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# Sentinel Species: Towards a Co-Evolutionary Relationship for Raising Awareness About the State of the Air

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Fig. 1. This body-worn interface represents an abstraction of a sentinel species—more specifically the miner's canary—to raise awareness about the environment.

Interactive technologies are increasingly being used as discursive objects for raising awareness about the environment in the cultural sector, but little is known about the user's lived experience during an interaction. In this study, we present the development and evaluation of an interface designed to raise awareness about the environment within a speculative art installation. For this purpose, we drew on the concept of sentinel species, specifically the miner's canary, to enable a multisensory experience with the state of the air. We then evaluated the interface with 14 participants while interacting in a prototypical arrangement in the laboratory. Overall, the findings indicate promising directions towards a sentinel-species-mimicking interface that communicates the state of the air through

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its physiological behavior and thus also engages with the user's empathy on a cognitive and emotional level. Based on the findings, we highlight the implications of this study and point to further directions for human–atmosphere interactions.

CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**; *Haptic devices.*

Additional Key Words and Phrases: Human-atmosphere interaction, sentinel species, air quality, body-worn interface, user experience research.

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## 1 INTRODUCTION

Since the central role of human-induced impacts on the Earth system has been highlighted by Crutzen and Stoermer [15], new challenges have emerged to raise awareness about the environment and to mediate the relationship between human beings and their changing world. According to Crutzen and Stoermer, human-induced impacts play a central role on the Earth system within the current geological epoch, the so-called Anthropocene [15]. While mastering these impacts is a major challenge, the society is at the same time affected by the resulting environmental consequences, such as air pollution. To address these impacts, new strategies need to be developed that also involve the civil society and reach beyond disciplinary thinking [39, 53]. While the natural sciences focus primarily on collecting and analyzing environmental data, other disciplines, such as the humanities, strive to heighten the awareness of the current epoch. They understand the Anthropocene as the current state of affairs and as a possibility to describe the complexity of global change [33]. Their holistic perspective also includes another way of being in the world that considers the coexistence of human and non-human species (e.g., animals and plants) [28, 33, 74]. In this context, artistic and critical design practices offer an alternative to mediate environmental awareness by stimulating individuals' senses beyond global change statistics [16, 21, 32, 62, 65]. Some of these positions use the air as a *medium* [e.g., 1, 11, 41, 43] or introduce interactions between species to enable a social encounter with the environment [e.g., 8, 9, 23, 49]. In this way, these positions bring environmental concerns to the foreground of human perception [32, 62], become antennas for future developments that foster discussions within society [16, 21, 33, 65], and shape technological development by transcending disciplinary boundaries in the field of human–computer interaction (HCI) [3, 4, 61].

To increase awareness about the atmospheric environment in the cultural sector, the aim of this study is the development and evaluation of an interface to be used as a discursive object to provoke user's experiences during an interaction. To achieve this aim, we formulated the following research questions:

- How does related knowledge guide the practical development of an interface designed to raise awareness about atmospheric environment?
- What do users experience while interacting with an interface that represents the state of the air?

To tackle these questions, we pursued the following objectives. First, to gain a general understanding, we investigated related studies in the research field of HCI. We focused in particular on tangible interactions with the air and metaphorical representations based on species. Then, to develop an interface, we described a conceptual background and drew on related studies. Based on this, the design and implementation process involved high-fidelity prototypes as well as the exploration of an approach for interacting with a changing atmosphere. Lastly, to obtain a first impression of the outcome, we conducted a user study. We set up a prototypical arrangement in the laboratory to evaluate the experiences of a sufficient number of participants during an interaction. Overall, this study provides the following practice-based and empirical contributions:

- a body-worn, sentinel-species-mimicking interface that draws on the miner's canary to convey the state of the air through the physiological behavior of breathing and singing.
- a staged approach for interacting with the air in the form of a speculative art installation where users can encounter high particle concentrations and thereby experience an immediate eco-feedback of the state of the air.
- a first-hand understanding of the participants' felt experiences (n=14) in terms of interface design, environmental awareness, and interspecies relationship.

This paper is organized as follows. First, we present related literature. Second, we explain how we designed and implemented the entire system. Third, we outline the procedure and findings of the user experience research. Finally, we discuss our findings before concluding with recommendations for further research.

## 2 RELATED WORK

In the following sections we outline related studies on interfaces that aim to raise awareness about the environment and employ species as metaphorical representation.

### 2.1 Environmental Awareness

In recent years, HCI research has introduced a wide range of technologies that aim to raise awareness about the quality of the environment [20]. These technologies include environmental sensor nodes that monitor the air quality within a certain area [e.g., 51, 75, 77, 78], graphical user interfaces to visualize air quality data sets [e.g., 42, 44, 71], and air pollution toolkits for participatory research [e.g., 8, 18, 26, 37, 46, 47, 50, 72]. In addition, physical interfaces associated with the interdisciplinary field of tangible and embodied interaction (TEI) [34, 35, 38] have spawned aesthetic encounters with the atmosphere. In particular, the preliminary taxonomy of atmospheric interfaces has outlined various inputs and outputs that can be used to create a physical data representation for expressing environmental information [11]. These interfaces are characterized by combining digital sensing technologies and crafted materials to enable an aesthetic interaction with the air.

