by Broscheit et al. (2018a). Furthermore, users must select an output that interprets the state of the air as a sensory experience. For example, previous studies have provided inspiring metaphorical presentations through shape-changing and colour-changing interfaces (see Figure 4.4 and 4.6). Lastly, users must define a type of interaction (see Section 4.1.3). Depending on the application, users may consider an exploratory or manipulative type of interaction. For example, the present study recommends using tools, such as an e-cigarette, to demonstrate the function of an interface by staging high particle concentration (see Figure 4.6c).

4.2.3 Limitations

The intention of developing the conceptual framework of atmospheric interfaces was to enable an aesthetic and social encounter with the air and consequently to contribute to the theoretical foundation of HCI. To this end, the conceptual framework was characterised by three key aspects, including a preliminary taxonomy that illustrates basic knowledge about the nature of air. To address other environmental factors, a next iteration of the taxonomy must be considered. Furthermore, it was found that related studies (e.g., Broscheit et al., 2021b; Ishii, 2004; Ishii and Ullmer, 1997) seemingly use auditory output as a secondary stimulus for providing a multisensory experience. For this reason, the conceptual framework considered sound as additional feedback, which is not yet visualised in the preliminary taxonomy. Overall, the conceptual framework of atmospheric interfaces was developed by drawing on related studies and practice-based research. To evaluate its practical use, this study recommends participatory research based on previous studies (Broscheit et al., 2018b,a). To this end, a prototyping toolkit could be developed to assess the conceptual framework as a research tool with potential target groups (e.g., interior designers, environmental artists, self-trackers, citizens, and STEM students).

4.3 Summary

This chapter presented the conceptual framework of atmospheric interfaces, which has emerged from the literature with meteorology foundations, related studies, and practice-based research. The findings yielded insights into human–atmosphere interactions in the real world that serve as a basis for the design and development of interactive technologies that aim to raise awareness about the environment among civil society. In summary, this chapter contributed the following:

- An exploration of the design and interaction space
- The conceptional framework of atmospheric interfaces, which includes (a) a taxonomy of inputs and outputs, (b) interface metaphors, and (c) types of interactions.

Parts of this chapter were published in Broscheit et al. (2021a). In addition, this chapter was informed by practice-based studies published in Broscheit et al. (2018a), Broscheit et al. (2021b), Broscheit et al. (2018b), and Broscheit (2020).

Chapter 5

IVORY – The Initial Sentinel Species Interface

This chapter presents the design and implementation process of a high-fidelity prototype that was informed by the conceptual framework (see Chapter 4). The following sections describe the design consideration (5.1), the design and implementation process (5.2), field notes from exhibition spaces (5.3), discuss the findings (5.4), and conclude with a summary (5.5). To date, the work described in this chapter has been presented in various exhibition spaces, introduced at the 4th SPARKS lightning talk of the ACM SIGGRAPH Digital Arts Committee, and discussed within the ACM TEI research community (Broscheit, 2020; Broscheit et al., 2019).

5.1 Design Consideration

Based on the conceptual framework (see Chapter 4), this section introduces the design consideration for an interactive technology that aims to raise awareness about the environment. Inspired by the concept of sentinel species, this study draws in particular on the miner's canary to create an interface metaphor that allows for an aesthetic and social encounter with the air. To this end, this study envisions an abstraction of a bird that simulates the physiological behaviour of breathing and singing and uses feathers as a material reference to convey the state of the air. To accomplish this idea, a shape-changing interface enriched with audio was chosen as sensory output to interpret the physiological behaviour and material properties of a breathing and singing bird sensitive to air quality. While an interaction with air quality is quite challenging in the wild, this study also considers approaches for staging a user interaction. Sections 5.1.1 and 5.1.2 provide background information on sentinel species to be used as an interface metaphor for experiencing ecological feedback, such as particulate matter.

5.1.1 Sentinel Species as an Interface Metaphor

As mentioned in the introductory chapter, relevant literature on the Anthropocene discusses the interconnectedness of human and non-human species (Haraway, 2003; Horn, 2020; Tsing, 2012). In particular, Donna Haraway (2003, 2016), emphasised the need to overcome humans' limited perspectives on the world by establishing relationships with other species. In her *Companion Species Manifesto*, Haraway (2003) provided a perspective on the co-evolutionary relationship between human beings and other animal species. While the manifesto originally focused on human companionship with dogs, Haraway (2016) later also considered other multispecies relationships for addressing environmental issues and global transformation. Moreover, she criticised the term Anthropocene and suggested other approaches, such as species storytelling, to mediate the entanglement of humans, non-humans, and ecological concerns (Haraway, 2016; Haraway and Endy, 2019).

Inspired by Haraway and related studies that have employed various organisms as an interface metaphor to mediate the state of the air (e.g., Broscheit et al., 2018a; Fabrizi, 2014; Grade, 2013; Liu et al., 2018; Seow et al., 2022; Yu, 2020), this study builds on the concept of *sentinel species* to establish a relationship with another organism to augment human senses and increase awareness of the atmospheric environment. According to O'Brien et al. (1993), the term sentinel species is defined as:

> Organisms in which changes in known characteristics can be measured to assess the extent of environmental contamination and its implications for human health and to provide early warning of those implications. (O'Brien et al., 1993, p. 352)

In this way, sentinel species represent a specific approach that highlights the interrelationship between human and animal health regarding the environmental condition. O'Brien et al. (1993, p. 353) identified five criteria for selecting a suitable sentinel species that can act as an early warning system: (a) "size", (b) "sensitivity", (c) "physiological characteristics", (d) "longevity", and (e) "latent periods". A selected sentinel must therefore be sensitive enough to environmental contaminations and must reflect this sensitivity through the aforementioned criteria. Various living organisms are suitable for monitoring air pollution, such as mosses, lichens,

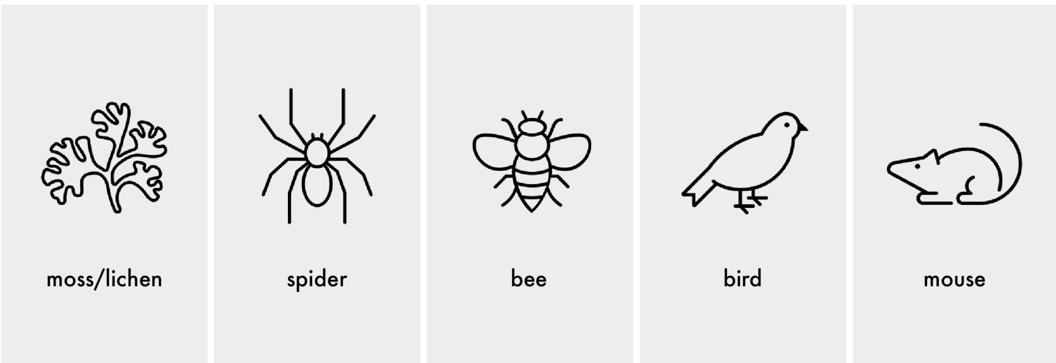


Figure 5.1 Overview of different kinds of organisms that can be used for monitoring the air quality, including moss/lichen, spider, honey bee, bird, and mouse.

(a) (b)

Figure 5.2 The archival collection illustrating (a) Sir Robert Henry Davis's apparatus for testing air, patented in 1912 (used with permission from Newcastle Region Library's Collections) and (b) a Staffordshire coal miner holding a canary at work down in a British coal mine (photograph by Philip Dunn, 1986, used with permission from the Mary Evans Picture Library).

honey bees, spiders, birds, and mice (Conti and Cecchetti, 2001; Rachwał et al., 2018; Reif, 2011; Ryalls et al., 2021, see Figure 5.1).

A classic example of a sentinel species is the miner's canary (National Research Council, 1991; Reif, 2011). In the era of early coal and steel industries, no technologies existed to measure the state of the air. To ensure that miners could enter new mine fields and be warned of so-called blackdamp (low-oxygen air), the Scottish physician and physiologist Haldane (1922) recommended small warm-blooded animals, such as birds or mice, as early warning recognitions for detecting environmental contaminations. Although Spencer (1962) found that the canary is an imprecise measuring approach regarding carbon monoxide exposures (see

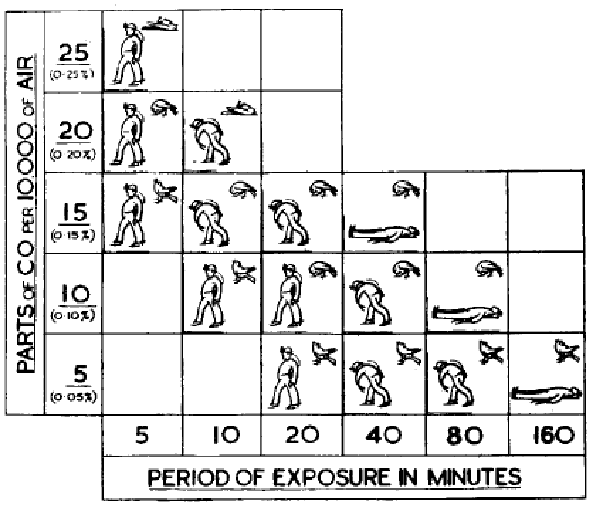


Figure 5.3 Effects of carbon monoxide exposure on humans and canaries by Spencer (1962). According to Spencer (1962, p. 234), this figure "shows situations that can occur in varying concentrations of CO in air. It will be seen that these can vary from a symptomless man and an unconscious canary to a situation where the roles are exactly reversed".

Figure 5.3), it nevertheless became an effective indicator to protect miners from dangerous gases in shafts.

As opposed to other animals, canaries were preferred as in situ sentinels because of their sensitivity and physiological characteristics (Reif, 2011). For example, if the air reached high levels of hazardous gases, canaries showed signs of distress or collapsed from their perches (National Research Council, 1991; Spencer, 1962). This sensitivity to environmental hazards provided the miners with the necessary time to initiate security interventions. To keep the birds alive, the British inventor Sir Davis (1912) patented a special cage, an *Apparatus for Testing Air*, which supplied the birds with oxygen after a collapse (see Figure 5.2a). When miners, for example, wanted to test their environment, they could open the air-locked cage. If the canary was harmed by toxic gases, the miners could close the cage again, and the bird would be revived with oxygen.

Despite the canary's worldwide role as a sentinel species in mine shafts, the bird has also significantly influenced cultural heritage (see Figure 5.4). Many miner's marching bands, for example, have honoured their indispensable compan-

(a) (b)

(c) (d)

(e) (f)

Figure 5.4 Archival collection photographed at the Harzer-Roller-Museum in Sankt Andreasberg, Germany: (a) porcelain figures for home decoration, (b) a breeder award, (c) a barrel organ and (d) a gramophone to train the birds' vocal skills, (e) a wooden cage, and (f) a gas detector that replaced the canary.

ion with a plume of feathers on their traditional costumes, such as the Austrian miner's band *Bergmannskapelle Schmitzberg-Ampflwang*. In addition, canaries became popular companion animals in domestic households and were bred in various colours, such as white, yellow, red, green, and brown. To make the domestic canary even more desirable, breeders used different kinds of methods to train the bird to sing (see Figure 5.4c-d). For this purpose, record players and barrel organs playing special melodies were used to train the talented singers and thus make them attractive as pets and for worldwide songbird competitions (Klähn, 2006).

Today, these birds no longer act as sentinel species, but the English idiom "canary in the coalmine" still exists, referring to any warning of potential danger or ethical dilemmas (Hornby, 1995, p. 215). Related works have thus embraced the miner's canary and developed various interactive technologies for different application areas. For example, the GUI, entitled *Canary in a Coal Mine*, visualises air quality datasets to empower citizens (Smid et al., 2011).

In short, based on the physiological behaviour and cultural heritage of, as well as the emotional attachment to, the miner's canary, this study chose this bird as a metaphorical representation for communicating the state of the air on an aesthetic and social level.

5.1.2 Particulate Matter as Ecological Feedback

In contrast to the historical use of the miner's canary, the intention of this study is to address the contemporary environmental issue of urban air pollution, such as particulate matter (PM). According to Ahrens (2015, p. 435), the term particulate matter describes "a group of solid particles and liquid droplets that are small enough to remain suspended in the air." These airborne particles, also commonly known as aerosols, are amongst the principal air pollutants that can enter the atmosphere directly (see also Chapter 4). In general, PM is measured in different sizes according to their aerodynamic diameters of the particles (see Figure 5.5) as follows:

- **PM-10** – particles with a diameters smaller than $10\,\mu m$
- **PM-2.5** – particles with a diameter less than $2.5\,\mu m$.

Ahrens (2015) explained that some particles are harmless to the human body or might be a health irritant (e.g., dust, smoke, and pollen), while other particles consisting of more dangerous substances (e.g., pesticides, iron, and lead). In particular, smaller particles, such as PM-2.5, are more threatening to human health because they can enter much further into the human body (e.g., the lungs) than larger particles and cause serious health issues. Recent studies have shown that long-term exposure to air pollution is linked to global health problems, such as cardiovascular diseases (Kaufman et al., 2020), diabetes (Yang et al., 2020), cancer (Xue et al., 2022), and chronic inflammations (Iyer et al., 2022). Because of these threatening health impacts, the United States Environmental Protection Agency (2016), cited by Ahrens (2015, p. 443), established an *Air Quality Index* (AQI) that encompasses particle pollution breakpoints and health advisories to inform society about clean air standards (see Figure 5.6). In addition to air pollution health impacts, particulate matter also affects natural ecosystems by remaining in the atmosphere for some time, reducing visibility, and by being carried by the wind over great distances before particle concentrations settle on the water or the ground (Ahrens,

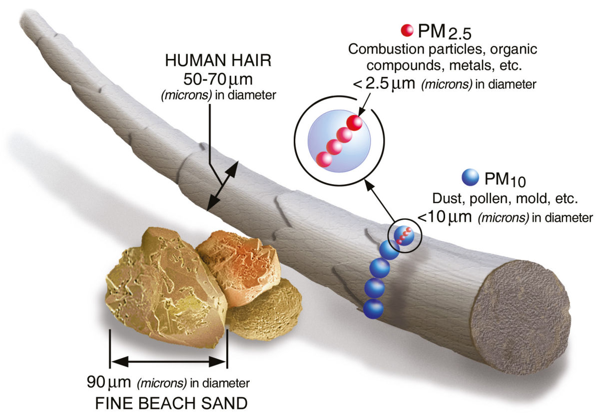


Figure 5.5 Size comparisons for PM particles. Retrieved from the United States Environmental Protection Agency (2016).

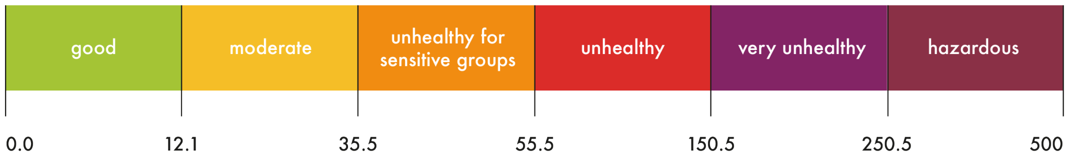


Figure 5.6 Air Quality Index (AQI) for revised breakpoints of PM-2.5 particle pollution (µg/m³, 24-hour average). Adapted from the United States Environmental Protection Agency (2016).

2015). Based on the findings, particulate matter appears to be a heterogeneous material that, on the one hand, is linked to health and environmental effects and, on the other hand, has characteristics that allow for a harmless and immediate interaction to validate the air quality driven feedback of an interface.

5.2 Design and Implementation

This section illustrates the design and implementation process of an entire system including the initial interface and a particle source to demonstrate the interaction with the air (see Figure 5.7).

5.2.1 Particle Source

Since airborne substances (e.g., solids, liquids, or gases) remain in the atmosphere for a long time and are unsuitable for a fast-changing interaction, this study considered a particle source to simulate a contaminated atmospheric environment, and thereby allowing for an immediate user interaction in an experimental setting. Based on the theoretical background and the experience that has been gained in a prior participatory design workshop (Broscheit et al., 2018a), the vapour from an e-cigarette was used to stage a particle source that manipulates the sensor measurements. The Eleaf iStick Pico 25 e-cigarette (85 W) from ELM Vaping with the nicotine-free basis liquid PG50/VG50 was chosen to simulate high particulate concentrations and thus to demonstrate the interface interaction.

