Towards Atmospheric Interfaces

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ABSTRACT

This paper introduces a preliminary taxonomy to bring the condition of air into the foreground of human perception. To create this taxonomy, we drew on the foundations of atmospheric research and studies in the field of human-computer interaction to provide an overview of different inputs and outputs that enable an interaction with the air. In addition, we present a potential use case that could benefit from a taxonomy to allow the development of atmospheric interfaces and empower the transfer of knowledge. We discuss our findings and conclude with challenges that can be addressed in future research.

CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**.

KEYWORDS

atmospheric interfaces, human-atmospheric interaction, atmosphere, air, air pollutant, environmental sensing, taxonomy

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1 INTRODUCTION

Human activities change the Earth's atmosphere, and although we depend on the air's condition, we are not aware of the state of this essential mixture most of the time [2, 17, 25, 27, 28]. In general, humans can perceive elements of the weather (e.g., wind that moves the leaves of a tree or fog that limits the visibility) but we are not able to determine the air quality that surrounds us [2]. Motivated to augment human perception, we contribute a preliminary taxonomy for atmospheric interfaces that aims to represent the state of air in the physical world.

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This paper is organized as follows: First, we outline literature about the foundations of atmospheric research and human-computer interaction (HCI). Second, we analyze this literature to classify different inputs and outputs and present a preliminary taxonomy for atmospheric interfaces. Third, we describe a potential use case for knowledge transfer. Finally, we discuss our findings and conclude with a summary and suggestions for future research. We hereby confirm that, to the best of our knowledge, this is the first study that presents a taxonomy for atmospheric interfaces which is based on a synthesis of atmospheric research and HCI.

1.1 The Earth's Atmosphere

The composition of the early Earth's atmosphere was different from the air we breathe today, and has changed over the last 4.6 billion years through chemical, physical, and biological processes [2, 27]. Today's atmosphere near the Earth's surface is composed of nitrogen (78.08%), oxygen (20.95%), and small amounts of other gases, such as the greenhouse gas carbon dioxide [2].

As a basis of existence, the atmosphere accompanies us from our first to last breath. It fills our lungs with oxygen, absorbs ultraviolet radiation from sunlight, and affects the way we hear and see [2]. However, with every breath we inhale, we intake not only life-sustaining oxygen but also other airborne substances, such as air pollutants [2]. According to Erich Weber, an air pollutant is "a substance in the ambient atmosphere, resulting from the activity of man or from natural processes, causing adverse effects to man and the environment" [62, p. 241]. For example, anthropogenic pollutants can result from motor vehicle exhaust and combustions of oil, gas, and coal, while natural pollutants can result from forest fires and volcanic ash [2]. Although various air pollutants exist in the Earth's atmosphere, most of them are not visible to the human eye (e.g., the invisible and toxic gas carbon monoxide).

To understand, predict, and monitor the complex and constantly changing atmosphere, humans have observed its behavior for a long time [27]. With the development of different measurement and observation techniques, humans have gained knowledge that has not only provided new insights into the atmosphere itself but has also revealed anthropogenic impacts on the environment (e.g., rising CO_2 concentration) [2, 17, 25, 27]. With this knowledge, the air has become a subject of systematic studies, political debate, and human decisions [28]. To maintain an air quality that allows for human comfort, we must make atmospheric information perceptible to reflect on our behavior and find solutions for a worthwhile future.

1.2 Atmospheric Interfaces

To bring the condition of air into the foreground of human perception, we propose atmospheric interfaces as a term that describes computer-based artifacts that represent atmospheric information to enable an interaction in the physical world. We envision that, rather than only collecting data, atmospheric interfaces can be integrated into our everyday lives. Atmospheric interfaces can become cultural artifacts [52], support personal health care [43], enable playful learning [9, 41, 42, 54, 56], and have the ability to control other systems in a computer environment (e.g., home automation) [5]. For example, a T-shirt that illuminates when the air quality is poor [39], shape-changing columns that respond to CO2 values to control indoor climate [38], or a dress that changes color in a polluted environment [1] are all potential applications.