Khan, for example, developed an interactive column architecture made out of shape-changing material that responds to carbon dioxide ($CO_2$) concentrations [41]. In addition, Broscheit et al. introduced a kinetic mirror that responds to $CO_2$ as audiovisual feedback [10]. And Stamhuis et al. implemented the *Office Agents* interface with the aim of debating with employees about healthier working conditions including the air quality [73]. While the aforementioned interfaces were developed to augment a real space, others have conquered the human body by drawing on the origins of Steve Mann's wearable computers [52]. Below, we present some examples of physical, data-driven interfaces that enable an exploratory and bodily interaction with the atmospheric environment.

Adhitya et al., for example, created a garment that reflects the air quality via thermochromic colors to motivate people towards a sustainable development [1]. Bentel also used reactive colors for a sweater that changes its pattern according to the condition of the atmosphere [5], while Kim et al. have developed an illuminating t-shirt that measures the air quality of the user's surroundings. In this project, the t-shirt illustrates high concentrations of volatile organic compounds (VOC) via an LED pattern that visualizes the intensity of car exhausts [43]. Similarly, media artist Molga introduced a wearable costume to explore London's air pollution through a dance performance. The costumes illuminate in different colors in response to real-time air pollution levels [55]. In addition, Hanne-Louise Johannesen and Michel

Guglielmi, aka Diffus Design, presented an interactive dress that reacts to $CO_2$ levels. The dress consists of conductive embroidery and LEDs to visualize different $CO_2$ concentrations [19]. Finally, Schulte et al. developed a air pollution mask that opens and closes autonomously according to air pollution levels. Through a “wizard of oz approach”, spectators selected an air pollution value from a graphical user interface to observe the functionality of the mask on a mannequin [69].

### 2.2 Species as Metaphorical Representation

Since metaphors are commonly used in HCI research to provide a general understanding of an interface [12, 57], we have investigated metaphorical representations that address environmental awareness through an encounter with a species. In the following, we present related studies that have employed various species as mental models for addressing ecological concerns.

Artist and researcher Beatriz da Costa, for example, introduced the project *PigeonBlog*, in which she has equipped pigeons with sensor backpacks to measure the air quality of southern California. While the birds flew through the air, the current readings obtained from the sensors were published to inform the general public via the internet [see 28, p. 20]. In addition, Smid et al. presented a GUI application, entitled *Canary in a Coal Mine*, that visualizes air quality data sets based on public tweets [71]. The study *Ivory* by Broscheit et al., also referred to the miner’s canary and has used the bird as an interface metaphor to represent particulate matter concentrations through a feathered, shape-changing interface enriched with sound [7, 9]. Broscheit et al. also used different images of animal species to inspire workshop participants to create an interface that represents air pollution. On the basis of animal characteristics (e.g., pufferfish, mouse, chameleon, and skunk), the participants developed prototypical augmentations for human beings as part of a participatory design workshop [8]. Yu developed the headpiece *AirMorphologies* to improve social interaction in polluted air environments. The design of the headpiece consists of pneumatic modules that were inspired by the pufferfish’s characteristics [76].

Furthermore, other studies have employed plants and microorganisms as an interface metaphor. Fabrizi, for example, introduced a shape-changing textile flower that opens and closes to indicate good or poor air quality indoors [23]. Similarly, Hsu et al. were also inspired by plants and developed the *Botanical Printer* for reflecting on both the natural and technological climate, whose interface measures both the $CO_2$ concentration and Wi-Fi signal strength and communicates the information via an integrated thermal printer [36]. Then, Sabinson et al. developed the *Plant-Human Embodied Biofeedback* interface to support the wellbeing of people in homes [67]. Lastly, Liu et al. introduced the concept of *collaborative survival* and developed several prototypes to encourage a relationship with fungi [49].

## 3 SENTINEL SPECIES: DESIGN AND IMPLEMENTATION

In this section, we describe the conceptional background, design, and implementation process of our interface that aims to raise awareness about the atmospheric environment through a species encounter. To this end, our methods involve (i) research through design including a critical design perspective on the transformation of human, non-human, and the atmospheric environment [21, 25, 79], (ii) the implementation of high-fidelity prototypes through the use of physical computing [59], (iii) a first-person method for revealing the design process [17, 31], and (iv) the use of sensor readings to understand the interactions via measurable values [70].