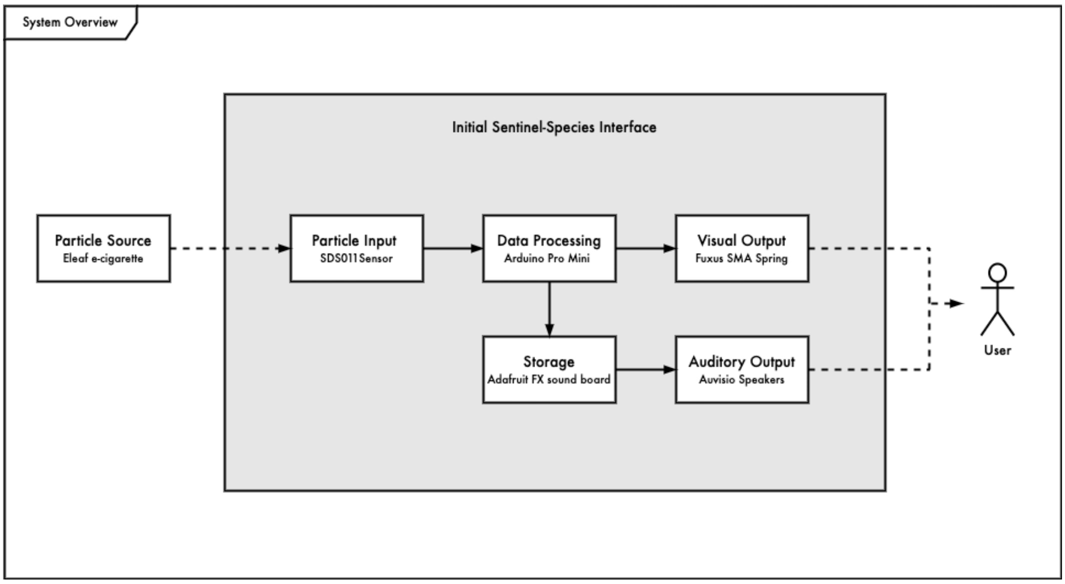


Figure 5.7 System overview.

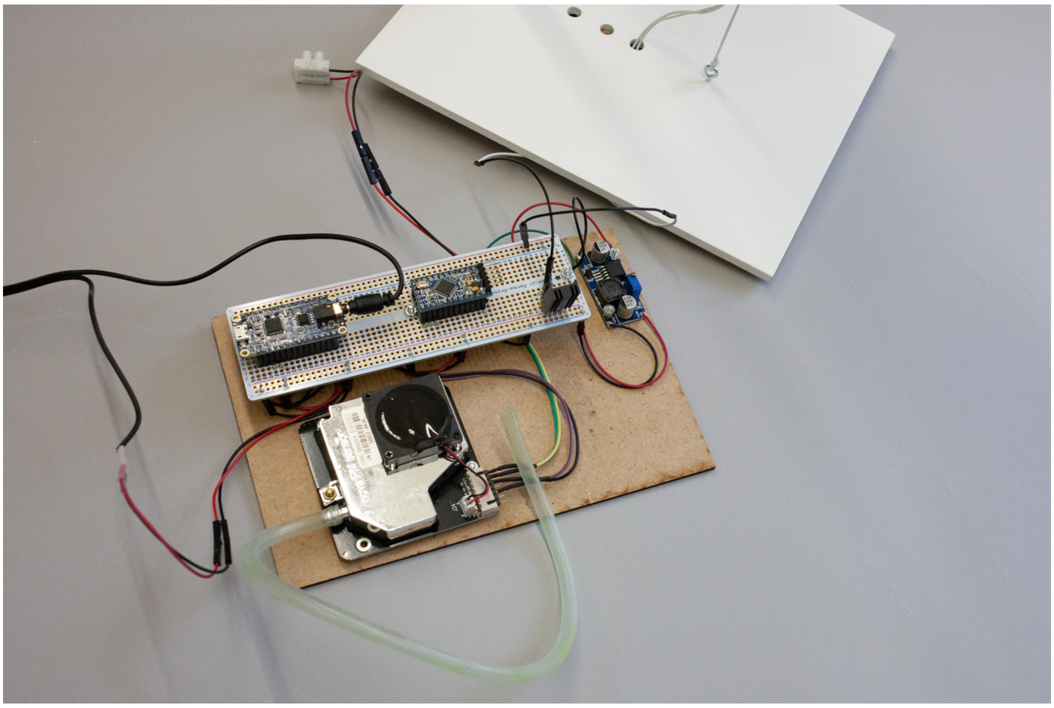
5.2.2 The Initial Interface

To develop the initial prototype,[1] this study used technical components, which were taken from the Creative Space for Technical Innovations (CSTI) inventory. The CSTI is equipped with a large stock of electronic components (e.g., microcontrollers, sensors, and actuators) to enable rapid prototyping of interactive technologies. The prototype kit of the initial interface consisted of the following components: an Arduino mini microcontroller, the Nova Fitness SDS011 particle sensor, the Fuxus shape-memory alloy (SMA) spring, the Adafruit fx sound board, and speakers (see Figure 5.8). What follows is a description of the design and implementation process.

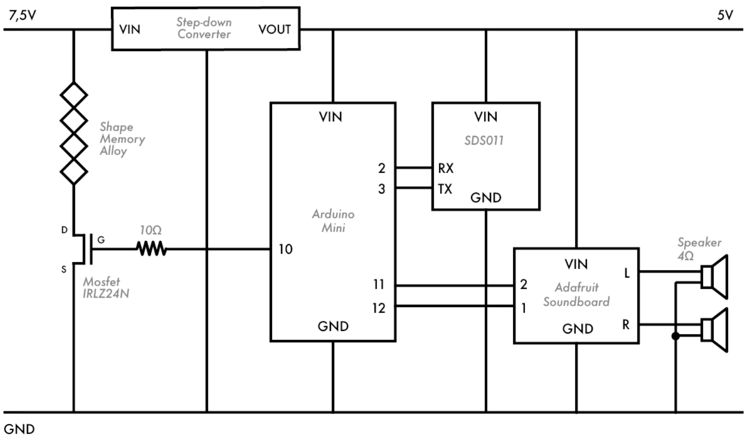
5.2.2.1 Input

To create an abstraction of a miner's canary that is sensitive to particle concentrations, this study investigated a suitable sensor. Since the PPD42NS dust sensor was used in a preliminary study and assessed as susceptible (Broscheit et al., 2018a), the

[1]The programming and assembly of the electronic components were carried out by Benjamin Salewski, who was supervised by the author.



(a)



(b)

Figure 5.8 (a) The assembled prototype kit and (b) the schematic diagram of the initial interface.

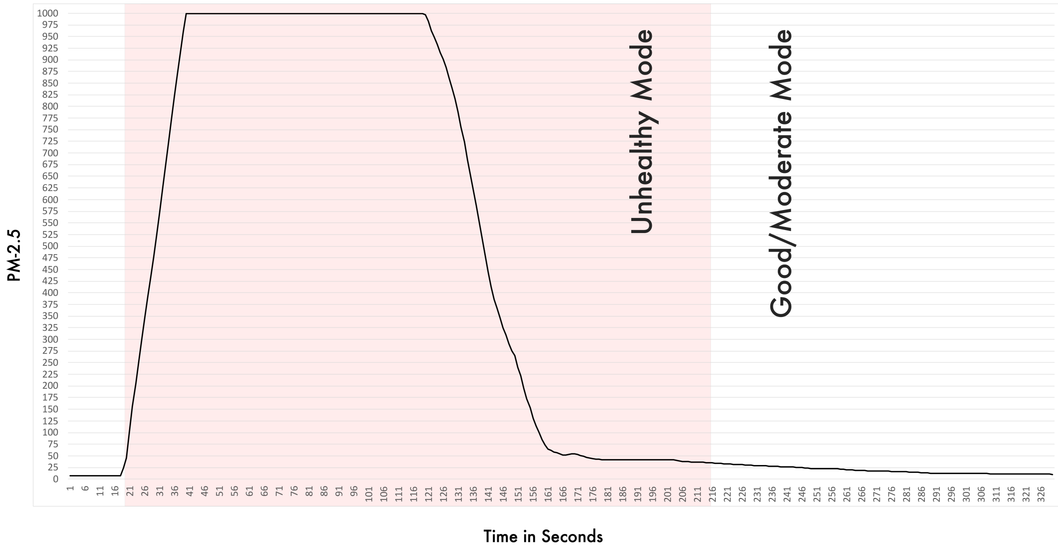
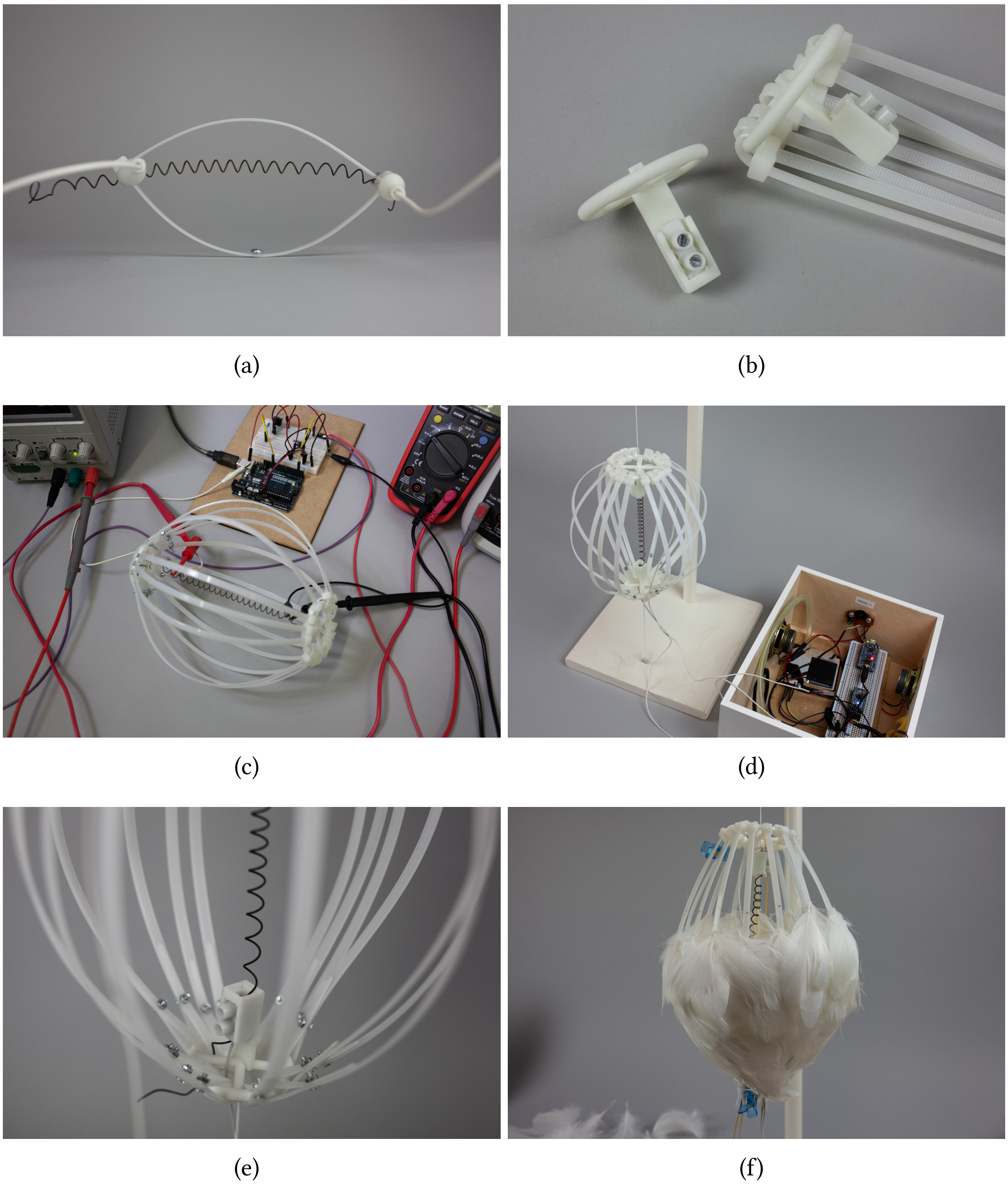


Figure 5.9 Data loggings of PM-2.5 concentrations measured per seconds, ranging from 0 to 999 μg/m³ and were triggered by nicotine-free vapour from an e-cigarette. In addition, the good/moderate mode (>35) and unhealthy mode (<=35) are highlighted.

successor particle sensor SDS011 from Nova Fitness was employed in this study. According to the data sheet, the sensor uses the principle of laser scattering to measure airborne particles ranging between 0.3 and 10 μm. The sensor transforms the scattered light into waveform signals that correlate with the particle diameters. The parameters of PM-2.5 and PM-10 can then be used for the data interpretation. In general, the sensor uses the UART serial communication protocol and runs on 5V power voltage. The dimensions of the sensor are 71 mm x 70 mm x 23 mm, and it weights 47 gramme. Unlike the PPD42NS sensor, the SDS011 sensor has a built-in fan that enables constant readings and stable particle circulation. In addition, the sensor has a response time of less than 10 seconds.

Drawing on the AQI for PM-2.5 particle breakpoints (see Figure 5.6), this study considered two interaction modes to mediate the state of the air: (a) a good/-moderate mode and (b) an unhealthy mode for sensitive groups (see Figure 5.9). The first mode signals a good/moderate air quality. When PM-2.5 values are less than 35 μg/m³, the prototype simulates a breathing and singing behaviour, represented as visual-auditory output. By contrast, the unhealthy mode signals a loaded



(a) (b)

(c) (d)

(e) (f)

Figure 5.10 Impressions from the prototyping process: (a) the exploration of the SMA spring, (b) the 3D-printed connection and cable ties, (c) the test of the SMA spring mechanism with the cable tie corpus, (d) the programming of the shape-changing corpus, (e) the kinetic cable tie construction driven by the SMA spring, and (f) the feathering process of the shape-changing corpus.

(a) (b) (c)

Figure 5.11 Different connections between the shape memory alloy spring and the electric cable: (a) an alligator clip, (b) a screw terminal, and (c) a screw terminal embedded in a 3D-printed holder.

atmospheric environment. When PM-2.5 values are less than or equal to 35 μg/m^3, the prototype stops the visual and auditory output. After determining appropriate thresholds, the environmental input was processed and interpreted by the microcontroller to control the visual and auditory output.

5.2.2.2 Visual Output

To represent the physiological behaviour and characteristics of the miner's canary as visual output, various shape-changing mechanisms and materials were explored to abstractly simulate a breathing bird. The experiments resulted in a cable tie construction driven by a shape memory alloy (SMA) spring for animating a feathered corpus (see Figure 5.10). SMA is an alloy with the material composition nickel-titanium that exhibits a shape-changing behaviour when heated – the so-called shape memory effect (Buljak and Ranzi, 2021). A shape memory effect can be achieved through the use of external heat and electrical current flow. With the initial interface, for example, the prefabricated SMA spring from Fuxus was used as a linear actuator that is heated by the electrical current flow (see Figure

Figure 5.12 Overview of different feathers available on the consumer market (e.g., rooster, goose, and ostrich).

5.10). When cold, the SMA spring is pulled apart by the tension of the rubber bands. However, when the SMA spring is heated, it shrinks back to its original shape. The SMA spring, with a resistance of approximately 0.75 Ohm, thus creates a silent and organic movement that dynamically changes the volume of the cable tie construction to achieve a shape-changing behaviour depending on the electrical current flow (see Figure 5.13). To connect the SMA spring to electric cables, alligator clips and screw-terminals were used during the prototyping process (see Figure 5.10). As the SMA spring showed a significantly faster response after the alligator clips were replaced with screw terminals, a measurement was taken.[2] To this end, a breadboard assembly with a stabilised 9V supply was used. When the SMA spring was activated by the electrical current flow, the SMA alligator clip system measured a voltage of 3.35V with a current of 4.47A, and the SMA screw terminal system measured a voltage of 5.22V with a current of 7.21A. Since the SMA screw terminal system exhibited a lower contact resistance, it was used to connect the SMA spring and the electric cables.

[2]The SMA measurement was conducted in cooperation with Prof. Dr. Thomas Lehmann.

Figure 5.13 The initial sentinel species-mimicking interface, entitled *Ivory*, by Broscheit et al. (2019). The interface measures particles in the near surroundings and aims to convey the detected information through the use of a feathered, shape-changing surface enriched with sound. The interface dimensions are 600 mm height x 200 mm width x 240 mm depth.

Based on this result, two circular holders were constructed in Fusion 360° and printed with white resin on the stereolithography 3D printer Formlabs 2 to hold the white cable ties (290 mm height x 5 mm width) and the SMA spring in position (see Figure 5.11). Thereafter, 16 white cable ties were attached around the circular holders and cut to a total length of 220 mm. Then, screws (3M, 10 mm) were used to hold the cable ties together.