Due to these diverse examples, we situate atmospheric interfaces in the interdisciplinary research field of tangible, embedded, and embodied interaction (TEI). In 1991, Mark Weiser and his team at Xerox Palo Alto Research Center coined the term "Ubiquitous Computing" to envision a world of seamlessly integrated and connected computer systems that run a particular task [63, 64]. Today, computer systems are integrated in our daily lives and encompass a broad spectrum of computer user interfaces [23]. For example, "Tangible User Interfaces" (TUI) consider a physical control of digital information; with TUIs, users are able to physically grab an object to interact with digital information [31, 33]. To enable a seamless interaction between virtual and physical space, the concept of "Tangible Bits" provides a bridge through the use of i) "Interactive Surfaces," ii) the "Coupling of Bits and Atoms," and iii) "Ambient Media," such as sound [33, p. 235]. In addition, "Radical Atoms" enable users to interact with dynamic materials. Materials, such as shape-memory alloys or thermochromic pigments, can change their shape or color and are considered as a kind of "digital clay" [32, p. 47]. To open this research field to an interdisciplinary community (e.g., computer science, product design, and interactive arts), Hornecker and Buur suggested the related term "Tangible Interaction". They stated that "tangible interaction, as we understand it, encompasses a broad range of systems and interfaces relying on embodied interaction, tangible manipulation and physical representation (of data), embeddedness in real space and digitally augmenting physical spaces" [29, p. 437].

2 RELATED WORK IN HCI

The aim of this investigation is to provide a spectrum of interfaces that encompass both basic types of perception and the perceptional dimension of air in the physical world. To this end, literature that was published between 2000 and 2020 was considered for this investigation. Because we situated atmospheric interfaces in the interdisciplinary TEI community, we restricted our analysis to publications that involve the conference on Tangible, Embedded, and Embodied Interaction (TEI), the conference on Human Factors in Computing Systems (CHI), the Tangible Media Group's project page [45], backward reference searching, and recommendations of relevant studies suggested by TEI community members. We manually examined studies that represent environmental data and analyzed input, output, and type of perception. We then surveyed studies that used the air as medium for interaction. Finally, we organized our findings into major research streams, which are as follows.

2.1 Color-Changing Interfaces

Color-changing interfaces encompass thermochromic pigments [7, 58] and illuminating components, such as LEDs or polymeric optical fibers [13]. For example, the *BIOdress* by Adhitya et al. visualizes air quality data through color-changing fabric. The thermochromic fabric of the dress changes its color according to particulate levels. If the air quality is good, the dress appears green and brown. If the air is polluted, the dress displays a magenta pattern [1]. *EarthTones* by Kao et al. is a cosmetic eye shadow that senses atmospheric hazards. The powder consists of thermochromic pigments that change color when elevated levels of carbon monoxide (CO), ultraviolet (UV) rays, and ozone (O3) are present [37]. The study *WearAir* by Kim et al. introduces a T-shirt that senses the air quality of the user's surroundings. The T-shirt contains a sensor that measures volatile organic compounds (VOC) and interprets different air quality levels by illuminating patterns on the shirt [39]. Finally, Diffus's *Climate Dress* uses embroidered light patterns to visualize carbon dioxide (CO2) levels in the nearby surroundings [18].

2.2 Tactile/Haptic Interfaces

Tactile/haptic interfaces include devices that reproduce tactile parameters [6] or require a tangibility [33]. For example, Ishii introduced the *Weather Forecast Bottle*. When users open the lid of the bottle, they hear audio recordings that correspond with weather forecast data [30]. The study on *Illuminating Clay* by Piper et al. presents a TUI for landscape analysis that enables users to transform an illuminated physical representation of various geological formation [50]. Moreover, tangible interfaces can be augmented with interactive data visualization on table-tops, projections, or fog screens [34, 35, 44].

2.3 Shape-Changing Interfaces

Shape-changing interfaces utilize various actuators to animate a changing surface (e.g., motors, electromagnetic actuators, pneumatic, or shape-changing materials) [53].

2.3.1 Shape-Changing Materials. Materials, such as shape-memory alloy (SMA) or polymers, can be controlled by direct or electrical stimuli to achieve kinetic behavior [8, 14, 16]. For example, *Shutters* by Coelho and Maes introduces a fabric surface with shape-memory mechanisms to control the climates in buildings [15]. Khan's *Open Columns* is an architecture made out of shape-changing material that responds to CO2 levels [38]. *Ivory* by Broscheit et al. measures particulate matter (PM2.5) and interprets the data through the use of kinetic behavior supported by sound [10]. Fabrizi's study on *Fiori in Aria* presents textile flowers that open and close by using SMA to indicate good or poor air quality [22].

2.3.2 Pneumatic Interfaces. Pneumatic inflation is another technique for implementing shape-changing interfaces that also presents properties of the air. Compressed air powers pneumatic interfaces to create a programmable shape-changing behavior [66]. For example, *AeroMorph* by Ou et al. provides a research about pneumatic interface implementation [48]. Yu's *AirMorphologies* introduces a wearable interface to improve social interaction in polluted air environments [67]. *Auto-Inflatables* by Webb et al. proposes a method for pop-up fabrication via chemical inflation; the inflating process takes advantage of the CO_2 output produced from the chemical reaction between sodium bicarbonate and citric acid [61].