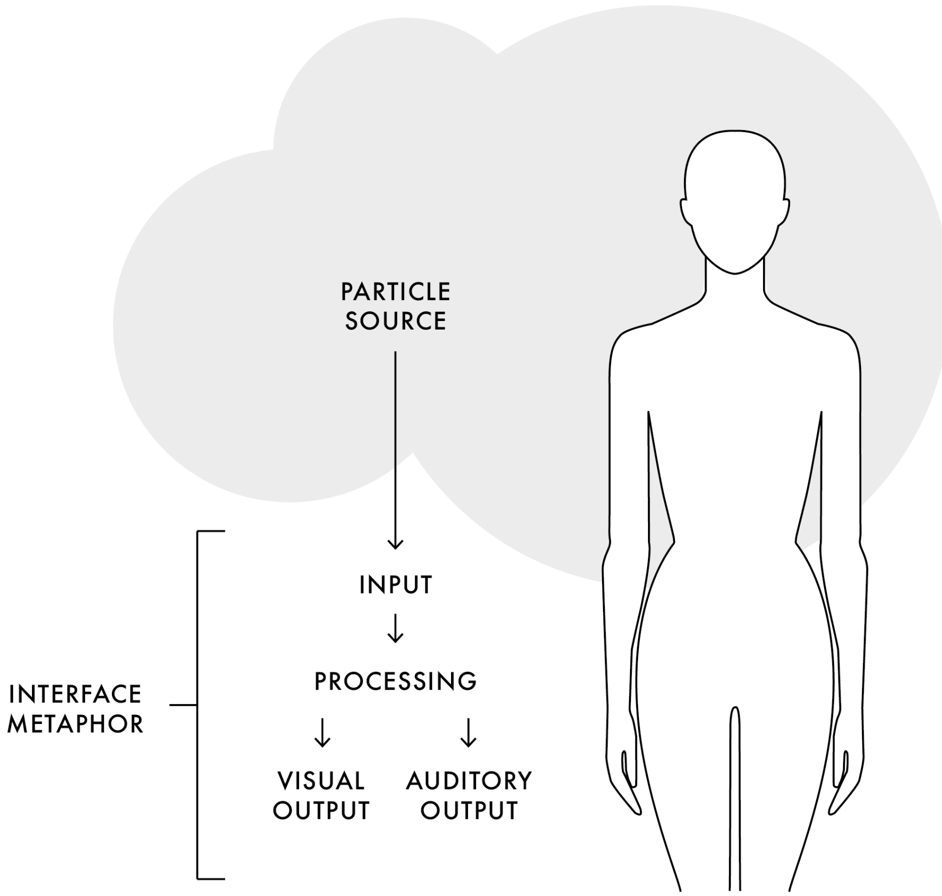


Fig. 2. System overview.

### 3.1 Conceptional Background

As mentioned in the introduction, relevant literature on the Anthropocene discusses the interconnectedness of human and non-human species [28, 33]. In particular, Donna Haraway, emphasized the need to overcome humans' limited perspectives on the world by establishing relationships with other species [27, 28]. Moreover, she criticized the term Anthropocene and suggested other approaches, such as species storytelling, to mediate the entanglement between humans, non-humans, and ecological concerns [28, 29].

Inspired by Haraway, we build on the previous study *Ivory* [7, 9] to increase awareness of the atmospheric environment through species storytelling. We therefore provide some background information of the concept of *sentinel species* to establish a relationship with another organism to augment human senses. The term sentinel species originates from field of biomonitoring and has been defined by O'Brien et al. as "organisms in which changes in known characteristics

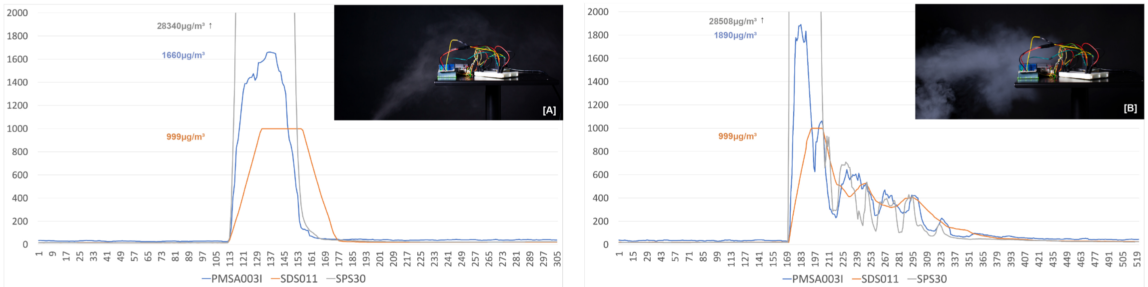


Fig. 3. Comparison of PM-2.5 sensor readings per second, provided by the SDS011, SPS30, and the PMSA003I. A) presents sensor readings that were triggered with mist from the ultrasonic diffuser. The SPS30 measured 28.340 µg/m$^3$, the PMSA003I measured 1.660 µg/m$^3$, and the SDS011 reached a maximum value of 999 µg/m$^3$. B) depicts sensor readings that were triggered with vapor from an e-cigarette. The SPS30 measured 28.508 µg/m$^3$, the PMSA003I measured 1.890 µg/m$^3$, and the SDS011 reached a maximum value of 999 µg/m$^3$.

can be measured to assess the extent of environmental contamination and its implications for human health and to provide early warning of those implications” [58, p. 352]. In this way, sentinel species represent a specific approach that highlights the interrelationship between human and animal health regarding the environmental condition. To determine a suitable sentinel that can act as an early warning system, O’Brien et al. identified various criteria for selecting a sentinel species, such as size, sensitivity, and physiological characteristics. A selected sentinel species must be sufficiently sensitive to environmental contaminations and able to reflect this sensitivity through its physiological characteristics. Fundamentally, various living organisms are suitable for monitoring the air, such as mosses, lichens, honey bees, spiders, birds, and mice [13, 60, 64, 66].

However, a classic example of a sentinel species is the miner’s canary [56, 64]. In the era of early coal and steel industries, miners were confronted with hazardous gases in shafts. During that era, small animals (e.g., rabbits, mice, and birds) were used as an early warning system to detect environmental contaminations. As opposed to other animals, canaries were preferred as in situ sentinels because of their sensitivity and physiological characteristics [64]. If the air reached high levels of hazardous gases, canaries showed signs of distress or collapsed. This sensitive behavior to environmental hazards provided the miners with the necessary time to initiate security interventions [56].