Once the shape-changing construction was completed, feathers were used to cover the cable ties. The study examined different types of feathers available on

(a) (b)

Figure 5.14 When PM-2.5 values are less than 35 μg/m³, the species-mimicking interfaces simulates a breathing and singing behaviour: (a) the state of inhalation, when the SMA spring is heated, (b) the state of exhalation, when the SMA spring is cold.

the consumer market (e.g., goose, ostrich, and rooster). Although canaries are bred in different colours (e.g., white, yellow, red, brown, and black), a white, feathered surface was considered for the initial prototype to focus on the form and functionality before adding colours to the interface design. This also ensured that all components corresponded to one another in the first design cycle and that the interface could be visually assessed, as it stands out from darker backgrounds. For this reason, white goose feathers (80–120 mm length) were fabricated onto the cable tie construction.

To present the shape-changing, feathered corpus and to store the technical components, a wooden box (240 mm length x 200 mm width x 120 mm height) with a wooden pole (480 mm length x 150 mm height x Ø17 mm) was built. Additionally, holes were drilled for the sensors (Ø5 mm), speakers (Ø51 mm), and cables (Ø5 mm). The wood was then painted with white acrylic lacquer, and the feathered corpus was installed. To create some tension in the SMA spring and hence create a faster movement for the simulated breathing behaviour, white rubber bands were applied to hold the corpus in place (see Figure 5.12).

5.2.2.3 Auditory Output

To enrich the visual output with sound, this study employed an auditory output to inform users about the state of the environment. The Adafruit audio fx soundboard was used to generate an event-based notification with the aims of abstractly simulating a singing bird. To create the event-based notification, various audio files were produced with the program Ableton Live, a paid digital audio workstation (DAW) that is licensed to the author's personal account. In the DAW, the grand piano package was utilised to record A0 and A# notes. Then, the two notes were saved in .wav format and converted into a compressed .ogg format for transfer onto the Adafruit audio fx sound board with 2 MB storage (files: T01HOLDL.ogg [29 KB]), T02HOLDL.ogg [334 KB]). Lastly, speakers were removed from the Auvisio active stereo sound system for notebooks (4 Ohm, 8 Watt) and installed into

Table 5.1 Technical components and material of the initial prototype.

Item	**Description**
Components	
Arduino Pro Mini	microcontroller for digital signal processing
SDS011 sensor	to sense particles in the near surrounding
Fuxus SMA spring	to change the surface for visual feedback
Transistor	to control the SMA spring
Buck Converter	to regulate the power supply
Adafruit fx sound board	to store and trigger the sound files
Speakers	to play the sound for auditory feedback
Power supply	switching power supply, 4.5–12 V, 2,000 mA
Materials	
Feathers	white goose feathers, 80–120 mm
Wooden box	240 mm x 200 mm x 120 mm
Wooden pole	wooden pole, 480 mm x 150 mm, Ø17 mm
Resin	white resin V4
Cable ties	16 white cable ties, 290 mm x 5 mm
Elastic band	white elastic band
Tube	soft, transparent, plastic tube, 5/7.5 mm
Paint	white water-based acrylic lacquer

the wooden box to play out the sound.

5.3 Field Notes from Exhibition Spaces

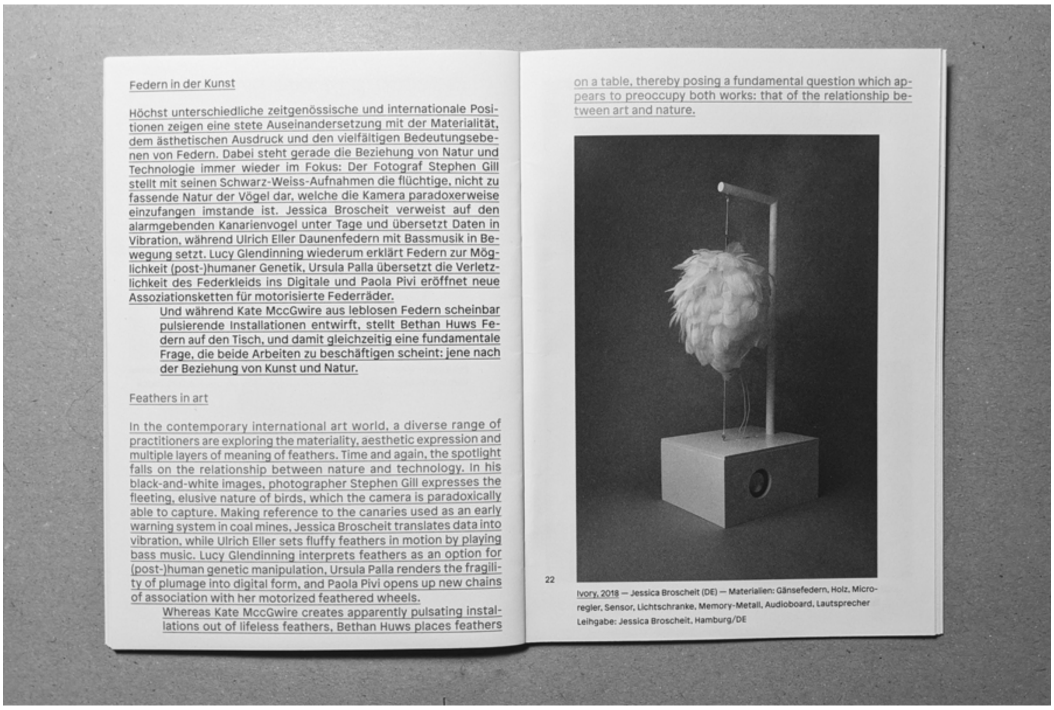
Different variations of the initial interface were presented in exhibition spaces to gain a first impression of how people engage with the interface in the cultural sector based on the author's first-hand observations. Notes from the author's personal experience are summarised in Sections 5.3.1–5.3.4 to illustrate the performance and limitations of the prototype. In addition, evidence was documented as visual material.

5.3.1 Gewerbemuseum Winterthur

The initial prototype was presented in the group exhibition *Feathers – warmth, seduction, flight* from November 30, 2019, to November 1, 2020, at the *Gewerbemuseum Winterthur* in Switzerland[3] (see Figure 5.13). In general, the museum focuses on presenting different materials and fabrication techniques. As a homage to the creatine-containing feather, the group exhibition explored the impact of the feather as a cultural artifact and the relationship between humans and birds. For this purpose, the author implemented a second edition, since the museum sought to present the running interface for one year. Although the author tried to follow the building instructions, the hand-crafted process has led to a slightly different appearance of the feathered, shape-changing surface. In addition, a video documentation was produced and exhibited next to the interface to convey the interaction to the audience. A link to the video documentation can be found at the end of this chapter. In summary, the interface ran for a year without any malfunction complaints.

[3] https://www.gewerbemuseum.ch/en/exhibitions/feathers-warmth-seduction-flight

(a)



Federn in der Kunst

Höchst unterschiedliche zeitgenössische und internationale Positionen zeigen eine stete Auseinandersetzung mit der Materialität, dem ästhetischen Ausdruck und den vielfältigen Bedeutungsebenen von Federn. Dabei steht gerade die Beziehung von Natur und Technologie immer wieder im Fokus: Der Fotograf Stephen Gill stellt mit seinen Schwarz-Weiss-Aufnahmen die flüchtige, nicht zu fassende Natur der Vögel dar, welche die Kamera paradoxerweise einzufangen imstande ist. Jessica Broscheit verweist auf den alarmgebenden Kanarienvogel unter Tage und übersetzt Daten in Vibration, während Ulrich Eller Daunenfedern mit Bassmusik in Bewegung setzt. Lucy Glendinning wiederum erklärt Federn zur Möglichkeit (post-)humaner Genetik, Ursula Palla übersetzt die Verletzlichkeit des Federkleids ins Digitale und Paola Pivi eröffnet neue Assoziationsketten für motorisierte Federräder.

Und während Kate MccGwire aus leblosen Federn scheinbar pulsierende Installationen entwirft, stellt Bethan Huws Federn auf den Tisch, und damit gleichzeitig eine fundamentale Frage, die beide Arbeiten zu beschäftigen scheint: jene nach der Beziehung von Kunst und Natur.

Feathers in art

In the contemporary international art world, a diverse range of practitioners are exploring the materiality, aesthetic expression and multiple layers of meaning of feathers. Time and again, the spotlight falls on the relationship between nature and technology. In his black-and-white images, photographer Stephen Gill expresses the fleeting, elusive nature of birds, which the camera is paradoxically able to capture. Making reference to the canaries used as an early warning system in coal mines, Jessica Broscheit translates data into vibration, while Ulrich Eller sets fluffy feathers in motion by playing bass music. Lucy Glendinning interprets feathers as an option for (post-)human genetic manipulation, Ursula Palla renders the fragility of plumage into digital form, and Paola Pivi opens up new chains of association with her motorized feathered wheels.

Whereas Kate MccGwire creates apparently pulsating installations out of lifeless feathers, Bethan Huws places feathers on a table, thereby posing a fundamental question which appears to preoccupy both works: that of the relationship between art and nature.

22

Ivory, 2018 — Jessica Broscheit (DE) — Materialien: Gänsefedern, Holz, Microregler, Sensor, Lichtschranke, Memory-Metall, Audioboard, Lautsprecher
Leihgabe: Jessica Broscheit, Hamburg/DE

(b)

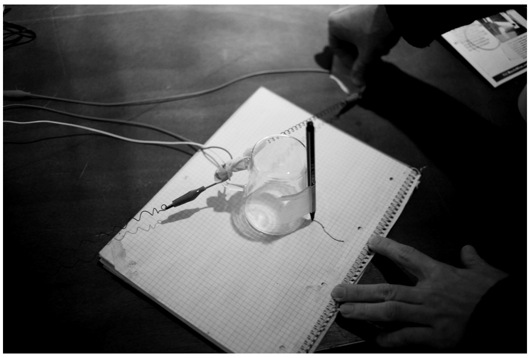
Figure 5.15 The initial interface and the video documentation were presented in the exhibition *Feathers – warmth, seduction, flight* from December 1, 2019, to November 1, 2020, at the *Gewerbemuseum Winterthur* in Switzerland: (a) the exhibition space and (b) the exhibition catalogue.


(a)


(b)


(c)


(d)


(e)


(f)

Figure 5.16 Impressions from the solo exhibition *Hybrid of Atmospheres – The Song of the Pale Ones* and the accompanying participatory workshop: (a) and (b) display the main artifact in the exhibition space, (c) details the feathered corpus triggered by vapour from an e-cigarette, (d) illustrates visitors interacting with the artifact through their cigarette smoke, and (e) and (f) present SMA experiments from the participatory workshops.

5.3.2 Faktor Gallery

As part of the solo exhibition *Hybrids of Atmospheres – The Song of the Pale Ones*, the author built and presented a significantly larger version of the initial prototype (feathered corpus: 500 mm height) with an evolved data-driven sound installation at Faktor Gallery[4] in Hamburg, Germany, February 8–10, 2019. Aside from the main interface, the solo exhibition presented different artworks to mediate environmental concerns, such as air quality, by using the metaphorical representation of the miner's canary (see Figure 5.15).

During the exhibition's opening, the interface was triggered through vapour from the e-cigarette as a staged performance. The audience was thus able to observe the interaction. After the general smoking ban was lifted in the late evening, some people started to interact with the interface through their exhaled cigarette smoke (see Figure 5.15d). After approximately half an hour of people smoking and triggering the main interface, the gallery filled up with smoke, and the sound varied between the thresholds. Because of the loaded air, the main interface represented a distorted audio sequences over a long period of time before it collapsed. This situation sparked a discussion about the environmental condition and led to someone opening the door. Through the resulting atmospheric circulation, the interface triggered the first threshold of good air quality again. In addition, the author offered personal guided tours to explain the concept behind the installation to the audience. Moreover, the author collected some statements from exhibition visitors, which are translated from German into English below:

> "Welcome to dystopia." "Nightmare and fairy tale between 'technological disaster and saviour' with chance and mutation." "Her aesthetically and gracefully appearing works of purest white, however, cast dark, much larger shadows on the galleries' walls and projections of our time. Puffing up as if into dark clouds on the horizon. It is here

[4] https://faktor.hamburg

> where anxieties and dusty industrial age mechanisms meet the vision of 'utopia and mutation'." "What fascinates me most about the 'breathing' objects is the analogue, organic feeling that is conveyed by the special actuator technology of the Nitinol wires. When you bring sensor values from the digital world into these 'analogue' hybrids and then link that with sounds, the result for me is a very natural, almost sensual impression of the object." "The keyword is goosebumps. You feel it, and you see it; you understand how it works. Absolutely amazing!"

As part of the exhibition, the author also conducted a participatory design workshop to encourage interested people for eco-technological approaches. To this end, a prototyping kit was developed that included the SMA spring. Then, a total of six participants signed up for the workshop and explored various mechanisms and limitations of controlling the SMA spring (see Figure 5.14e–f).

5.3.3 Tempe Center for the Arts

Another version of the initial interface was presented within a group exhibition to the TEI community on March 19th, 2019 at the Tempe Center for the Arts in Arizona, the United States. Due to travelling by plane, the author built a modular display especially for this conference exhibition. All parts of the modular display could be disassembled and packed into a suitcase. As the voltage in the United States is lower than in Europe, a voltage regulator had to be organised. In addition, the code for controlling the shape memory alloy had to be adjusted according to the indoor climate at the venue. While the interface was being set up, the auditory output was noticeable in the exhibition space. After the audience filled the exhibition space, the sound was barely audible and could no longer be adjusted because the volume control was installed inside the box. Moreover, the interaction through the use of the vapour from the e-cigarette could not be performed due to

Figure 5.17 The author discussing with researchers from the community the interface presented at the TEI conference art track exhibition. Photo: Cyn Szuyuliu and Aehong Min.

the venue's smoking restrictions. Despite the technical challenges, the author was able to discuss the functional interface with the ACM TEI research community. During the discussion, the author received positive feedback on the metaphorical representation along with recommendations for technical improvements, such as employing sound processing and a surface transducer.

5.3.4 St. Catherine's Church

The initial interface was also presented within the group exhibition *Clear River, Calm Sea*[5] from November 21 to December 11, 2022, at the St. Catherine's Church in Hamburg, Germany (see Figure 5.18). As part of *China Time* – a partnership event between the cities Shanghai and Hamburg – the exhibition was curated by Bettina Freimann and sponsored by the Hamburg Ministry of Culture and Media. The exhibition presented positions from Chinese and German artists exploring the

[5]https://clearrivercalmsea.com

(a)

(b)

Figure 5.18 (a) The initial interface in the exhibition space at St. Catherine's Church in Hamburg, Germany, and (b) the author exhaling vapour on the artifact to demonstrate the interaction.

relationship between the individual, nature, and society. Referencing the Chinese expression, "peace can only reign in the universe when the rivers are clear and the seas are calm", the exhibition title describes a utopia in which the forces of nature are once again in harmony.

Before the exhibition opening, the current flow controlling the SMA spring had to be adapted to the church's room climate to achieve the desired shape-changing behaviour. Then, during the exhibition opening, the author presented the interface and demonstrated the interaction as part of a guided tour. For this purpose, the author was allowed to use the e-cigarette, filled with nicotine-free liquid, to exhale the vapour onto the interface (see Figure 5.18b). Afterwards, the author had several discussions with people from the audience. In these discussions, one guest wanted to know how to interact with the artifact directly and speculated about various approaches. In addition, it seems that people connected with the miner's canary metaphor. As the exhibition was presented in the church, the audience included both culturally interested people and regular church visitors.

5.4 Discussion

This section presents a discussion of the research implications, further recommendations, and study limitations.

5.4.1 Implications

This study presented the design and implementation of an initial interface that mimics a sentinel species, more specifically the miner's canary, for raising awareness about the environment by being sensitive to particle concentrations. In this section, the implications of this study are outlined in regard to the interface design, environmental awareness, and interspecies relationships.

5.4.1.1 Interface Design

This section discusses the design of the initial interface and the technical components. First, to demonstrate an interaction with the interface, this study utilised an e-cigarette based on the author's prior studies (Broscheit et al., 2018, 2021a) and the definition of particulate matter by Ahrens (2015). The data loggings (see Figure 5.7) show that the vapour produces high particle concentrations that affect the sensor measurements. However, these extreme particle concentrations do not comply with the regulations of the air quality index (see Figure 5.4) and cannot be compared with measurements in the field. Nevertheless, they provided promising outcomes in staging a contaminated environment for an immediate user interaction. Unfortunately, first observations in exhibition spaces revealed the limitations of staging high particle concentrations indoors. Due to fire and smoke restrictions in some exhibition spaces, future studies could investigate other devices that can be used as particle sources for demonstrating the interaction.

Second, to create a sentinel species-mimicking interface that is sensitive to particulate matter pollution, the SDS011 particle sensor was used as input to measure the concentrations from the particle source (see Figure 5.6). Although a continuous data stream was provided, the sensor is unfortunately quite large (dimensions: 70 mm x 55 mm x 21 mm). Further research could test additional sensors that are smaller and suitable for physical prototyping.