2.4 Mid-Air Haptic

Mid-air haptic provides tactile sensations without direct physical contact via air vibrations [51]. For example, *WindyWall* by Tolley et al. simulates wind data and consists of a three-panel, 90-fan array that provides a horizontal wind coverage [59]. *UltraHaptics* by Carter et al. introduces mid-air haptics on top of a graphical user interface [12]. The study *Perception of Ultrasonic Haptic Feedback on the Hand* by Wilson et al. presents an array of ultrasonic transducers that produces air pressure waves and generates haptic stimuli on the user's hand [65]. *AIREAL* by Sodhi et al. uses compressed air pressure to simulate a sensation on the user's skin [57]. Lastly, the study on *HaptiRead* by Paneva et al. presents an interface to provide touchless Braille information [49].

2.5 Olfactory Interfaces

An olfactory interface provides a computer-controlled smell to an user [46]. For example, *Bin-ary* by Amores et al. uses hydrogen sulfide (H_2S), ethylene (C_2H_4), carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen (H) sensors to detect bad odors from trash and releases a scent in response [4]. In addition, Amores et al.'s study on *Essence* introduces a necklace that releases a fragrance based on biometric and contextual data [3]. *Clayodor* by Kao et al. explores smell through the modification of a clay-like material. Users can form the clay into a specific shape (e.g., a banana or a strawberry), and the clay produces a matching odor through the use of a piezoelectric transducer and a machine-learning algorithm [36]. *Scented Pebbles* by Cao and Okude creates an ambient experience with lighting and smell. If the scented pebbles detect the user's touch or movement, they generate a scent by utilizing a piezoelectric transducer [11]. *On-Face* by Wang et al. is a lightweight olfactory wearable that can be worn on the skin, or attached to glasses or piercings [60]. The study *SensaBubble* by Seah et al. presents a mid-air olfactory experience through the use of scented bubbles [55].

3 PRELIMINARY TAXONOMY FOR ATMOSPHERIC INTERFACES

The literature review of atmospheric science foundations and HCI research studies has presented various inputs and outputs that can be used to make the atmosphere's condition perceptible. Furthermore, the analysis of these studies has led us to conceive a preliminary taxonomy (see Figure 1) that provides an overview of basic atmospheric information that was categorized as input (see 3.1) and different interface approaches that was categorized as output (see 3.2).

3.1 Input

Within the taxonomy, input contains three classifications. First, the center of the taxonomy defines "the composition of the atmosphere near the Earth's surface," which includes permanent gases, variable gases, and particles [2, p. 6]. Second, the section "primary air pollutants" includes carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds (VOC), sulfur dioxide (SO_2), and particulate matter (PM), which can enter the atmosphere directly and are produced by natural and anthropogenic sources [2, p. 435]. Third, the section "elements of weather" consists of air temperature, air pressure, humidity, clouds, visibility, wind, and precipitation (e.g., rain and snow). These elements are responsible for atmospheric dynamics [2, p. 15]. To use atmospheric information as an input, users can work with environmental sensors, comma-separated values, or open application programming interfaces (API), such as the air quality data provided by OK Lab Stuttgart [47].

3.2 Output

Output presents a selection of different approaches to create an atmospheric interface. The category contains i) tactile/haptic interfaces and mid-air haptics to provide a haptic perception; ii) color-changing-, shape-changing-, and pneumatic interfaces and shape-changing materials to provide a visual perception; and iii) olfactory interfaces that enable the perception of smell. In addition, these interfaces can be enriched by sound to provide an auditory perception. Users of this taxonomy can build on basic research and gain inspiration for interpreting environmental data according to their preferred senses.

3.3 Interaction

The state of the atmosphere can be perceived through atmospheric interfaces that mediate forecasts, current or historical information [e.g., 4, 30, 39]. In addition, users are able to manipulate sensor values through their direct activities (e.g., exhalation to increase CO_2 sensor levels) or indirect activities (e.g., using a vaporizer to increase particle sensor levels; see Figure 2).

3.4 Potential Use Case

Based on the experience that has been gained in a prior pilot study that focused on PM [9], we believe that this proposed taxonomy is a starting point to empower the creation of atmospheric interfaces within participatory workshops.