In contrast to the original usage of the miner’s canary, however, our goal is to address a contemporary environmental issue, such as urban air pollution. Particulate matter, for example, is a primary air pollutant and consists of a mixture of solid particles and liquid droplets that affect both human health and the environment [2]. These particles are measured in different sizes according to their aerodynamic diameter (e.g., PM-10, PM-2.5). While some particles are harmless to the human body, others can cause health problems and are small enough to enter the lungs. Recent studies, for example, have shown that long-term exposure to air pollution is linked to global health problems, such as cardiovascular diseases [40]. In addition, particulate matter also affects natural ecosystems by remaining in the atmosphere for some time [2].

### 3.2 Design and Implementation

Based on the conceptional background and the previous studies by Broscheit et al. [7, 9], we have envisioned 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 draw attention to ecological concerns, such as air pollution, in the cultural sector. For this purpose, we conceived an interface that interprets the physiological behavior of the miner’s canary, such as breathing and singing,

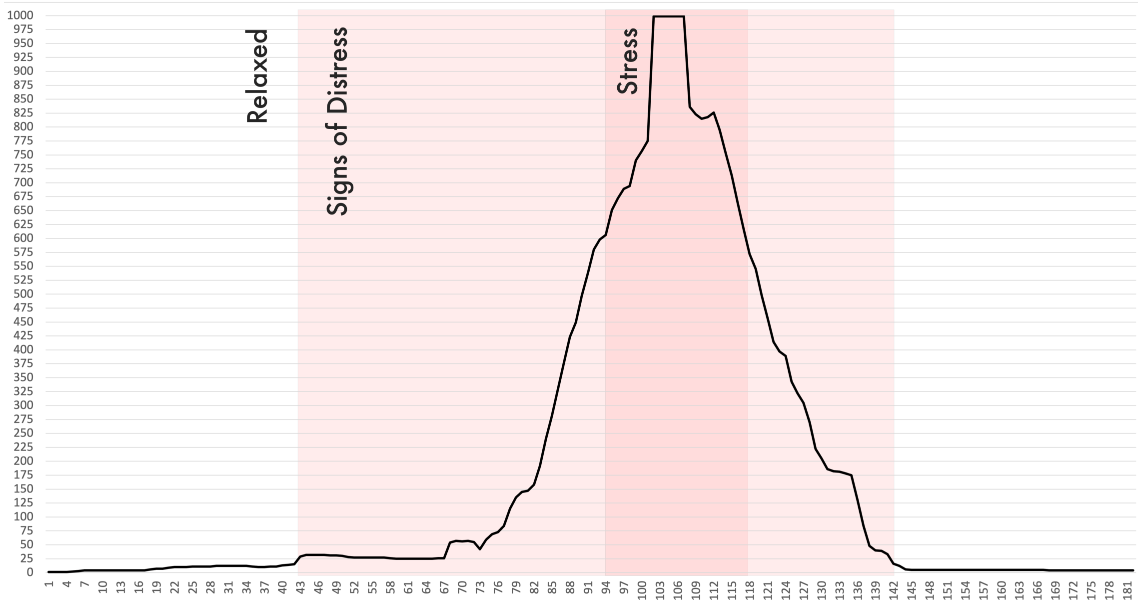


Fig. 4. Diagram of PM-2.5 values measured per second by the Nova Fitness SDS011 particle sensor. Additionally, the three breathing behaviors that represent (i) relaxed (<20), (ii) signs of distress (>=20), and (iii) stress (>=600) have been highlighted according to the measurements.

and uses feathers as a material reference to augment human senses regarding the state of the air. Instead of developing a sculptural artifact, such as *Ivory* [9], or placing canaries in cages as with miners [64], our intention was to create a critical yet aesthetic position in the form of an interface that illustrates a bodily connected relationship between human and non-human species. The design of the interface must therefore also consider different body types to ensure that it is robust and safe and can be used for both user research and in exhibition spaces. In the following sections, we outline the design and implementation process according to the system overview (see Figure 2).

*3.2.1 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, we have considered the use of a concentrated particle source to allow users to explore fields with high and low levels of particle contamination and thereby experience immediate eco-feedback within a speculative art installation. We therefore compared two particle sources: (i) vapor from a nicotine-free e-cigarette and (ii) mist from a diffuser (see Figure 3). As shown in Figure 3, the vapor from the e-cigarette is quite thick and lasts much longer in the atmosphere than the mist from the diffuser, which causes longer delays in the interaction. For this reason, we chose a commercially available ultrasonic diffuser as source to simulate a high contaminated particle field. Moreover, while 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.

*3.2.2 Input.* To create an abstraction of a miner's canary that is sensitive to particle concentrations, we compared three optical particle sensors (SDS011, SPS30, and the PMSA003I). After testing the sensors, we have chosen the Nova Fitness SDS011 particle sensor based on the smoothed data points (see Figure 3). Additionally, we selected the Adafruit BME680 sensor for data triangulation. Together, both sensors provide readings on PM-10, PM-2.5, temperature, and relative humidity, which are used as the environmental input. We then assembled the following electronic components together: a microcontroller D1 MINI ESP-8266 with on board WiFi, the Nova Fitness SDS011 particle sensor, the Adafruit BME680 sensor breakout board, the Adafruit micro-USB breakout board, the MASTER DS2312 MG servo motor with metal gear, and a power bank. Following this, the data was processed and interpreted on the microcontroller to control the visual and auditory output, as detailed below.

*3.2.3 Visual Output.* Based on the taxonomy of atmospheric interfaces [11], we conceived a visual output in the form of a shape-changing interface [63] made out of feathers to illustrate the breathing behavior of a sensitive bird.