Third, to interpret sensitive physiological behaviour, a feathered, shape-changing surface enriched with sound was implemented as visual output. The fabrication of this surface was an underestimated challenge. The creation of the surface is a time-consuming activity involving handcrafting, which led to slightly different outcomes each time. As the alligator clips and screw terminals also showed significant differences in their contact resistance, further research could focus on developing efficient connections between SMA springs and electric cables and optimising the power consumption. Moreover, although the life-like and silent movement of the SMA spring is aesthetically pleasing, the linear actuator presented a number of limitations that affected the moving behaviour of the feathered corpus. The interpretation of the breathing behaviour, for example, depends on various physical factors (e.g., room temperature, tension, and resistance). Thus, the movement of the shape-changing corpus does not depend on a design decision but rather on the physical circumstances. Although the presentation of the interface in exhibition spaces confirmed that the SMA spring is quite durable, different room temperatures affected the behaviour of the SMA spring, and the code to control the SMA spring thus had to be adapted for each venue. Further research on the visual output could (a) focus on the connection between the shape-changing construction and feathers, (b) explore the movement spectrum of the SMA, (c) optimise the power consumption, and (d) develop a self-calibrating system.

Lastly, to provide a multisensory experience, the visual output was enriched with sound. The Adafruit soundboard was used to store sound files for the auditory output. Due to the limited soundboard storage of 2 MB and the prototyping speakers, the audio performance was limited in terms of composition and frequency spectrum. While not all sounds that were tested worked as auditory sensations, the piano sound was chosen to interpret a singing bird because this sound was supported by the resonance of the wooden box. Further research could replace the speakers with a surface transducer or external speakers in the room to achieve a cleaner appearance of the display without holes on the sides. Moreover, functional buttons (e.g., volume control) were needed during the presentation in exhibition spaces to adjust the loudness of the auditory output. A next iteration could consider (a) different types of speakers for a high-quality reproduction of sound, (b) volume control, and (c) the translation of sensor measurements into sound by drawing on the concept of sonification.

5.4.1.2 Environmental Awareness

Regarding the concept of sentinel species (O'Brien et al., 1993), the miner's canary was used as a metaphor for creating an interface that aims to raise awareness about the environment through its physiological behaviour of breathing and singing. Unlike related studies that have presented, for example, living pigeons that monitor the environment with attached sensors (da Costa, 2006) and the *Canary in a Coalmine* GUI illustrating environmental statistics (Smid et al., 2011), this study used the canary as a metaphorical representation to develop an abstraction for the culturally interested society. For this purpose, the development of the interface included both the interpretation of the canary's physiological behaviour, such as breathing and singing, and the use of feathers as material references to convey the state of the air on a multisensory level. A feathered, shape-changing corpus enriched with sound was fabricated to mimic an abstract life form that interprets a breathing and singing bird sensitive to particle concentrations in the near surroundings. Overall, the high-fidelity prototype provided a functional initial interface to convey the state of the air on a sensory and cognitive level. While the sentinel species-mimicking interface was exhibited in the cultural sector and discussed with the scientific community (see Section 5.3), it showed promising directions towards a discursive object that engages with individuals. Following Dunne and Raby's concept of critical and speculative design (2014), this study envisions great potential for the interface to become an object of debate for raising awareness about the environment and addressing environmental concerns in the cultural sector.

5.4.1.3 Interspecies Relationships

Referring to Haraway (2016), this section reflects on the social encounter between people and the sentinel species-mimicking interface. As the author observed in exhibition spaces, some visitors interacted with the interface by using their cigarette smoke and others commented on the organic feeling of the interface. Based on the observations and discussions that took place in the exhibition spaces, it seemed that people understood the metaphor of the miner's canary and could connect with the mental model.

5.4.2 Recommendations

Although the observations and discussions yield promising insights, the author recommends changing the type of interaction from manipulating a stationary interface into exploring a changing environment with a body-worn interface. After presenting the interface in exhibition spaces, the author found that visitors are generally viewed the interface from a certain distance. To allow visitors a bodily experience with the state of the air, this study recommends the development of a body-worn interface and the investigation of another device that can be used as a particle source to stage an immediate interaction with the air. In this way, visitors could become explorers and experience a changing atmosphere with their own body. This somaesthetic approach (Höök et al., 2015; Shusterman, 2008) could increase one's engagement with and awareness of their own body in relation to the world.

5.4.3 Limitations

The sentinel species-mimicking interface, titled *Ivory*, served as a proof of concept to get a first impression of its potential, which was evaluated technically and through initial field observations. For the development of the proof of concept, electronic equipment from the CSTI was used for the prototyping process without comparing alternative components. Although a selection of motors was available, the SMA spring was the first actuator of choice based on its silent and smooth behaviour. In addition, the Adafruit soundboard was used to trigger sound files according to the PM thresholds and to test the impact of the multisensory feedback. Due to the rapid prototyping process used to test the overall concept of a sentinel species-inspired interface, conducting a systematic comparison of alternative components was beyond the scope of this study. Since the initial interface provided promising insights, further research could consider the comparison of different components, such as the shape-changing mechanism, particle sources, sensors, and alternative audio platforms, to refine the prototype kit.

5.5 Summary

This chapter presented an initial sentinel species-mimicking interface developed on the basis of the conceptual framework. This involved the design and implementation of a high-fidelity prototype that uses the metaphorical representation of a sentinel species, in particular the miner's canary, to interpret the physiological behaviour of breathing and singing. In addition, first observations revealed insights into how the interface performs in exhibition spaces. Overall, the interface offered promising directions to convey the state of the air through the metaphorical representation of a sentinel species. However, this study recommends further research on the interface that enables an exploratory and bodily experience with environmental information. In summary, this chapter provided the following contributions:

- Background information about both sentinel species and particulate matter pollution
- The design and implementation of a functional prototype that aims to represent air quality by interpreting the physiological behaviour and characteristics of the miner's canary
- Measurements of sensor loggings
- Field observations in exhibition spaces

Parts of this chapter were published in Broscheit et al. (2019) and cited in Broscheit (2020), Broscheit et al. (2021b), and Broscheit et al. (2021a). In addition, video documentations of the initial interface and SMA tests were published in the author's personal media library[6][7].

[6]Broscheit, Jessica (2018), Ivory, Retrieved May, 2022 from https://vimeo.com/281624662
[7]Broscheit, Jessica (2022), SMA, Retrieved October, 2022 from https://vimeo.com/758316536

Chapter 6

ONYX – The Body-Worn, Sentinel Species Interface

This chapter presents a sentinel species interface that aims to provide a bodily experience for exploring a field of particle concentrations. The following sections describe the design and implementation process of the body-worn, sentinel species interface to be used in a speculative art installation (6.1), the user experience research (6.2), discuss the findings (6.3), and conclude with a summary (6.4). To date, the work discussed in this chapter has been published in Broscheit (2020) and Broscheit et al. (2023).

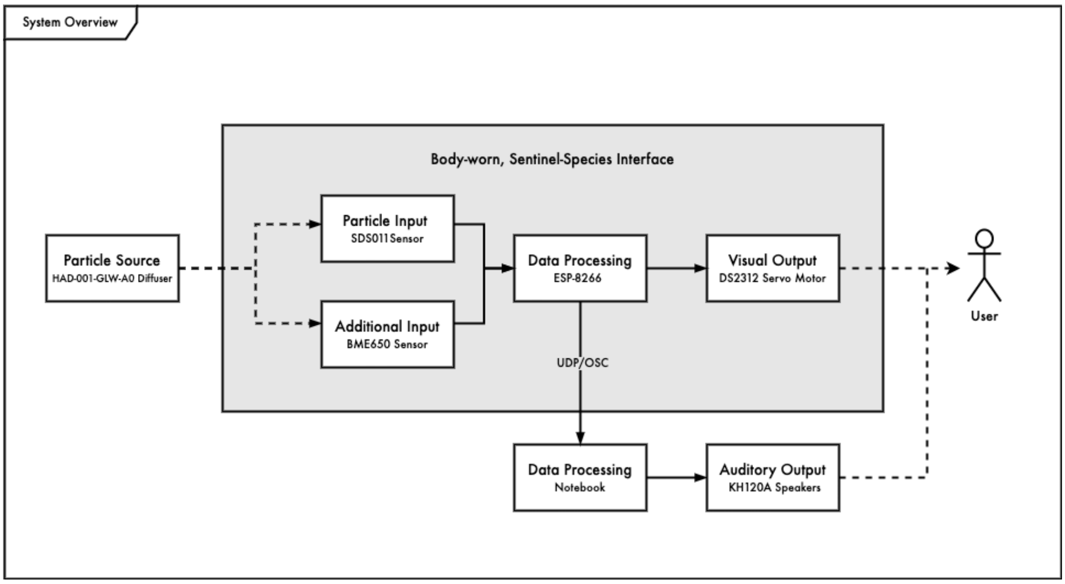


Figure 6.1 System overview.

6.1 Design and Implementation

Based on the recommendations of the previous study *Ivory*, this study envisions the miner's canary as an interface metaphor to invite individuals to explore the state of the air in a speculative art installation, and thereby drawing attention to ecological concerns, such as air pollution, in the cultural sector. This section illustrates the design and implementation process of an entire system that includes the body-worn, sentinel species interface and a particle source to explore a loaded atmosphere in an experimental setting (see Figure 6.1).

6.1.1 Particle Source

Based on the results of the previous study (see Chapter 5), an alternative particle source had to be found that allows users to explore high particle concentrations. Different devices for exhausting particle concentrations were thus investigated and tested (e.g., a fog machine, an ultrasonic diffuser, and electronic components to build an ultrasonic diffuser). The ultrasonic diffuser HAD-001-GLW-A0, made by the brand MUJI, was chosen. Then, the mist from the ultrasonic diffuser and the

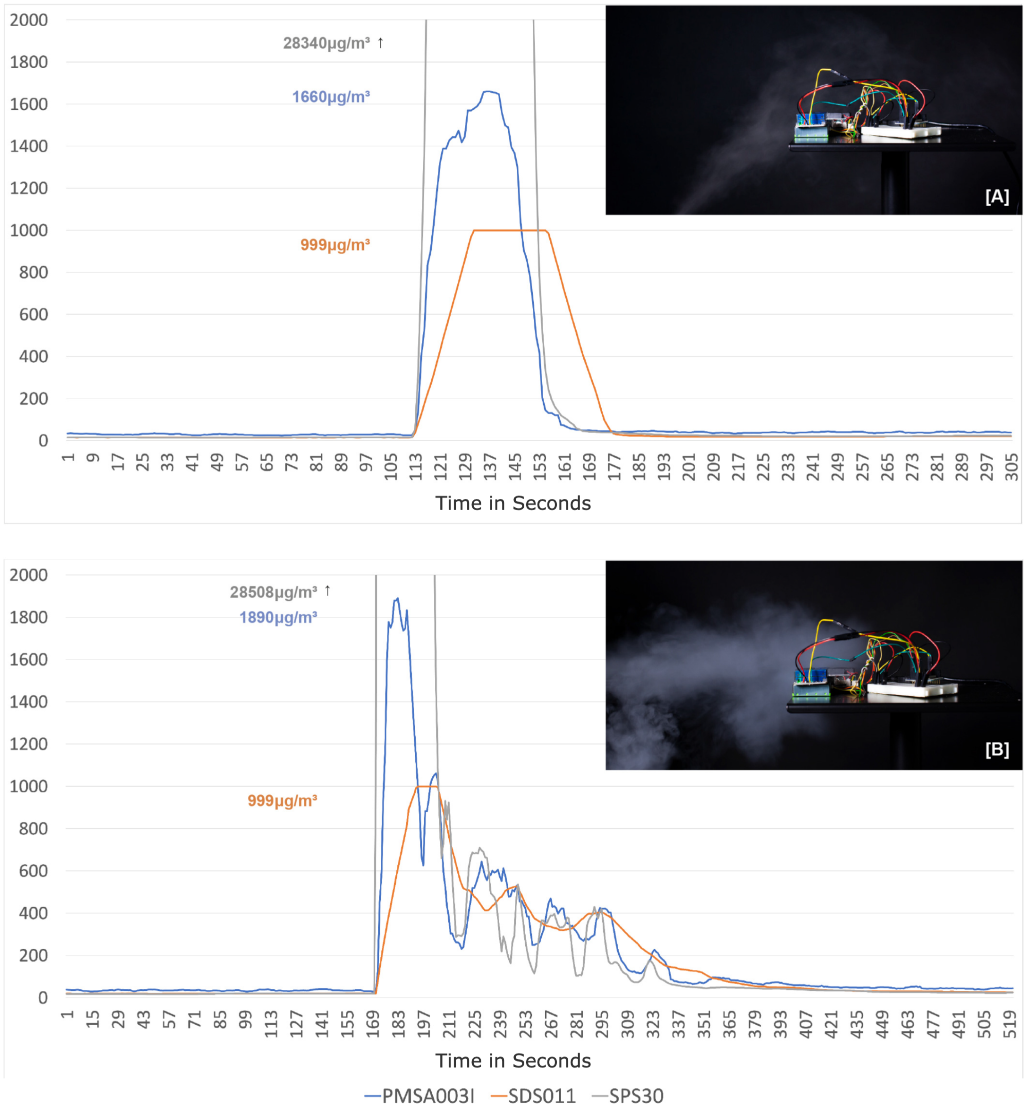


Figure 6.2 Comparison of PM-2.5 sensor readings per second, provided by the ● SDS011, ● SPS30, and ● PMSA003I sensor. (a) Sensor readings that were triggered with mist from the ultrasonic diffuser. The SPS30 measured 28.340 µg/m³, while the PMSA003I measured 1.660 µg/m³, and the SDS011 reached the maximum value of 999 µg/m³. (b) Sensor readings that were triggered with vapor from an e-cigarette. The SPS30 measured 28.508 µg/m³, while the PMSA003I measured 1.890 µg/m³, and the SDS011 reached the maximum value of 999 µg/m³.

vapour from a nicotine-free e-cigarette were compared (see Figure 6.2). Unlike the thick vapour from an e-cigarette, the diffuser uses ultrasonic waves to vaporise water into cool, dry mist. As depicted in Figure 6.2, the vapor from the e-cigarette is thick and lasts much longer in the atmosphere than the mist from the diffuser, thus causing longer delays in the interaction. Therefore, the commercially available ultrasonic diffuser was chosen as a permanently running source to simulate a field of high particle concentrations, thereby enabling an immediate interaction between people and the state of the environment. Moreover, since the water-based particle concentrations from the diffuser are harmless to the human body and do not trigger fire alarms indoors, they can be used in an experimental setting.

6.1.2 The Body-worn Interface

The second interface generation considers a bodily experience through which users can explore a dynamic atmospheric environment within a speculative art installation. For doing so, the interface was informed by the conceptual framework (see Chapter 4) and the initial interface (see Chapter 5). Some of the basic requirements from the initial interface were retained to develop an abstraction of a sentinel species, in particular the miner's canary, that is sensitive to the particle concentrations. Instead of developing a sculptural artifact, such as *Ivory*, or placing canaries in cages, as with miners (see Chapter 5), the intention was to create a critical yet aesthetic position in the form of an interface that illustrates a bodily connection between human and non-human species. The design of the interface therefore also had to consider different body types and to ensure that it was robust and safe for use in both user research and in exhibition spaces. Sections 6.1.2.1–6.1.2.3 describe the design and implementation process.