3.4.1 Participatory Workshops. In the framework of an urban artist research and mediation project, we realized that participants have different concerns and interests to perceive the state of air [9]. Providing personal health care to prevent asthma attacks, creating a warning system for fresh air supplies in classrooms, or wearing inflatable suits to store healthy air were some of the discussed topics (see Figure 3). Using a taxonomy could support peoples' creative processes to visualize the invisible aspects of the air according to individual preferences. With methods, such as "Life-long Kindergarten," [54] "Critical Making," [26] or "Speculative Design," [20, 21] we want to empower personal expression, playful learning, and the creation of objects to debate. To this end, we would use the taxonomy to introduce basic knowledge about the atmosphere and different interface approaches. Participants could then choose what information they like to measure and how they want to display this information in the physical environment. After this introduction, the creative process then depends on difficulty level, budget, and time.

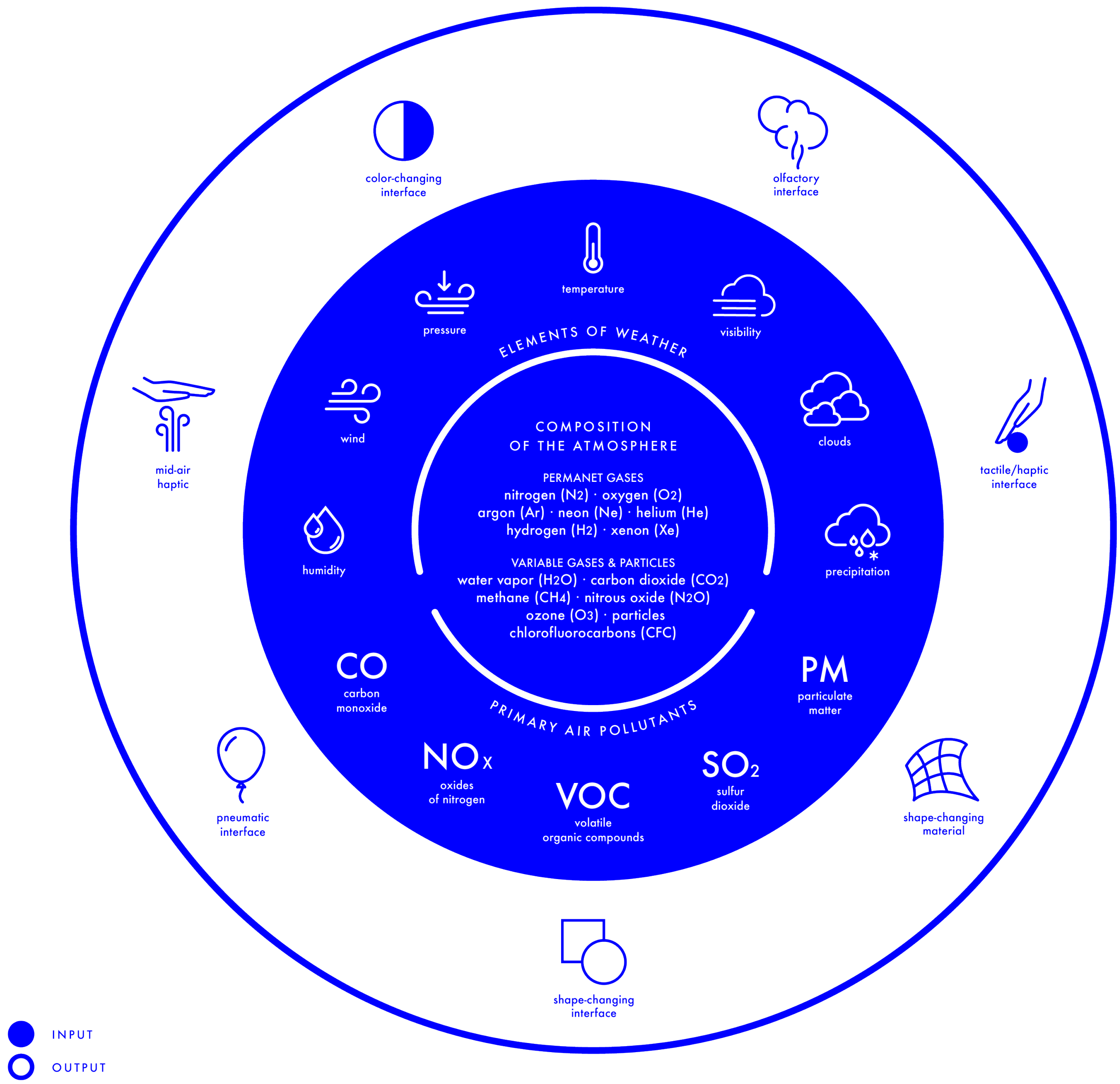

Figure 1: This figure depicts the preliminary taxonomy for atmospheric interfaces. The blue section illustrates atmospheric inputs, and the white section presents major research streams.