Fig. 5. (A) illustrates the material swatch of the feathered, shape-changing surface to explore the movement behavior, (B) presents the fabrication of the feathered, shape-changing textile, and (C) depicts a close-up of the feathers combined with the auxetic structure.


Fig. 6. (A) presents a proof-of-concept to test both the electronic components on the human body and the interaction with the environmental actuator. (B-D) illustrate three of the prototypes created during the design process.

Before we started with the design process, we first observed our own bodies and discovered that the arm would be a suitable body position for a species-mimicking interface that supports an exploratory interaction. To test our assumptions, we attached the technical components on the forearm and interacted with the particle source at the beginning of the design process (see Figure 6A). This bodily experience confirmed that the arm is a good position to recognize the changing behavior of the interface.

Then, to simulate breathing characteristics that reference a bird, we tailor-made a feathered, shape-changing structure. Although canaries are bred to have different colours (e.g., white, yellow, red, brown, and black), we followed the previous study *Ivory* [9] and selected white feathers to (i) concentrate on the form and functionality before adding colors to the interface design and (ii) make the studies comparable. We then developed a soft textile surface that can be used as a modular element in different designs. For this purpose, we chose an auxetic structure, which is known for its deformable properties [48]. We then cut the auxetic structure out of white foam rubber and feathered the surface (see Figure 5B and C). Following this, we placed the material swatch in a box and investigated different motion characteristics (see Figure 5A). We then observed our own respiration and classified three breathing rates: relaxed, signs of distress, and stressed behavior. Based on this classification, we animated the feathered surface by using 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 4). For example, when the particle concentrations are high, the feathered, shape-changing surface on the interface represents a fast breathing rate to indicate stressful, air-gasping behavior.

After developing the modular textile and defining the breathing rate, we took inspiration from various so-called one-size-fits-all solutions for the construction of a body-worn interface (e.g., arm bracer, mount strap, functional gear, prothesis, and a muff).

After sketching several designs, we implemented three design options, as the visual impact between the sketch and three-dimensional object made a considerable difference. Ultimately, we decided to represent the visual output on a muff-inspired construction (see Figure 6d) for the following reasons. We found that the interface inspired by an arm bracer (see Figure 6B) is too functional and not provocative enough. Furthermore, the prosthesis-inspired interface (see Figure 6C) illustrates the connectedness of human and non-human species in the form of an extreme item that is not easy to wear. Lastly, we found that the muff-inspired interface (see Figure 6D) represents the connectedness of a human and non-human species as well as demonstrates an ease and robustness of usage.

*3.2.4 Auditory Output.* To enrich the visual output with sound, we considered a data-driven auditory output that refers to the concept of sonification [45] for interpreting a singing bird based on real-time data. To this end, the environmental input (PM-2.5, PM-10, relative humidity, and temperature) was transmitted from the microcontroller to a notebook and the Max/MSP software via a shared network by utilizing user datagram protocol and open sound control. The real-time data streams were then mapped into compatible numbers for controlling frequencies of the audio composition. The audio composition encompasses two oscillating states depending on the sensor readings. The first state represents low-pitched frequencies, indicating a relaxed and harmless environment, while the second state represents high-pitched particle frequencies that signal a harmful environment. Finally, the Max/MSP software played the sound over the external speakers.

## 4 USER EXPERIENCE RESEARCH

After we created a sentinel-species-mimicking interface and explored various approaches for interacting with air components, we evaluated our outcome as a prototypical arrangement in the laboratory to obtain a first impression of user's experiences during an interaction. In this section, we outline a description of the entire setting, information about participants, the data collection, and the data analysis.

### 4.1 Setting

For the speculative art installation, we envisioned a dark ambience with a centered, illuminated particle source, and an omnipresent sound 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, we followed a previous study on evaluating interactive art [30] and used our laboratory to provoke participants' reactions. The prototypical arrangement included the sentinel-species-mimicking interface, one particle source, a notebook with a camera and microphone, two external active loudspeakers, an audio recorder as backup, tripods, and a black background to visualize the mist of the diffuser for video recordings and avoid visual disruptions for the participants (see Figure 7).

### 4.2 Participants

To recruit participants for the user study, we contacted individuals via an email distribution list and word of mouth. The announcement outlined basic information about the provisional title, general task, duration, and location. In addition, the anonymous and confidential data collection process was highlighted. Participants qualified in case they articulated whether they had an interest in having an experience with a body-worn interface within a multimedia art installation. Finally, we arrived at a total of fourteen participants (self-identified as six male, five female, and three 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 has approved this user study. In addition, we assigned a number to each participant when summarizing the findings to protect their anonymity.