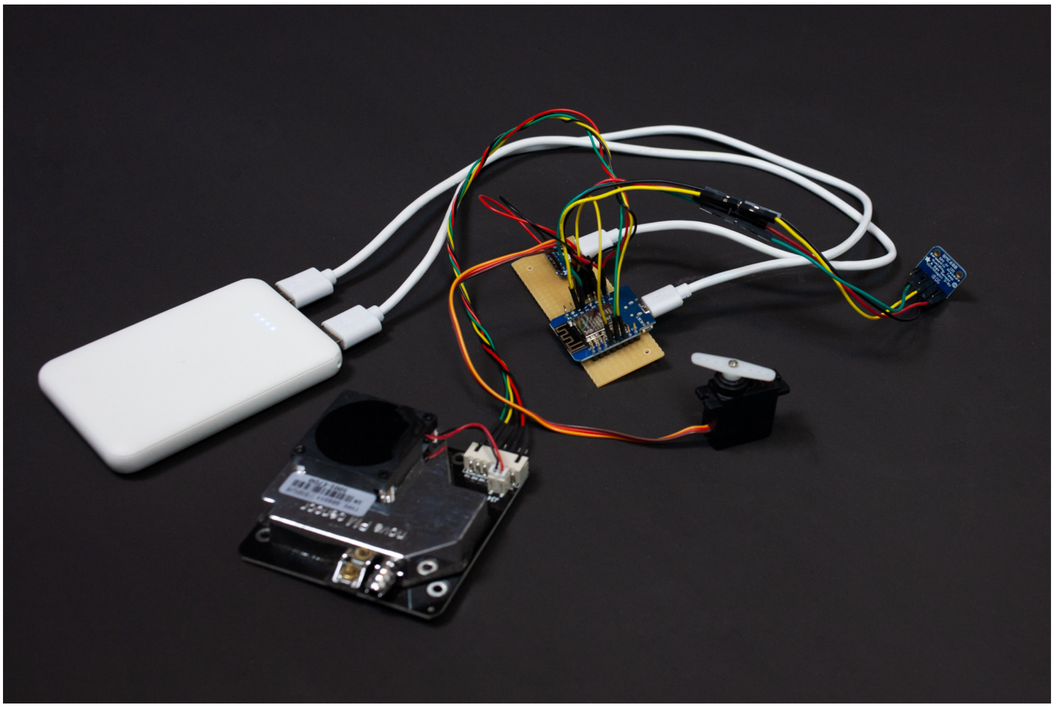
6.1.2.1 Input

Following the recommendations from the previous study on *Ivory* (see Chapter 5), in this iteration different optical particle sensors were compared in terms of the data sheets (see Table 6.1). The Nova Fitness SDS011, Sensirion SPS30, and Plantower PMSA003I were eventually selected for testing with mist from the ultrasonic diffuser and vapour from the e-cigarette (see Figure 6.2). A breadboard assembly was built to record PM-2.5 measurements every second. First, the sensors were triggered with mist from the ultrasonic diffuser (see Figure 6.2a). Then, the sensors were triggered with vapor from an e-cigarette (see Figure 6.2b). Although the SDS011 particle sensor is slightly larger than the other sensors and exhibits a delay of a few seconds, the sensor was chosen again based on (a) the smoothed data points and (b) the tube adapter connection. As an alternative, the Sensirion SPS30 sensor is recommended, which showed promising results compared with the PMSA003I sensor. In addition, the Adafruit BME680 sensor was selected for data triangulation; this sensor measures temperature, humidity, barometric pressure, and VOC gas via a I^2C and SPI digital interface and is suitable for a 3.3V or 5V microcontroller. Together, both selected sensors can provide readings on PM-10, PM-2.5, temperature, humidity, barometric pressure, and VOC gas.

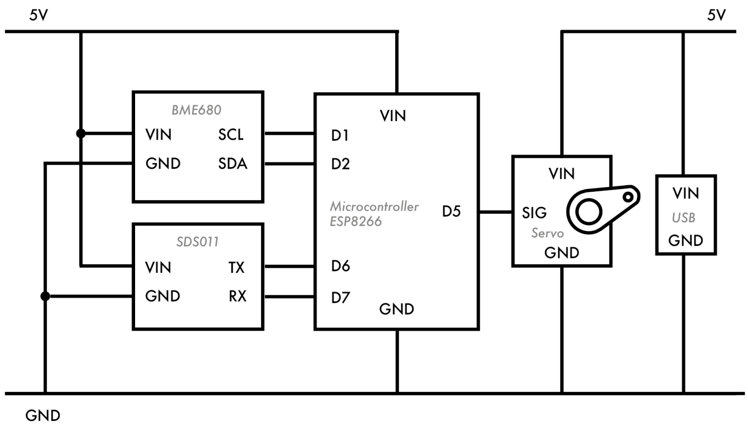
To process the environmental data, a prototype kit was developed after comparing different sensors (see Table 6.1), motors (see Table 6.3), and audio platforms (see Table 6.4). The prototype kit (see Figure 6.3) includes a microcontroller D1 MINI ESP-8266 with on-board Wi-Fi, the Nova Fitness SDS011 particle sensor, the Adafruit BME680 sensor breakout board, the Adafruit microUSB breakout board, the MASTER DS2312 MG servo motor with metal gear, and the Evary 5,000 mAh power bank with two USB output ports (5V, 2.0A). The data was processed and

Table 6.1 List of particle sensors for physical prototyping.

Item	Description
Seeed PPD42NS	59 mm x 45 mm x 22 mm, 28g, 5V
Nova Fitness SDS011	70 mm x 70 mm x 22 mm, 47g, 5V
Plantower PMSA003I	51 mm x 35 mm x 14 mm, 21g, 5V
Sensirion SPS30	41 mm x 41 mm x 12 mm, 26g, 5V



(a)



(b)

Figure 6.3 (a) The assembled prototype kit and (b) the schematic diagram of the body-worn interface.

interpreted on the microcontroller to control the visual and auditory output, as detailed below.

6.1.2.2 Visual Output

Similarly to the initial interface, *Ivory* (see Chapter 5), a feathered, shape-changing corpus was considered as visual output that mimics the breathing behaviour of a bird. In contrast to the initial interface, this iteration had to represent a broader range of dynamics and had to be placed in a visible position on the user's body. The implementation process of the visual output is detailed next.

To simulate the breathing characteristics of a bird, a modular shape-changing structure was tailor-made out of white goose feathers (see Figure 6.4). Unlike the kinetic construction of *Ivory*, the aim here was to develop a soft textile surface that could be used as a modular design element. An auxetic structure was chosen, which is known for its deformable properties. According to Lim (2015), auxetics materials are solids that are characterised by a negative Poisson's ratio. Lim (2015, p. 1) further explained that "when materials are stretched in one direction, they contract in the direction transverse to the loading direction". This flexible characteristic supports an organic motion, which serves as the basis for the feathered surface. The auxetic structure was fabricated out of white foam rubber and finished with white goose feathers (see Figure 6.4b). The material swatch was then placed in a box, and different motion characteristics were investigated (see Fig-

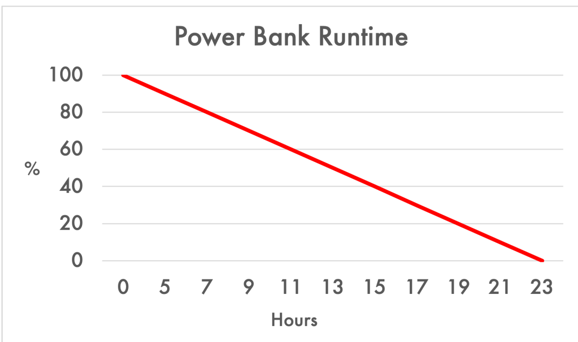


Figure 6.4 Power bank runtime at a low servo motor speed.

(a)

(b)

(c)

Figure 6.5 Fabrication process of the modular shape-changing structure: (a) the material swatch of the feathered, shape-changing surface to explore the movement behaviour; (b) the fabrication of the feathered-auxetic structure; and (c) a close-up of the feathered-auxetic structure.

ure 6.4a). For this reason, the author observed her own respiration and classified three breathing rates according to PM-2.5 thresholds: (a) relaxed, (b) signs of distress, and (c) stressed behaviour. The shape-changing surface interprets a relaxed behaviour when PM-2.5 values are less than 25 μg/m³, signs of distress through faster movement when PM-2.5 values are greater than or equal to 25 μg/m³, and stress through very fast movement when PM-2.5 values are greater than or equal to 600 μg/m³. Based on this classification, the feathered surface was animated us-

(a) (b) (c) (d) (e) (f)

Figure 6.6 Impressions from the prototyping process of the sentinel species-mimicking interface: (a) the paper prototype, (b) fabric case with zipper, (c) integration of sensors and servo motor, (d) placement of the auxetic structure, (e) feathering process, and (f) the final interface.

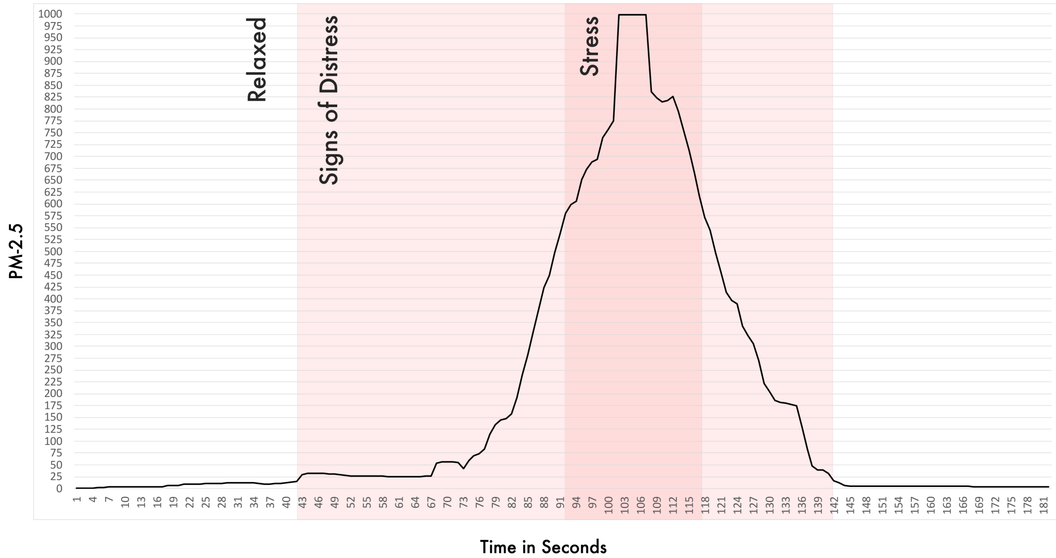
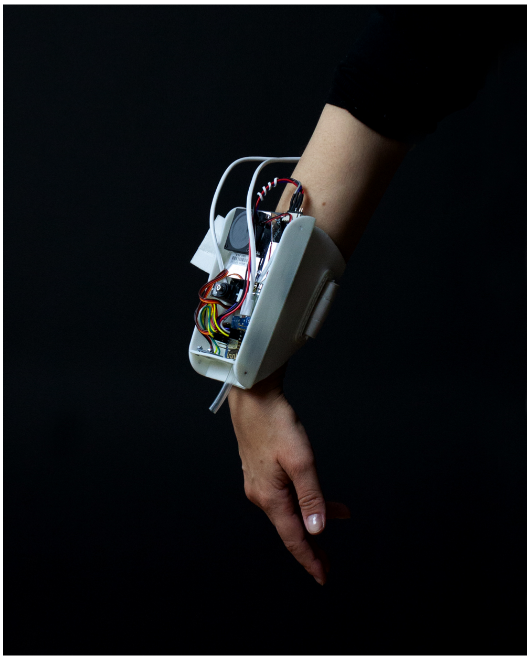


Figure 6.7 PM-2.5 values measured per second, ranging from 0 to 999.9 $\mu g/m^3$ and were triggered by a diffuser. The three conditions for (a) relaxed (>25), (b) signs of distress (<=25), and (c) stress (<=600) are highlighted according to the measurements.

ing a servo motor programmed from 0 to 90 degrees at different speeds to simulate the three breathing rates according to the PM-2.5 thresholds (see Figure 6.7). For example, when the particle concentrations are high, the feathered, shape-changing surface mimics a rapid breathing rate to indicate stressful, air-gasping behaviour.

Once the modular shape-changing structure was created, the design and implementation of the body-worn interface commenced. In contrast to the stationary system *Ivory* (see Chapter 5), where technical components can be stored in a box, with the body-worn interface, all technical components must find their place on the human body. Therefore, *one-size-fits-all* devices were investigated that are suitable for different body types. Adjustable body mounts and fashion accessories, available on the consumer market, served as a source for inspiration and were classified as follows (see Table 6.2).

After the one-size-fits-all classification, a self-test was conducted to access the visibility of different positions. Nine dots (Ø 50 mm) were cut out of paper and placed on the author's upper body according to the position of the above-mentioned adjustable body mounts. The author then explored and assessed the



(a)

(b)

(c)

(d)

Figure 6.8 Iterations of the body-worn interface: (a) a proof of concept to test both the electronic components on the human body and the interaction with the particle source and (b–d) illustrate three design options of the prototypes created during the design process.

dots. Through exploration of the dot-covered body, the marked forearms were perceived as the most visible and practical position. The right forearm was then defined for the interface's position from the perspective of a right-handed person. To test the chosen body position, the technical components were attached on the forearm and the author interacted with the particle source at the beginning of the design process (see Figure 6.7.a). This bodily experience confirmed that the arm is a prime position to recognise a changing behaviour.

Once the forearm was established as the position for the interface, the sizing had to be determined. Since size charts for forearm girths range between 21 cm and 35 cm, random samples from 14 colleagues (five female and nine male) were collected to determine an average size that could be used for the construction of the interface. The measurements resulted in a range from 23 cm (minimum) to 31 cm (maximum), with an average value of 26.8 cm. The results served as reference values for the fabrication of the body-worn interface.

Several interface designs were then sketched based on the investigated one-size-fits-all devices. As the visual impact between the sketch and the three-dimensional object made a considerable difference, three design options were chosen and implemented: (a) an arm bracer, (b) a prosthesis, and (c) a muff (see Figure 6.7b–d). The

Table 6.2 List of one-size-fits-all items.

Body parts	**Item**
Head	headsets, head straps, hearing aids, glasses, and helmets.
Neck	hands-free phone holder.
Arm	wristbands and armbands for mobile phones, arm bracers, muffs, watches, gloves, skater elbow pads, protheses, and shoulder under arm bags.
Chest	chest-mounted straps for cameras and heart rate sensors, protective vests, and chest bags.
Waist	belt and hip bags.
Legs	knee pads and drop-leg holsters.

Figure 6.9 The final body-worn interface with the particle source.

muff-inspired construction was ultimately chosen as the interface design for the following reasons (see Figure 6.7d). First, the interface inspired by an arm bracer (see Figure 6.7b) was found to be too functional and not provocative enough. Second, the prosthesis-inspired interface (see Figure 6.7c) illustrates the bodily connectedness of human and non-human species in the form of an extreme item that is not easy to wear. By contrast, the muff-inspired interface (see Figure 6.7d) represents the connection between human and non-human species, and it demonstrates an ease and robustness of usage.

Table 6.3 List of actuators.

Item	Description
Plastic Gear Servo	EMAX ES08A II, 8,5 g, 23 x 11,5 x 24 mm, 4,8-6V
Metal Gear Servo	MASTER DS2312 MG, 13 g, 23 mm x 12 mm x 25 mm, 4,8-6V
Linear Micro-servo	DS15, 1.9 g, 21.4 mm x 12 mm x 6 mm, 3.7-5V
Step Motor	28BYJ-48, 40 g, 31 mm x 27 mm x 19 mm, 5V
Step Motor	SANYO SS2502-8040, 150 g, 50 mm x 50 mm x 16 mm, 5.9V

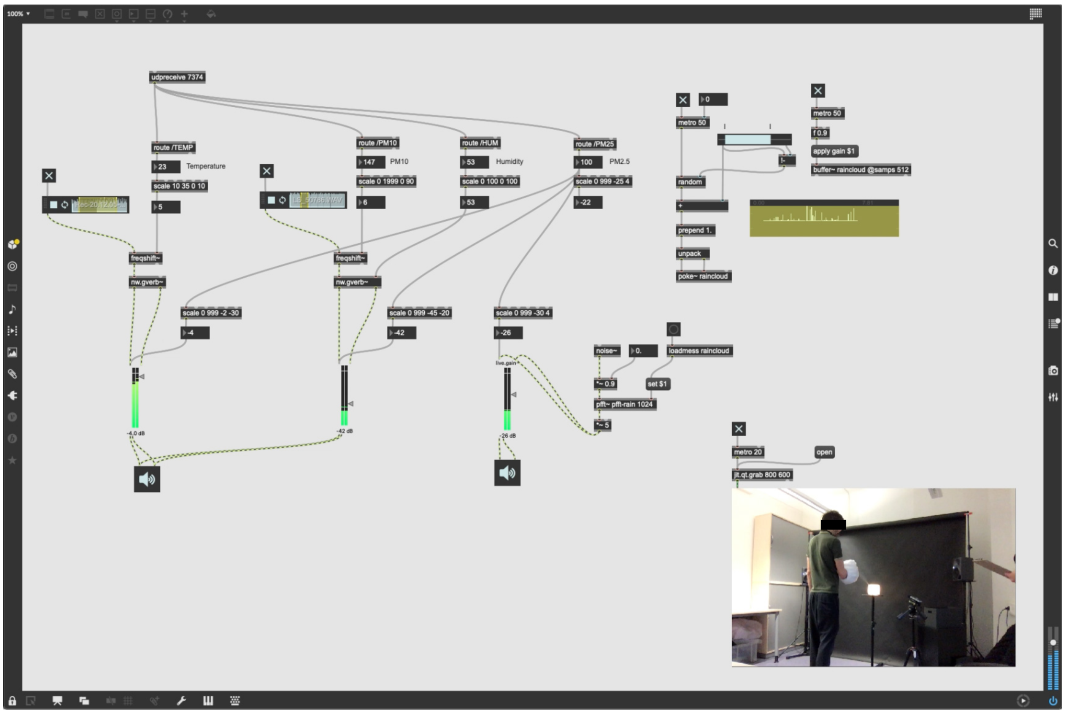


Figure 6.10 A screenshot from the Max/MSP patcher.

6.1.2.3 Auditory Output

To enrich the visual output with sound, data-driven auditory output was considered that relates to the concept of sonification for interpreting a singing bird based on real-time data. Kramer et al. (1999, p. 3) defined the term *sonification* "as the use of nonspeech audio to convey information. More specifically, sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation." Unlike the initial interface, *Ivory*, which supports single event-based sound information (see Chapter 5), the auditory output of this iteration maps the parameters of environmental information directly into real-time and high-resolution sound. To this end, various audio platforms were investigated. After testing of the audio platforms (see Table 6.4), the Max/MSP software was chosen for presenting a high-resolution and data-driven sound as ambient media, which can also be perceived by potential spectators in an exhibition space. The main reason for choosing Max/MSP was to reduce the technical components on the wearable to create a robust, lightweight, and small prototype with low power consumption for use in a bodily experience. Max/MSP is a modular programming software from Cycling'74 that generates audio, video, and code. It is a paid-for software and licensed to the author's personal account. The software was used to translate the environmental data into sound, which was processed on the microcontroller of the body-worn interface by utilising user datagram protocol (UDP) and open sound control (OSC) within a shared network. OSC is an open data transport specification for real-time message communication; it is used for sound and multimedia devices (Wright et al., 2003). The UDP then enables packet-switched computer communication within the network (Postel, 1980). After Max/MSP received the real-time data stream of PM-2.5, PM-10, relative humidity, and temperature from the microcontroller, the information has been mapped into compatible numbers for controlling frequencies of the audio composition (see Figure 6.10). The audio composition encompasses two oscillating states depending on the sensor readings. The first state comprises low-pitched frequencies, indicating a relaxed and harmless environment, while the second state comprises high-pitched particle frequencies that signal a harmful environment. With regard to data mapping, the temperature, ranging from 10°C to 35°C, was

Table 6.4 List of audio platforms.

Audio Platform	Description
Mozzi	Audio library for Arduino and Teensy microcontroller
Adafruit sound board	A board to trigger sound files 2/16 MB Flash
Teensy board	Embedded computing platform for interactive audio projects
Bela board	Embedded computing platform for interactive audio projects
Super Collider	Open-source software for algorithmic audio synthesis
Pure Data	Open-source software for for multimedia projects
Cycling'74 Max 8	Software for audio-visual projects

Table 6.5 Technical components that were used for the development of the entire system, and all materials that were used for the design of the body-worn interface.

Item	Description
Components	
Microcontroller	D1 Mini ESP8266 for digital signal processing and connectivity
SDS011	Particle sensor for sensing the near surroundings
BME680	Sensor for sensing additional data for cross referencing
Servo	MASTER DS2312 MG to animate the shape-changing surface
Micro USB	Adafruit MicroUSB breakout board to power the servo separately
Notebook	For programming the audio software
Cycling’74 MAX	Audio software for musical sonification
Speaker	Two external Neumann active speakers
Diffuser	MUJI, HAD-001-GLW-A0 ultrasonic diffuser for affecting the sensors
Power Supply	5,000 mAh Evary powerbank with two USB output ports (5V, 2.0A)
Materials	
Feathers	White goose feathers, 80-120 mm
Felt	White felt; 900 mm x 1200 mm x 2 mm
Leather	Natural vegetable tanned leather; 400 mm x 300 mm x 1,2–1,4 mm
Foam Rubber	White foam rubber, 210 mm x 297 mm x 2 mm
Elastic Bands	Transparent thermoplastic elastomer elastic band, 90 mm x 6 mm
Tubular Rivets	Metal tubular rivets, Ø7,5 mm, 3–4mm
Zipper	White zipper, 30 cm
Resin	Formlabs, white (v4a)
Hook-loop tape	White hook-loop tape; 1.20 m x 20 mm
Buttons	Metal sew-on snap fasteners, Ø11 mm
Yarn	Various types of white yarns for machine and hand sewing
Bolt/Nut	Diverse bolts, nuts, and washers; M2 x 6–12 mm
Tube	Soft, transparent, plastic tube; 5/7,5 mm
Finnboard	Finnboard; 700 mm x 1000 mm x 1.5 mm; 745 g/m^2
Paper	Brown kraft paper roll, 96 cm x 30 m, 130 g/m^2

mapped as numbers from 0 to 10. Large PM-10 particles that range from 0 to 1999 μg/m3 were mapped as numbers from 0 to 90. Small PM-2.5 particles that range from 0 to 999 μg/m3 were mapped as numbers that range from -27 to 4. The relative humidity, ranging from 0 to 100%, was mapped as numbers from 0 to 100. Finally, the Max/MSP software played the data-driven sound over two Neumann KH120A active loudspeakers, connected to the notebook via a DMX cable.

6.2 User Experience Research

After a body-worn, sentinel species-mimicking interface was created and various approaches for interacting with air components were explored, this study evaluated the outcome as a prototypical arrangement in a laboratory setting to obtain a first impression of a user's experience during an interaction. Sections 6.2.1–6.2.5 present information about the entire setting, participants, data collection, data analysis, and the findings, respectively.

6.2.1 Setting

Similarly to the exhibition *Hybrid of Atmospheres* (see Figure 5.15), a dark ambience with a central, illuminated particle source, and an omnipresent sound was envisioned as a speculative art installation to provide an immersive experience that invites culturally interested people to explore the space with the sentinel species-mimicking interface on their bodies. However, to test the arrangement before presenting it in the cultural sector, this study followed a previous study on evaluating interactive art (Höök et al., 2003) and used a laboratory to provoke participants' reactions. The prototypical arrangement included the body-worn interface, the particle source, a notebook with a camera and microphone, two external active loudspeakers, an audio recorder as backup, tripods, and a black background to visualise the mist of the diffuser for video recordings and to avoid visual disruptions for the participants (see Figure 6.8).

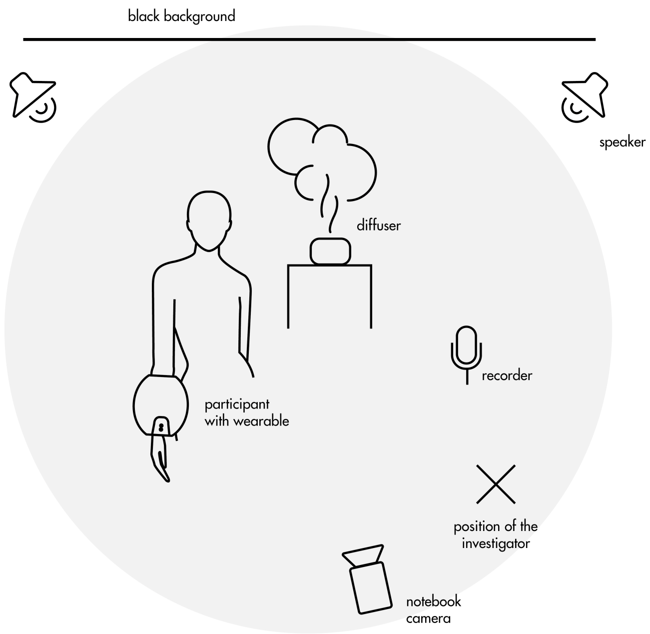


Figure 6.11 Overview of the setting.

6.2.2 Participants

To engage with culturally interested people, individuals were recruited via an email distribution list and word of mouth. The announcement outlined basic information about the provisional title, general task, duration, and location of the study. In addition, the anonymous and confidential data collection process was highlighted. Participants qualified if they expressed an interest in having an experience with a body-worn interface within a multimedia installation. There were a total of 14 participants (six self-identified as male, five as female, and three as non-binary) aged between 19 and 53 years (mean = 39, median = 42, SD = 11.4). All participants volunteered and agreed to participate in the user study with their declarations of consent. To ensure ethical research practices, the university's ethics committee approved this user study. In addition, a number was assigned to each participant when summarising the findings to protect their anonymity.

6.2.3 Data Collection

The data collection was tested with colleagues (n = 2) from the Hamburg University of Applied Sciences' computer science department as a pilot study on November 3, 2021. Thereafter, some minor adjustments were made (e.g., adjusting the sound volume and the stand height for the particle source). The user study was then conducted with 14 participants in the German language from November 8 to November 25, 2021. The principal investigator informed each participant about the overall procedure, provided the information sheet, and guided the participants in signing the consent form. The investigator then invited the participants to place the body-worn interface on their preferred arm and asked them to explore the mist from the diffuser. Mixed methods were applied for the data gathering, including the thinking aloud technique for collecting verbal data about the participants' cognitive processes while interacting in the setting. If there was silence for 15–60 seconds, the investigator reminded the participants to produce verbal data during the interaction. As the participants explored the setting, audio-visual material and sensor loggings were gathered for data triangulation with the software Max/MSP, which was then screen captured on the notebook (see Figure 6.10). After approximately one to two minutes of exploring the setting, the investigator commenced with the semi-structured interview to ascertain participants' perspectives through conversation while the participants were still in the setting. After completing the task and removing the body-worn interface, participants had to answer a Likert-scale questionnaire to collect their measurable opinions. Each run took 15 to 25 minutes, in which multiple forms of data were gathered. Based on these qualitative and quantitative datasets, a content analysis was performed and is detailed later in this chapter (see Section 6.2.5).

6.2.4 Data Analysis

Overall, the data analysis included verbal data, the questionnaire, and the triangulation of data. First, the verbal data was transcribed in German. Then, the data was manually coded by following Saldaña's coding methods (2013). Through the use of the initial coding process, a first impression of the collected dataset was gained. The second cycle utilised axial coding to cluster the initial codes into categories (see Table 6.5). To organise the axial coding process, this study drew on Mekler and Hornbæk's (2019, p. 1) theoretical framework for meaningful interaction. Their framework originates from the psychological literature on meaning and can be used to analyse HCI research. It consists of the following five components: (a) "connectedness", (b) "purpose", (c) "coherence", (d) "resonance", and (e) "significance". After the coding process was completed, the participants' quotes were translated from German into English. In addition, the verbal data was supported with by closed-ended data from the Likert-scale questionnaire. All questionnaires were digitalised and illustrated as diagrams. Lastly, the recorded visual material and the sensor loggings were used to ensure the internal validity of the qualitative research.

6.2.5 Findings

In this section, the findings were structured in relation to the aforesaid five components of meaningful interaction (see Table 1) and the results of the Likert scale were illustrated separately (see Figure 7).

6.2.5.1 Connectedness

According to Mekler and Hornbæk (2019), meaning arises from aspects of the self and world with which the individual is connected. This study accordingly highlights associations with the body-worn interface that seem to arise from the participants' personal lives. Four participants had associations with their pets, such

Table 6.6 Overview of the initial codes that were structured into axial codes. The axial codes refer to Mekler and Hornbæk's framework on meaningful interaction (2019).

Axial Codes	Initial Codes	Definition
connectedness	association	associations with the interface that might originate from participant's personal lives (e.g., animals, nature, and culture).
resonance	interface design	associations that were directly linked to the interface.
	empathy	participants showed signs of empathy towards the interface.
	functionality	statements about the functionality in general.
	shape-changing surface	statements about the visual output.
	sound	statements about the auditory output.
	materiality	expressions about the materiality.
purpose	augmentation	statements about cognitive and bodily augmentations, including environmental awareness.
	application	speculations about potential applications.
coherence	awareness	visions about interfaces for ambient awareness and healthcare.
	personalized	visions towards an individual interface design.
significance	worldview	participant's worldview.
	pandemic	statements about the perception of air during the pandemic.

as cats and a horse. P3 said: "I quickly established a connection with this artifact. Almost like with a cat." Two other participants mentioned movies and documentaries. P2 was amazed and stated: "Welcome to *Blade Runner*." P9 associated the situation with the usage of a "Geiger counter". Another two participants referred to fashion. P10 stated: "Above all, I find it simply beautiful. It has almost something of a luxury item. It has something of a Gucci piece." In contrast, two participants mentioned objects from the medical sector, such as a "prothesis" (P2) and "health equipment in the hospital" (P11). Finally, three participants had associations with an experience in nature. P7, for example, stated: "I am immediately in nature. I don't have the feeling that I'm standing here with you in a studio, that's gone right away."

6.2.5.2 Resonance

Resonance denotes a direct and non-reflected response to an immediate experience (Mekler and Hornbæk, 2019). In the following, this study summarizes the participants' immediate experiences and observations made by the principal investigator.

In general, it was observed that all participants put on the body-worn interface without any hesitation, and that the interface was straightforward in its usage. In addition, it was noted that the body-worn interface was suitable for left- and right-handed users, and could be worn on a forearm circumference up to 30 cm. However, participants with a forearm circumference of 30 cm were able to wear the interface, but they had an imprint on their skin after the user study. P10 commented: "It's not bad at all."

Most of the participants showed signs of care and empathy. For example, when the artifact was in a state of stressed condition, P1 commented: "Now it [artifact] sounds very excited. Do you like it, or do you not like it?" P3 said: "Come on now, calm down a bit. I'll calm down, too...Yes, I don't like to hold the [artifact] in the [mist] anymore." P5 explained: "When he [artifact] breathes so hectically, so quickly, then I'm just a bit stressed and would rather take him out of the smoke so that he can calm down again." P10 stated: "And you also feel a bit sorry. Because I think it's almost like panting now ... So it's not a relaxed breathing, that's why you worry a bit." In addition, three participants asked if they could pet the wearable. P10 said: "Now it's more relaxed, it feels nicer to me. Is it possible to pet it?" Moreover, four participants wanted to keep the artifact. P3 stated: "I'll take you [artifact] with me!" This study also identified that participants associated the interface as a kind of living being. P8 said: "I have a living being on my arm." Moreover, the artifact was often identified as bird species, such as "chicken" (P2, P4, P9, P13, P14), "swan" (P7), and "ptarmigan" (P8). Lastly, P8 stated: "Well, that's a bird for me, of course. A ptarmigan."

In general, the findings indicate that the visual output conveyed the state of the air (see Figure 7), and most of the participants seemingly interpreted the dynamic breathing behaviour as a kind of warning signal about the mist. P3 stated: "It can be assumed that in this constellation, this steam is not good for the little animal." P5 said: "that he [artifact] does not get enough air and then alarms." P6 stated: "The whole thing [artifact] acts like a living organism that reacts accordingly [to the mist] ... As if it had, so to speak, I say, breathing difficulties, when it comes into the fog." P14 commented: "I noticed that it [artifact] gasps for air when I get closer to it [mist]." In contrast, a minority of participants (n=2) did not recognize the conceptual model and interpreted the artifact's behavior as a kind of need for inhaling the mist. P8 pondered: "Okay, he or she [artifact] probably doesn't really like the fog. Or, he or she is reactivated. It can breathe, it can inhale."

In contrast to the visual output findings, the auditory output was not perceived as dominant by the participants (cf. Figure 7a and b). First, the unintentional noise produced by the servo motor inside the artifact was the dominant sound source for some participants. Moreover, a few users were so focused on the body-worn interface's behaviour that they did not noticed the changing ambient sound at all and were even surprised when they had to answer these questions after the procedure. P9 said: "Ahhh, I didn't get that at all...Now, in retrospect, it comes to me." And P3 stated: "So far, I've left that [ambient sound] completely out of the story." Overall, it seems that the sound source on the body-worn interface supported the warning behavior for some participants. P5 said: "When he [artifact] is in the smoke, it's more stressful. Because he breathes a bit more with sound." And P7 noted: "It sounds a bit stressed." However, the ambient sound that aims to represent good air quality was mostly perceived as relaxed and calm, with the following participant descriptions: "dreamy and as if from another world" (P11), "feel-good sounds" (P6), and "meditative, spherical sounds" (P12). Furthermore, the ambient sound for high particle contaminations was not perceived as so clearly and did not evoke any associations with threatening particles. P12 described these sounds as "artificial, exaggerated sounds of nature."

Furthermore, two unintended haptic outputs were identified. One haptic output was mentioned by three participants, who recognized a vibration on their skins coming from inside the wearable. P4 said: "It is very gentle, but I think you can definitely feel it." P9 stated: "I feel like it's affecting my skin." The other haptic sensation was identified by P2, who enjoyed the cool mist from the diffuser at his fingertips and expressed: "This cold, of course, is a total blast."

Two participants highlighted the impact of the feathers. P3 stated: "And then these very beautiful feathers...That's the fragility of course, it's very beautiful." And P13 explained: "If it [artifact] wasn't simply feathery and feathered, and had some other surface structure...I would not consider it as a species or say that it lives." In addition, to the statements about the feathers, P6 noted: "It's definitely nice and warm, just a little scratchy [inside the artifact]." Lastly, P10 said: "It's quite massive, I can feel the weight now."