### 4.3 Data Collection

Before we started with the user study, the data collection was tested with colleagues (n=2) from the computer science department as a pilot study on November 3, 2021. We then made some minor adjustments and conducted the user study with fourteen 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 led the participants in signing the consent form. The investigator then invited the participants to put the interface on their preferred arm and asked them to explore the mist from the diffuser. We then applied mixed methods for the data gathering, including the thinking aloud technique [6, 22] for collecting verbal data about the participants‘ cognitive processes while interacting in the setting. In case of 15 to 60 seconds of silence, the investigator reminded the participants to produce verbal data during the interaction. As the participants explored the setting, audiovisual material and sensor logging were gathered for data triangulation [14] with the software Max/MSP, which was then screen captured on the notebook. After approximately one to two minutes of exploring the setting, the investigator started with the semi-structured

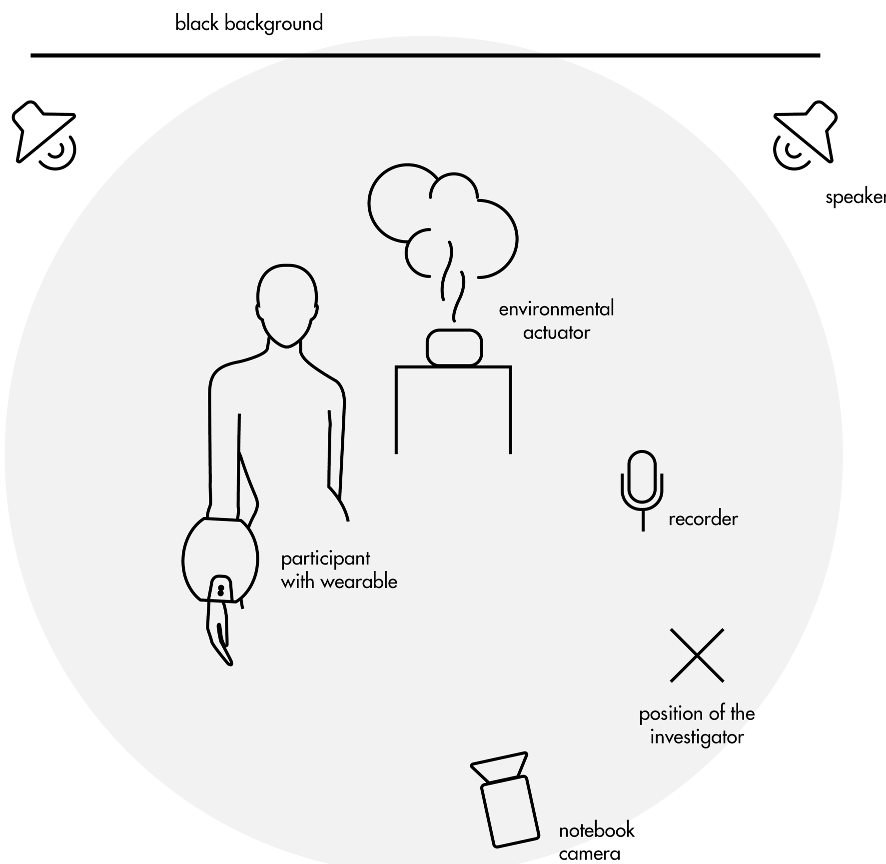


Fig. 7. Overview of the setting.

Table 1. Overview of the initial codes that were structured into axial codes. The axial codes refer to Mekler and Hornbæk's framework on meaningful interaction.

| Axial Codes | Initial Codes | Definition |
|---|---|---|
| connectedness | association | associations from participant's personal lives (e.g., animals, nature, and culture). |
| resonance | interface design | associations that were directly linked to the interface design. |
| | 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 | statements 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. |

interview [70] to explore participants' experiences through conversation while the participant was still in the setting. After completing the task and taking off the wearable, participants had to answer a Likert scale questionnaire to collect their measurable opinions. Based on these qualitative and quantitative datasets, we provided a content analysis, which we detail later in this paper.

### 4.4 Data Analysis

Overall, the data analysis included verbal data, the questionnaire, and the triangulation of data. First, we transcribed the verbal data in German. We then manually coded the data by following Saldaña's coding methods [68]. Through the use of the initial coding process, we developed a first impression of the collected dataset. Following this, the second cycle utilized axial coding to cluster the initial codes into categories (see Table 1). To organize the axial coding process, we drew on the theoretical framework for meaningful interaction provided by Mekler and Hornbæk [54]. This framework originates from the psychological literature on meaning and can be used to analyze HCI research. It consists of the following five components: (i) connectedness, (ii) purpose, (iii) coherence, (iv) resonance, and (v) significance. After the coding process was completed, we translated the participants' quotes from German to English. In addition, we supported the verbal data with closed-ended data from the Likert scale questionnaire. All questionnaires were digitalized and illustrated as diagrams. Lastly, the recorded visual material and the sensor loggings were used to ensure the internal validity of the qualitative research.

## 5 FINDINGS

In this section, we structure the findings in relation to the aforesaid five components of meaningful interaction (see Table 1) and illustrate the results of the Likert scale separately (see Figure 8).

### 5.1 Connectedness

According to Mekler and Hornbæk, meaning arises from aspects of the self and world with which the individual is connected [54]. We accordingly highlight associations with the interface that seem to arise from the participants' personal lives. Four participants had associations with their pets, such 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." In contrast, two participants mentioned objects from the medical sector, such as a "prothesis" (P2) and "health equipment in the hospital" (P11). Lastly, 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."

### 5.2 Resonance

Resonance denotes a direct and non-reflected response to an immediate experience [54]. In the following, we summarize the participants' immediate experiences and observations made by the principal investigator.

*5.2.1 One-size-fits-all.* In general, we observed that all participants put on the interface without any hesitation, and that it was straightforward in its usage. In addition, we noted that the 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."

*5.2.2 Care and Empathy.* Most of the participants showed signs of care and empathy. For example, when the interface 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 interface. 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 interface. P3 stated: "I'll take you [artifact] with me!" We also identified that participants associated it as a kind of living species. 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."