6.2.5.3 Purpose

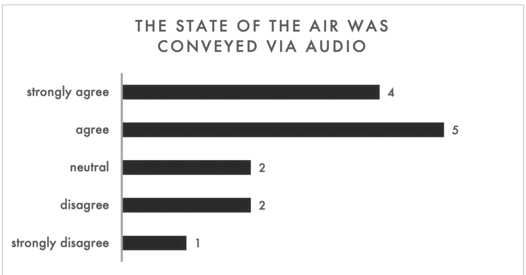
Purpose can be seen as a motivational and future-oriented component of meaning (Mekler and Hornbæk, 2019). Below, we outline participants' speculations about the intended usage of the body-worn interface. Five participants communicated their awareness about the cognitive and bodily augmentation. P1 noticed "an extension of my perception." P3 said: "I think it's a super cool idea to make something perceptible or visible that is otherwise not perceptible or visible." P7 stated: "You don't have to go out into nature and climb mountains or walk on the beach, you can also experience nature in spaces with installations like this." P2 commented: "I have a very weird VR experience without glasses." P10 expressed: "I don't know if I have a bird on my arm or if the bird is part of me. That's what I find interesting right now." Although the participants did not directly identify an augmentation on particulate matter, they speculated about various air components, such as "aerosols" (P3), "CO2" (P8), "pollutants" (P12), and the "density of air" (P14). P12 concluded: "Well, against pollutants or things in the air symbolized by this mist."

6.2.5.4 Coherence

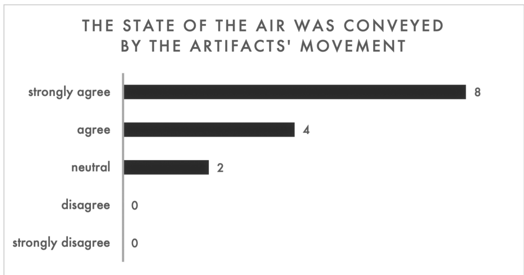
Coherence in this context refers to how participants would envision a system to make it meaningful to them (Mekler and Hornbæk, 2019). Several participants imagined applications for ambient awareness, such as systems for "weather forecast" (P3), "CO2" (P6), "air quality" (P9), and "corona" (P14). Additionally, other participants suggested concrete applications for personal health care. P6 stated: "For asthmatics. So particulate matter pollution or something like this." P5 envisioned a system that also detects vital data of the body and said: "So not only whether there is enough oxygen in the air but also checks the body." P11 imagined a system that detects "volume level," "stress,“ and "maximum load" but also reflected critically on his opinion, and said: "On the other hand, I'm not sure I could still move as freely as I do now if I had one of those things that warns me against particulate matter, for example." Moreover, two participants considered a system that augments their senses on emotions. P3 imagined: "It would be totally exciting if something like that could react to people' moods." And P7 stated: "A warning system for other people's moods and also for my own." Some of the participants also had several ideas regarding how they would personalized the wearable‘s design. For example, P10 said: "I would like it to sit on my shoulder. Like a parrot." P14 noted: "I would like it to be tighter." P5 commented: "That's a bit too big to take with you all the time." P6 envisioned an assistance system, "but not in such - let me say pompous dimensions."

6.2.5.5 Significance

To explore significance, this study used the body-worn interface as an opportunity to ask participants about their worldviews and perceptions of air during the global pandemic. A common worldview among twelve participants was that "humans are

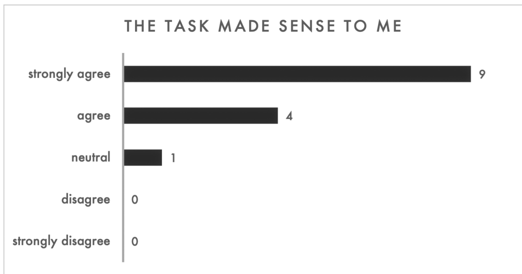


(a)

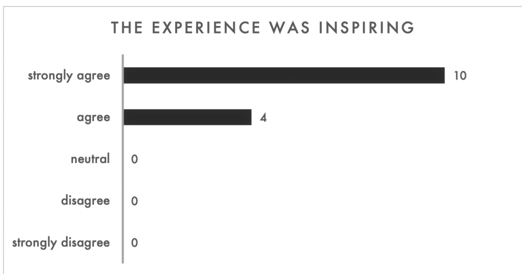


(b)

(c)



(d)



(e)

Figure 6.12 Results of the Likert scales.

part of nature." P6 explained the statement as follows: "If you look at nature as the natural evolution of all kinds of processes here on this planet, I would say we are part of nature ... In my opinion, we have not yet reached transhumanism. But we are at least heading towards that possibility." Moreover, eleven participants also shared experiences regarding how the pandemic changed their perceptions of air. P1 said: "I knew before [the pandemic] that there were viruses and stuff floating around, but I had never considered that to be a society-changing threat." Additionally, some participants mentioned their awareness for polluted air. P3 commented: "Unpleasant and toxic or harmful odours are more noticeable to me." P4 stated: "With the mask, I felt that the air was more polluted than I thought." P8 noted that her breathing habits had changed due to the pandemic and that she sometimes "dare to breathe" and somehow forgotten "that deep breathing." P10 shared an experience of having a "panic attack" during the lockdown, and P12 reported a "general feeling of alertness" when being indoors.

6.3 Discussion

This section presents a discussion of the research implications, further recommendations, and study limitations.

6.3.1 Implications

This study presented the development and evaluation of a body-worn interface that draws on the concept of a sentinel species, more specifically the miner's canary, for raising awareness about the atmospheric environment through its physiological behaviour and materiality. This section outlines the implications of this study in regard to the interface design, environmental awareness, and interspecies relationship.

6.3.1.1 Interface Design

First, the practice-based contributions were differentiated from those of previous studies. The study *Ivory* (Broscheit et al., 2019, see Chapter 5), for example, provided a sculptural interface which imitates a living organism that detects the atmospheric environment in the near surroundings. On this basis, a body-worn interface was developed for use as a discursive object in the cultural sector. Whereas *Ivory* was placed into the environment, a speculative art installation was presented in this study as a bodily combination of human and non-human species capable of exploring the air. In contrast to the previous study (*Ivory*), this study made different design decisions to create a body-worn interface that is sufficiently robust for use in both a user study and an exhibition space.

First, the shape memory alloy spring was replaced with a servo motor to achieve different breathing speeds and to reduce the power consumption. Second, instead of a kinetic construction, a modular, shape-changing textile was created and integrated in various design options. The development of this modular, shape memory textile afforded the study to have an agile design process because the author could use the module to test different design options and sizes. Third, as an extension to the event-based sound information in the previous study (*Ivory*), a real-time, data-driven auditory output was composed that directly maps the parameters of environmental information in high-resolution sound.

The measurements of PM-2.5, PM-10, and relative humidity allowed for a dynamic sound composition. The temperature, however, did not change significantly, although the mist from the diffuser had a lower temperature than the room. For the presentation of the auditory output, external speakers were selected to create an immersive ambient sound. Unfortunately, this decision created two sound sources (motion noise from the servo motor and the composition from the external speakers based on actual data), which participants perceived differently. As an advancement of the previous study (*Ivory*), the body-worn interface not only provided a multisensory experience with air in the form of dynamic material and sound but also triggered unexpected haptic sensations through the mist and servo motor vibrations. Moreover, the runtime of the power bank lasts approximately 23 hours at low servo motor speed. This is enough time to present the body-worn interface in an exhibition space without changing the power supply. Lastly, in contrast to related works have presented body-worn interfaces in the wild (e.g., Kim et al., 2010; Molga, 2016), this study created a prototypical arrangement of a speculative art installation that generates a highly concentrated particle field for human–atmosphere interaction. This provoked a reaction from the participants to evaluate their experience, as discussed in the following sections.

6.3.1.2 Environmental Awareness

Regarding the concept of sentinel species (O'Brien et al., 1993), this section discusses the ability of the sentinel species-mimicking interface to raise awareness about the environment. According to the results based on the Likert scales (see Figure 6.12a–b), 12 out of 14 participants agreed that the state of the air was conveyed by the movement of the interface, and 11 participants agreed that the state of the air was conveyed via audio. Thus, it can be assumed that most participants recognised the warning signals about the state of the air through the physiological behaviour of the interface. In addition to the audio-visual eco-feedback, the interface also provoked several associations with nature. It can be assumed that these associations were triggered by the participants' overall experience, including that of (a) the interface, (b) the immersive sound, and (c) the mist from the diffuser. For example, some participants referred to their experiences in nature, while another imagined being in nature. In addition, this study used the interface as an opportunity to discuss current affairs. Most participants therefore shared their experiences with the air during the pandemic. These experiences included both participants' awareness of their own sensitivity towards the air and a general reflection on the vulnerability of the Earth's system. Furthermore, in terms of a worldview, it was found that 12 participants confirmed the statement that humans are part of nature, which may indicate that most participants are aware of the interrelationship between human beings and the environment. Finally, a participant mentioned the science fiction movie *Blade Runner*, based on Philip K. Dick's novel *Do Androids Dream of Electric Sheep?* The novel illustrates a world in which many animals, especially birds, have become extinct due to radioactive dust. For this reason, animals have become so rare that most people cannot afford a real pet and instead buy a robot animal to increase their social status. Thus, the comment "Welcome to Blade Runner" could indicate that the participant linked the interface with a dystopian fiction that thematises a damaged planet.

6.3.1.3 Interspecies Relationships

Referencing Haraway (2003, 2016), this section reflects on the social encounter between participants and the sentinel species-mimicking interface. The most unexpected finding was that most participants showed signs of care and empathy towards the interface. It can be assumed that these traits were likely triggered by (a) the interface behaviour, (b) the materiality, and (c) the participants' connectedness to personal pets. Some participants, for example, were concerned about the hectic and panting behaviour of the interface. Others mentioned their domestic animals, such as cats and horses. Some participants wanted to pet or even keep the interface. Moreover, a few participants highlighted the feathers as a representation of a species as well as of beauty and fragility. Although none of the participants associated the interface with the miner's canary, almost all of them referred to a living organism or even a bird species whose behaviour was identified as a warning against the mist from the diffuser. These findings could be due to the size of the interface, as only birds larger than a canary were mentioned.

6.3.2 Recommendations

Since 12 out of 14 participants agreed that the task was easy to carry out, 13 participants agreed that the task made sense to them, and all 14 participants agreed that the experience was inspiring (see Figure 6.12c–e), this study recommends two directions for future research: (a) using the interface to engage with people in exhibition spaces and (b) conducting long-term, auto-ethnographic studies in everyday life.

6.3.2.1 Art Intervention to Engage with People in the Cultural Sector

Before the sentinel species-mimicking interface can be presented as a speculative art installation in the cultural sector, this study suggests some adjustments. Unlike *Ivory*, this contribution provided a visual output at the top of the interface. Even though most participants (n = 12) recognised the visual output, this study recommends expanding the shape-changing surface to the sides of the interface, so that other spectators can also observe the changing behaviour of the interface. An underestimated challenge was the design of an interface that can presumably be used with different body types. Although the one-size-fits-all design allowed all participants to participate in the study, the interface reached its limits with an arm circumference of 30 cm. Thus, a body-worn interface for the exhibition space should consider various sizes or more flexibility to fit on wider arm circumferences. Additionally, this study recommends replacing the inlay of the interface with a softer fabric to ensure that it does not scratch the user. Furthermore, although some participants (n = 3) perceived the ambient sound only as a subtle sound source, this study recommends retaining the ambient sound to present an immersive full-body experience that might be interesting for other spectators in an exhibition space as well. To validate these assumptions, further studies should collect additional data from users' perspectives and from other spectators in the exhibition space. This study therefore recommends the use of Likert scales to collect data from visitors;

this would make different exhibitions comparable.

6.3.2.2 Long-term Auto-ethnographic Research in Everyday Life

Although the interface was intended for use in a speculative art installation, further research could push the application towards a real-world application. Since most participants envisioned a kind of a personalised interface for awareness and healthcare and showed signs of caring and empathy for the sentinel species-mimicking interface, a personalized iteration for long-term, auto-ethnographic research is recommended. The author therefore plans to build on previous goals (see Broscheit, 2020) to create an interface that measures information from both the human body and the environment. In addition, the author will draw on suggestions considering the long-term impact of interactive technologies (Rahm-Skågeby and Rahm, 2022). Based on this and the participants' statements, the author envisions a sentinel species-mimicking interface to improve people's self-knowledge and awareness of living in a changing environment. Additional design studies are thus recommended, including participatory research, to create an interface that covers different requirements for everyday usage.

6.3.3 Limitations

With the intention of acquiring a first impression of users' experiences, this research was limited to a qualitative study. Although the Likert scales seemed to be irrelevant for evaluating a small sample size, they supported the qualitative analysis and could become a useful tool for evaluating the interface in exhibition spaces. In addition, this study had to overcome several challenges during the ongoing pandemic. The recruitment process, for example, was affected by a new peak of coronavirus infections, which led to appointment cancellations. Moreover, increased safety standards had to be considered (e.g., face masks), which partly affected the clarity of the users' statements. Furthermore, a prior study suggested that participants should practice thinking aloud before the user study (Boren and

Ramey, 2000). During the study, it was noticed that some participants had no problems thinking aloud, whereas others were unfamiliar with the practice. Depending on the participant, the author individually handled the thinking aloud task. Moreover, a few participants explored the setting with the interface quite systematically and played with the distance to experience different particle concentrations, while others needed some guidance from the author. Regardless of the challenges, the author noticed an initial saturation after collecting data from 10 participants. In line with other studies (Faulkner, 2003), the sample size of 14 participants offers a first impression regarding users' interactions that can be employed as a foundation for future research. Lastly, although the technical sensors are suitable for monitoring the environment in the wild, using the interface outside the given installation is beyond the scope of this study. If a future study is conducting in the wild, the author recommends another iteration that integrates speakers into the interface or utilises the sound of the servo motor as auditory output.

6.4 Summary

This chapter presented a body-worn, sentinel species-mimicking interface for use in a speculative art installation to raise awareness about the environment in the cultural sector. This study evaluated the interface through a user study (n = 14) in a laboratory setting to obtain an first impression of the entire experience. This evaluation involved designing and implementing an interface that draws on the concept of sentinel species, in particular the miner's canary, with the aim of conveying the state of the air through the physiological behaviour of the interface. In addition, an approach was explored for staging a changing atmosphere to provoke users' immediate opinions about the interaction. This allowed the author to gain an initial understanding of participants' felt experiences and their relationships with the environment. Overall, the findings indicate promising directions towards a sentinel species that mediates air quality through non-verbal communication and that sparks users' empathy on a social, cognitive, and emotional level. Based on these results, future research should focus on two new directions: (a) presenting the body-worn interface in exhibition spaces to provide a lived experience with a changing atmosphere, thereby creating a discursive object that transfers knowledge between science and society, and (b) creating personalised interfaces for auto-ethnographic research to investigate long-term impacts on environmental awareness and personal healthcare in everyday life. In summary, this chapter introduced essential steps for further research on environmental awareness through interspecies encounters, and it highlighted implications for novel forms of sensitivity regarding the state of the atmosphere and engaging with a changing environment. Furthermore, this chapter provided the following contributions:

- A body-worn, sentinel species-mimicking interface that enables a lived experience with particle concentrations in a speculative art installation.
- A first-hand understanding of the participants' experiences in terms of interface design, environmental awareness, and interspecies relationships.

Parts of this chapter were published in Broscheit (2020) and Broscheit et al. (2023). In addition, a video documentation was published on the author's personal media library.[1]

[1]Broscheit, Jessica (2021), SENTINEL SPECIES: Towards a Co-Evolutionary Relationship for Raising Awareness about the state of the Air, Retrieved May, 2022 from https://vimeo.com/776085663

Chapter 7

Conclusion and Future Research

This chapter concludes the work of this study. The following sections reflect on the research objectives (7.1), interspecies relationships (7.2), methodology (7.3), limitations (7.4), future research recommendations (7.5), and conclude with a summary (7.6).

7.1 Revisiting the Research Aim and Objectives

Against the backdrop of the Anthropocene (see Section 1.1), the main aim of this study was to raise awareness about the environment by enabling an aesthetic and social encounter with the air through the use of interactive technologies that can be used to engage with society in the cultural sector. Through the design, implementation, and evaluation of multiple interactive technologies (e.g., Broscheit, 2020; Broscheit et al., 2018a, 2019, 2021b), this study addressed human-induced impacts on the environment, such as air quality, and crossed disciplinary boundaries by practising at the intersection of science and society. Referencing Tress et al. (2005), this study achieved promising results for raising awareness about the environment in academic and non-academic fields. For example, the outcome of this study emphasised transdisciplinarity by engaging with people in the cultural sector through exhibitions and participatory workshops and by crossing disciplinary boundaries through the use of environmental, technological, and research-through-design approaches (see Figure 7.1). This study hence supports the dialogue between science and society, which could positively influence future sustainable developments in the Anthropocene epoch. The following sections discuss the achievements of the dissertation by revisiting the research objectives.