*5.2.3 Visual Output.* 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 behavior 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 interface'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."

*5.2.4 Auditory Output.* In contrast to the visual output findings, the auditory output was not perceived as clearly by the participants (cf. Figure 7a and b). First, the unintentional noise produced by the servo motor inside the interface was the dominant sound source for some participants. Moreover, a few users were so focused on the interface‘s behavior 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 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.”

*5.2.5 Haptic Output.* 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 interface. 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.”

*5.2.6 Materiality.* 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.”

### 5.3 Purpose

Purpose can be seen as a motivational and future-oriented component of meaning [54]. Below, we outline participants’ speculations about the intended usage of the 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), “$CO_2$” (P8), “pollutants” (P12), and the “density of air” (P14). P12 concluded: “Well, against pollutants or things in the air symbolized by this mist.”

### 5.4 Coherence

Coherence in this context refers to how participants would envision a system to make it meaningful to them [54]. Several participants imagined applications for ambient awareness, such as systems for “weather forecast” (P3), “$CO_2$” (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

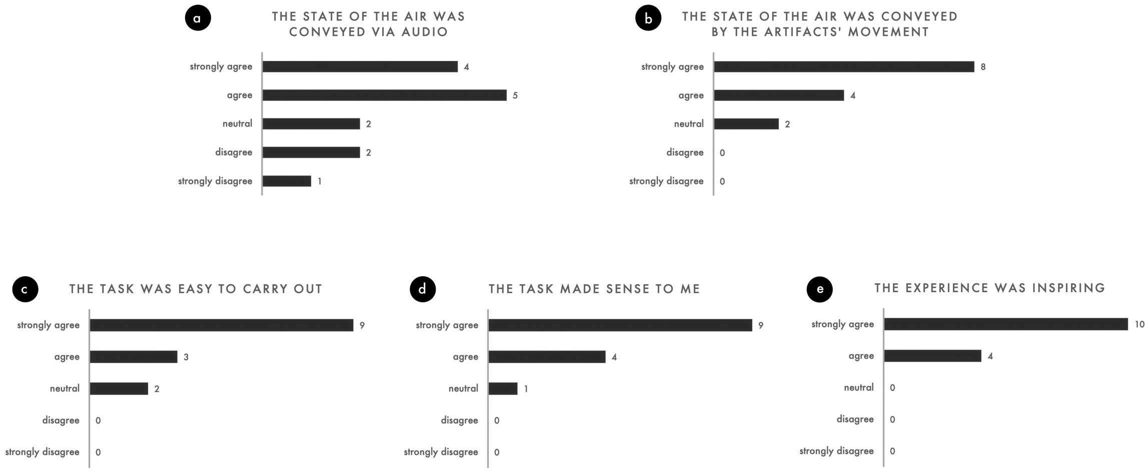


Fig. 8. Results of the Likert scales.

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 interface‘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.”

### 5.5 Significance

To explore significance, we used the interface as an opportunity to ask participants about their worldviews and perceptions of air during the global pandemic [54]. A common worldview among twelve participants was that “humans are 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 DISCUSSION

In the following section, we discuss our findings, further directions for research, and study limitations.

### 6.1 Interface Design

First, we differentiate our practice-based contribution from previous studies. The study *Ivory* [9], for example, provided a sculptural interface that imitates a living organism that detects the atmospheric environment in the near surroundings. On this basis, we developed a body-worn interface to be used as a discursive object in the cultural sector. Whereas *Ivory* was placed into the environment, our study presents a bodily combination of human and non-human species capable of exploring the air in a speculative art installation. In contrast to the previous study *Ivory*, we made different design decisions to create a body-worn interface that is sufficiently robust to be used in a user study and an exhibition space. First, we replaced the shape memory alloy spring with a servo motor to achieve different breathing speeds and reduce the power consumption. Second, instead of a kinetic construction, we created a modular, shape-changing textile that was integrated in various design options (see Figure 6). The development of this modular, shape memory textile allowed us to have an agile design process because we 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*, we composed an real-time, data-driven auditory output that directly maps the parameters of environmental information in high-resolution sound. The measurements of PM-2.5, PM-10, and relative humidity allowed 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, we selected external speakers 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 were perceived differently by the participants. 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. Lastly, in contrast to related works that were presented in the wild [e.g., 43, 55], we created a prototypical arrangement of a speculative art installation that generates a highly concentrated particle field for human–atmosphere interaction. This allowed us to provoke a reaction from the participants to evaluate their experience, as discussed in the following sections.

### 6.2 Environmental Awareness

Regarding the concept of sentinel species [58], we discuss the ability of the sentinel-species-mimicking interface to raise awareness about the environment. According to the results based on the Likert scales, 12 out of 14 participants agreed that the state of the air was conveyed by the artifact’s movement, and 11 participants agreed that the state of the air was conveyed via audio. Thus, it can be assumed that most participants recognized the interface’s warning signals about the state of the air through the physiological behavior of the interface. In addition to the audiovisual eco-feedback, the interface also provoked several associations with nature. We assume that these associations were triggered by the overall experience, including (i) the interface, (ii) the immersive sound, and (iii) the mist from the diffuser. For example, some participants referred to their experiences in nature, while another had the imagination of being in nature. In addition, we have 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 an awareness of their own sensitivity towards the air and a general reflection on the vulnerability of the Earth’s system. Furthermore, in terms of the 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, as the science fiction movie *Blade Runner*, based on Philip K. Dick's novel *Do Androids Dream of Electric Sheep?*, has been mentioned, we reflect on its meaning. The novel illustrates a world in which many animals, especially birds, 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. For us, the comment "Welcome to Blade Runner" indicated that the participant linked the interface with a dystopian fiction that thematizes a damaged planet.