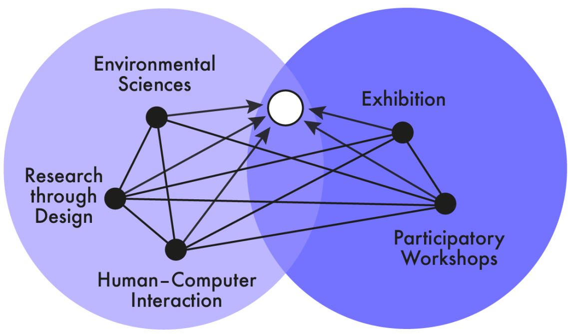


Figure 7.1 Redrawn diagram, following the concept of transdisciplinarity provided by Tress et al. (2005), illustrating academic and non-academic fields covered in this study to address anthropogenic concerns such as air pollution.

Research Objective 1

In regard to the first objective (see Section 1.2), this study provided a state-of-the-art literature review with a particular focus on interactive technologies that represent the state of the air and that were created at the intersection of art, design, and technology. Overall, it was found that interest in environmental sensing technologies that measure, analyse, and predict ecological processes is growing. In addition to sensing technologies that represent numerical data, other interactive technologies were identified that use expressive materials and metaphors to raise awareness about the environment on an aesthetic and social level. Aside from academic knowledge, the literature review was enriched with artworks that were partly valued through secondary sources. The literature review also included preliminary studies by the author that were used to define the scope of the research project.

The *Air Mask* (Broscheit, 2020), for example, revealed several difficulties in interacting with the air quality in the wild, such as conducting a comparable user study under unsteady environmental conditions. *Reflection on Air* (Broscheit et al., 2021b) explored interactions with CO_2 concentrations. In addition, Meyer et al.'s (2019) study on the visualisation of air quality measurements in an interactive VR environment confirmed the decision to create discursive objects for the real world and to thus make them tangible and accessible to people in the cultural sector. Moreover, this dissertation rests on the author's master thesis that has been published in a conference paper (Broscheit et al., 2018). The master thesis focused on a participatory environmental workshop addressing air pollution, which paved the way for mediating the air quality through species-inspired interfaces.

Based on the findings of the literature review, this study identified existing research gaps, including (a) the need for theoretical foundations, (b) the development of expressive interfaces representing the state of the air that can be used as discursive objects in the cultural sector, and (c) evaluation of the user's experience during an interaction.

Research Objective 2

In regard to the second objective (see Section 1.2), this study developed the conceptional framework of atmospheric interfaces to address the shortcomings of theoretical foundations (see Section 2.3.2). For this purpose, this study explored the design and interaction space by drawing on meteorological principles, related studies, and practice-based research to provide basic knowledge for the creation of interactive technologies that focus on an aesthetic and social encounter with the air (see Chapter 4).

With the goal of making invisible information, such as air quality, accessible for the spectrum of human senses, the framework impacts the following areas of HCI research: (a) environmental awareness and sustainable interaction (DiSalvo et al., 2010; Hansson et al., 2021), (b) material interaction (Hornecker, 2011; Ishii et al., 2012), and (c) the accessibility of information through non-verbal communication (Sharp et al., 2019). Moreover, as recent studies have highlighted the important role of community building for addressing anthropogenic issues (Bendor, 2018; Bendor et al., 2021), the conceptual framework could provide promising impacts for transdisciplinary collaborations by becoming a tool for creating technologies that aim to raise awareness about the atmospheric environment. Interdisciplinary research groups, for example, could create discursive objects that address environmental concerns through creative and physical prototyping to overcome disciplinary boundaries, think across the known, and ensure the same level of knowledge. In addition, the framework can be used for creative environmental education to transfer knowledge to STEM students and civil society (e.g., Broscheit et al., 2018b,a; Kuznetsov, Davis, Paulos, Gross and Cheung, 2011; Solomon et al., 2018). In brief, the conceptual framework demonstrates promising implications as a transdisciplinary research tool for creating interactive technologies that can be used as discursive objects within interdisciplinary research groups and participatory design interventions. Parts of the conceptual framework have contributed knowledge to the HCI community through publication in the proceedings of the international ACM TEI conference (Broscheit et al., 2021a).

Research Objective 3

In regard to the third objective (see Section 1.2), this study involved the design and implementation of an interactive technology raising awareness about the state of the air that can be used for transdisciplinary discourse across science and culturally interested members of society (see Chapter 2). By drawing on the conceptual framework (see Chapter 4), the author developed multiple iterations of high-fidelity interfaces that can either be placed in the physical world or worn on the human body. The author was inspired by Haraway's species storytelling (2016) to develop an interface that draws on the concept of sentinel species (O'Brien et al., 1993), in particular the miner's canary, for raising awareness about the atmospheric environment. To this end, the physiological behaviour of the miner's canary, such as breathing and singing, was interpreted to enable an aesthetic and social encounter with the air. Additionally, feathers were utilised as material reference to fabricate an abstraction of a bird. While the first stationary iteration *Ivory* (see Chapter 5), imitates a living organism that seeks the empathy of the spectator in the real world, the second iteration, *Onyx* (see Chapter 6), visualises a bodily connection between human and non-human species. In addition to these interfaces, this study also investigated different types of interactions to stage a changing atmospheric environment in an experimental setting, thereby providing approaches to create an immediate eco-feedback and to discuss anthropogenic impacts, such as air pollution. These interfaces and types of interactions have implications for HCI research on expressive materials and multisensory experiences with the air. However, unlike related works that have also utilised the miner's canary as a metaphor (e.g., the GUI by Smid et al., 2011), the interfaces of this study provide an expressive and multisensory experience with the air quality to engage users on an aesthetic and social level. In line with studies that have highlighted the importance of artistic and critical design practices for addressing anthropogenic concerns (Bendor, 2018; Bendor et al., 2021; Dunne and Raby, 2014; Rahm-Skågeby and Rahm, 2022), this study demonstrated the interface's impact as a discursive object for raising awareness about the environment and heightening epochal consciousness. Moreover, in regard to previous literature that has emphasised the interconnections of humans and non-humans in the epoch of the Anthropocene (Fowkes and Fowkes, 2022; Haraway, 2016; Horn, 2020), this study also has the potential to convey the anthropogenic worldview by enabling interaction between a human and a sentinel species-mimicking interface that responds to the air quality. In short, the development of multiple iterations of sentinel species-mimicking interfaces have contributed to the transdisciplinary knowledge transfer by being both published and discussed within the research community (e.g., Broscheit, 2020; Broscheit et al., 2019, 2023) and exhibited to the society (e.g., Gewerbemuseum Winterthur, St. Catherine's Church, and Faktor Gallery).

Research Objective 4

In regard to the last objective (see Section 1.2), this study involved a user study wherein mixed methods were applied to address the lack of empirical research (see Chapter 2). In a laboratory setting, the body-worn, sentinel species-mimicking interface *Onyx* was used to provoke the reactions of 14 participants in an prototypical arrangement in the laboratory, thereby allowing for a first impression of the outcome (see Chapter 6). Within the prototypical arrangement, participants were invited to explore a field of highly concentrated particles through the use of a sentinel species-mimicking interface worn on their bodies. In line with critical and speculative design research (Dunne and Raby, 2014), the body-worn interface was used as a discursive object to gain insights into participants' experiences by applying qualitative and quantitative methods (e.g., thinking aloud, a semi-structured interview, and Likert-scales). As a discursive object, the interface provided insights into the experience of exploring a field with highly concentrated particles, and it provided an opportunity to gather statements about participants' worldview, current affairs (e.g., global pandemic), and personal needs (e.g., personal healthcare). By structuring the statements according to Mekler and Hornbæk's framework of meaningful interaction (2019), this study provided empirical findings that were also supported by quantitative measurements. Overall, the findings revealed important insights in terms of the interface design, environmental awareness, and interspecies relationships, leading to further recommendations. The recommendations for future research included using the interface as a discursive object to engage with people in exhibition spaces. In addition, the study identified another direction for improving environmental awareness and healthcare through self-knowledge. Lastly, the results of the user study contributed to HCI research through publication in the proceedings of the international ACM TEI conference in Broscheit et al. (2023).

7.2 Interspecies Relationships

This section presents an overall reflection on environmental awareness through interspecies relationships. Unlike previous studies that have represented the state of the air via objects, such as *Reflection on Air* (Broscheit et al., 2021b) and *Air Mask* (Broscheit, 2020), the species-inspired interfaces seem to connect with people on social, cognitive, and emotional levels. In particular, the body-worn, sentinel-species interface that extends human senses to the state of the air, has the potential to distract people from their everyday lives, and allows them to experience a speculative space that encourages them to view the world differently. In line with critical and speculative design approaches (Dunne and Raby, 2014), the interface can be used as a discursive object for addressing environmental concerns in exhibition spaces, thereby transferring knowledge between science and the culturally interested members of society. Since the present study also identified other sentinel species (e.g., lichens, spiders, bees, and mice), further research can be conducted to create interfaces based on different species and compare them with one another in terms of their emotional impact and connectedness. For example, the behaviour of lichens may be further explored to interpret their sensitivity towards air pollution as a colour-changing interface (e.g., with thermochromic fabric). Moreover, when creating a multisensory experience, one can support this visual output through the support of an olfactory interface that represents the smell of a forest to indicate good air quality. Regardless of all the possibilities related to creating a multisensory experience with the air, the combination of a visual and auditory output is highly recommended, as this appears as a strong combination for raising people's awareness about the environment (Broscheit et al., 2019, 2021b, 2023).

7.3 Methodological Reflection

The research presented in this dissertation was underpinned by the philosophy of pragmatism and designed as a case study, including methods organised as follows: (a) exploration, (b) design and implementation, and (c) evaluation (see Chapter 3). The practice-orientated and experience-based aspects of pragmatism in particular had an important impact on this research project. The methods for, 'exploration', for example, provided a conceptual framework that explores the design and interaction space, drawing on theoretical knowledge as well as preliminary studies that were conducted in a practice-oriented manner (see Chapter 4). The methods for, 'design and implementation', contributed sentinel species-mimicking interfaces and staged forms of interaction that were accessed through qualitative and quantitative methods to provide comprehensive insights into the development process (see Chapters 5–6). In particular, the first-person method was important during the development process and provided useful insights when the first iteration was presented to a culturally interested audience in exhibition spaces (see Chapter 5). Based on these first-person observations, the requirements for the second iteration were then defined. The methods for, 'evaluation', provided empirical findings that led to an understanding of users' experiences, emotions, needs, and worldviews (see Chapter 6). This study ultimately drew a conclusion from the overall findings based on inductive reasoning. Furthermore, the entire study is based on the personal experience of the author, who became interested in environmental sensing to perceive components of the air in an aesthetic and material way during a residency in China (see Section 1.4). In summary, the philosophy of pragmatism, the strategy of a case study, as well as the collection of qualitative and quantitative data have played an essential role in this research project.

7.4 Limitations

Although this study employed mixed methods, it is limited to a qualitative case study to provide first insights into a little-known subject, namely raising awareness about the environment through human–atmosphere interaction. The author's interest in raising awareness about the atmospheric environment through interactive technologies presented in the cultural sector stemmed from the her personal background, own experiences, and field observations in China (see Section 1.4). This study is therefore limited to the knowledge and skills of the author, who practises at the intersection of art, design, and technology to address environmental concerns. While the author was particular interested in exploring interactive technologies that can be used as discursive objects in the cultural sector, the literature review also encompasses artworks that were additionally validated through secondary sources. Although the HCI research field, and especially the TEI research community, values artistic practices, additional artworks were included to demonstrate the relevance of this research and to overcome the shortcomings of academic studies in this field.

Aside from the theoretical, practice-based, and empirical contributions, the Chapters 4–7 provided further recommendations, which are recapitulated below.

Chapter 4, for example, introduced a conceptual framework by drawing on meteorological principles, related HCI studies, and practice-based research. However, to date, the conceptual framework has not been evaluated in terms of its practical use. Future research could validate the conceptual framework with different target groups. Chapters 5 and 6 presented the development and evaluation of stationary and body-worn interfaces that were inspired by the concept of sentinel species, more specifically the miner's canary, to convey the state of the air through the physiological behaviour of breathing and singing. Although the author developed different kinds of interfaces during this dissertation, the miner's canary appeared to be the most promising metaphor compared with the other interfaces that utilised objects (e.g., symbols, a mirror, and a face mask, which were published in Broscheit, 2020; Broscheit et al., 2021b). This study is therefore limited to various iterations of the miner's canary interface metaphor. A comparison of all developed interfaces is beyond the scope of this study. Chapter 6 provided a first-hand understanding of participants' experiences that revealed the need for both environmental awareness and personal healthcare. Due to limited time resources, this study has not provided another iteration that can be used for self-knowledge in daily life.

7.5 Future Research

Overall, this research has provided theoretical, practical, and empirical contributions through the design, implementation, and evaluation of interactive technologies that raise awareness about the environment in the cultural sector. Based on the aforementioned limitations, further research recommendations are summarised below.

7.5.1 Validating the Conceptual Framework

This study provided a conceptual framework of atmospheric interfaces with the potential to become a tool for transdisciplinary research (see Chapter 4). Based on the knowledge gained through prior research on environmental awareness (Broscheit et al., 2018a), a participatory workshop is recommended to validate the use of the framework. Participatory workshops could involve potential target groups (e.g. interdisciplinary collaborations, civil society, and STEM students) to evaluate the framework as a research tool for raising awareness about the environment through playful learning and creative knowledge transfer using prototyping methods. To this end, this study suggests the development of a toolkit including the conceptual framework, electronic components, and different materials for inspiration and rapid prototyping (e.g., swatch box, cardboard, pencils, scissors, and glue). To conduct participatory workshops, cooperation with environmental research centres, educational projects, open knowledge foundations, and maker spaces could be considered. In summary, an evaluation of the conceptual framework within a participatory workshop could provide promising results about participants' needs and concerns, knowledge transfer, the most preferred inputs and outputs, and general usage.

7.5.2 Interventions in the Cultural Sector

This study developed interactive technologies that raise awareness about the environment. To date, the first iteration was presented in several exhibition spaces (see Chapter 5), and the second iteration was evaluated in a prototypical arrangement in a laboratory setting (see Chapter 6). Further research could exhibit these interactive technologies as short-term interventions to deepen understanding of environmental awareness and transfer knowledge to the society in the cultural sector. The insights gained, for example from observations, Likert scales, and interviews, could then be evaluated to inform further studies. Cooperation with museums, galleries, and institutions that address transformational processes could be considered for exhibiting these interactive technologies.

7.5.3 Environmental Awareness and Personal Healthcare

This study focused on interactive technologies that can be used to raise awareness about the environment among an audience in the cultural sector. The author designed and implemented various interfaces that were observed in exhibition spaces and evaluated in a user study (see Chapter 6). The findings revealed promising insights into environmental awareness as well as a need for interfaces that support personal healthcare. In line with the aims of a previous study (Broscheit, 2020), further research is therefore recommended, with a focus on the development of interfaces for environmental awareness and personal healthcare for people who are sensitive to air pollution. To this end, the development of a third interface iteration is proposed that is suitable for daily use and that gathers both environmental and personal vital data. This iteration could then be evaluated in a long-term auto-ethnographical and data-mining research project to understand the impacts of the air quality on the health of individuals and the emotional benefits of a sentinel species-mimicking interface.

7.6 Summary

This study presented the design, implementation, and evaluation of interactive technologies for raising awareness about the atmospheric environment. It involved theoretical, practice-based, and empirical research to enable an aesthetic and social encounter with the air through interactive technologies, and it provided a conceptual framework for developing such technologies. Guided by the conceptual framework, the study involved the design and implementation of interfaces that draw on the concept of sentinel species, in particular the miner's canary, with the aim of conveying the state of the air through the physiological behaviour of breathing and singing. Additionally, this study explored an approach for staging a changing atmosphere to provoke users' immediate opinions about the interaction.

Then, the study evaluated the felt experience of 14 participants who explored the atmospheric environment with a sentinel species-mimicking interface worn on the body in an experimental setting. Collectively, these parts of the study build on one another and provide important implications for the following topics: (a) expressive interfaces for use as discursive objects to raise awareness about the atmospheric environment in the cultural sector, and (b) promising conditions for transdisciplinary knowledge transfer between science and society. Furthermore, this study provided recommendations for future research, including the validation of the conceptual framework as well as short- and long-term studies in the field of human–computer interaction. In summary, this study introduced essential steps for future research on interactions with the atmospheric environment and highlighted implications for novel forms of sensitivity regarding the state of the atmosphere and engaging with a changing environment.

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