### 6.3 Interspecies Relationship

Referring to Haraway's thoughts [27, 28], we reflect 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. We assume that these traits were probably triggered by (i) the interface behavior, (ii) the materiality, and (iii) the connectedness to personal pets. Some participants, for example, were concerned about the hectic or panting behavior 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 beauty and fragility. Even though 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 behavior was identified as a warning against the diffuser's mist. It is possible that these findings are due to the size of the interface, as only larger birds than a canary were mentioned. Since the interface extends human senses to the state of the air and also engages with people on a social, cognitive, and emotional levels, it has the potential to distract people from their everyday lives and allow them to experience a speculative space that encourages them to look at the world in a different way. In line with critical and speculative design approaches [21], the interface can be used as a discursive object for addressing environmental concerns in exhibition spaces, and thereby transfer knowledge between science and the culturally interested society.

### 6.4 Further Directions

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, we recommend two directions for future research: (i) using the interface to engage with people in exhibition spaces and (ii) conducting long-term, auto-ethnographic studies in everyday life.

*6.4.1 Art Intervention to Engage with People in the Cultural Sector.* Before presenting the sentinel-species-mimicking interface as a speculative art installation in the cultural sector, we suggest some adjustments. Unlike *Ivory*, our contribution provided a visual output at the top of the interface. Even though the visual output was recognized by most participants (n=12), we recommend expanding the shape-changing surface to the sides of the interface, so that other spectators can also observe its changing behavior. Then, 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, we reached our limits with an arm circumference of 30 cm. Thus, a body-worn interface for the exhibition space has to consider various sizes or more flexibility to fit on larger arm circumferences. Additionally, we recommend replacing the inlay of the interface with a softer fabric to ensure that it is not so scratchy for the user. Furthermore, although the ambient sound was only perceived as a subtle sound source by some participants (n=3), we recommend keeping 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 our assumptions, further studies should collect more data from the users' experiences and from other spectators in the exhibition space. We therefore recommend the use of Likert scales to collect data from visitors and thereby make different exhibitions comparable.

*6.4.2 Long-term Auto-ethnographic Research in Everyday Life.* Although the interface was intended for the usage in a speculative art installation, we would like to push this research further towards a real-world application. Since most participants envisioned a kind of personalized interface for ambient awareness and healthcare, and showed signs of caring and empathy for the sentinel-species-mimicking interface, we suggest a personalized version for long-term, auto-ethnographic research. We therefore plan to build on our goals from a previous study to create an interface that measures information from both the human body and the environment [7]. In addition, we will draw on suggestions considering the long-term impact of interactive technologies [61]. Based on this and the participants' statements, we envision a sentinel-species-mimicking interface to improve self-knowledge and the awareness of living in a changing environment. Consequently, we recommend additional design studies, including participatory research, to create an interface that covers different requirements for everyday usage.

### 6.5 Limitations

With the intention of acquiring a first impression of the users' experiences, our research was limited to a qualitative study. Although the Likert scales seem 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 into account (e.g., face masks), which partly affected the clarity of the users‘ statements.

Then, a prior study suggests that participants should practice thinking aloud before the user study [6]. During the study, we noticed that some participants had no problems thinking aloud, while it was an unfamiliar practice for others. Depending on the participant, we individually handled the duration of the thinking aloud task. Furthermore, a few participants explored the setting with the interface quite systematically and played with the distance to experience the interaction, while others needed some guidance from the principal investigator.

Regardless of the challenges, we noticed an initial saturation after collecting data from ten participants. In line with other studies [24], the sample size of fourteen participants represents a first impression regarding user's interactions that can be used as a foundation for future research.

Lastly, although the technical sensors are suitable for monitoring the environment in the wild, it is beyond the scope of this study to use the interface outside the given installation. If a future study considers operating in the wild, we recommend another iteration that integrates speakers into the interface or utilizes the sound of the servo motor as auditory output.

## 7 CONCLUSION

In this paper, we have presented a body-worn, sentinel-species-mimicking interface to be used in a speculative art installation for raising awareness about the environment in the cultural sector. We evaluated this interface through a user study (n=14) in the laboratory to get an first impression about the entire experience. This involved designing and implementing an interface that draws on the concept of sentinel species, in particular the miner's canary, with the aim to convey the state of the air through it's physiological behavior. We also explored an approach for encountering a changing atmosphere to provoke users' immediate reactions about the interaction. This allowed us to gain an initial understanding of the participants' felt experiences and their relationships with the environment. Overall, the findings indicate promising directions towards a sentinel species that mediates the state of the air through non-verbal communication, and also sparks users‘ empathy on an emotional and cognitive level. Based on these results, we recommended future research to focus on two directions: (i) presenting the interface in exhibition spaces to provide a lived experience with a changing atmosphere in a speculative art installation, thereby creating a discursive object that transfers knowledge between science and society; and (ii) creating personalized species-mimicking interfaces for auto-ethnographic research to investigate long-term impacts on environmental awareness and personal healthcare in everyday life. In summary, this study introduces essential steps for future research on human-atmosphere interactions and highlights implications for novel forms of sensitivity regarding the state of the atmosphere and engaging with a changing environment.

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