3.4.2 *Cooperation and Outreach.* Climate change has made monitoring environments relevant in the framework of citizen science projects [25]. Citizen science enables individuals to participate in alternative research projects that address various issues. This method is actively used in the area of HCI to provide technological solutions for environmental sustainability and urban development [19], such as networked air quality sensors that are used as tools for bottom-up community data collection [24, 40, 47] or participatory workshops to transfer knowledge about environmental issues [9, 41, 42]. Therefore, cooperation and outreach could be considered with environmental research centers, educational projects, open knowledge foundations, maker spaces, museums, and galleries.

4 DISCUSSION

Our goal was to create a preliminary taxonomy based on existing methods that provides examples of both types of perception and the perceptual dimension of air. We presented results of interfaces that provide a haptic-, visual-, and olfactory perception. These interfaces

Figure 2: This field observation demonstrates a speculative prototype triggered by vapor, which participants designed in a prior workshop.

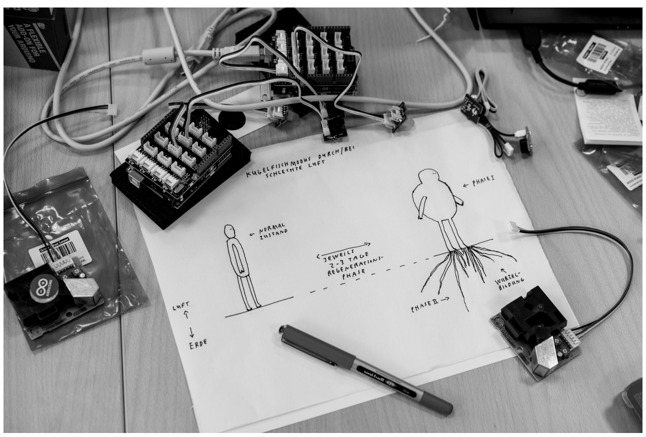

Figure 3: This participant's sketch envisions a body suit that inflates if a particle sensor detects hazardous values. This enables the suit's wearer to store air for breathing.

can be enriched by sound or combined with other approaches to enable a multisensory experiences [e.g., 10, 11, 30, 36, 50, 55]. So far, gustatory interfaces that represent environmental data, appear to be a research gap. Although, olfactory interfaces and mid-air haptics are not directly related to TUIs, discussions are taking place concerning how the air could be perceived through its own perceptional dimension. According to Eva Horn, exploring the sensory quality of the air is important to bring "air (back) to the foreground of our perception as both object and condition of perception" [28, p. 23]. In our literature review on related work, pneumatic interfaces and shape-changing materials are included in the umbrella term shape-changing interfaces. Because these interface approaches are prominent research streams, they were presented with their own icon to visualize a wide range of outputs. The categorized inputs provide the first glimpse into atmospheric science foundations. Because this field of research is broad, we wish to develop different versions of the taxonomy's core to feature various topics over time. In this version, measurements of primary air pollutants can detect contaminated environments or invite for human-atmospheric interactions (e.g., with particle sensors and fog; see Figure 2). In addition, we intended to develop a tool that presents interface approaches beyond graphical user interfaces to expand participants' creativity, even if they do not have the required technical know-how to produce ideas like an inflatable body suit (see Figure 3). Hence, we considered the taxonomy from different perspectives that depend on difficulty level, budget, and time. For example, a one-day workshop could provide an output of a sketch or functional paper prototype (see Figure 2 and 3). A half-year project with students could deliver more complex applications (e.g., the implementation of tangibles on tabletops for environmental data visualization or the development of toolkit modules for workshops). However, the COVID-19 pandemic has restricted the opportunities to run workshops on-site. But regardless of the pandemic, it should be discussed how hands-on workshops and debugging prototyping kits could be conducted in virtual spaces.

5 CONCLUSION AND FUTURE WORK

In this paper, we presented a preliminary taxonomy for atmospheric interfaces. For the taxonomy's development, we referred to the foundations of atmospheric research and analysed data from studies in the field of HCI. In addition, we considered a potential use case for transferring knowledge and discussed our findings. To ground the preliminary taxonomy, future studies should address the following challenges: First, we invite discussions about the proposed taxonomy with TEI community members, designers, and media artists. Second, we are currently investigating the interaction space of atmospheric interfaces. In this context, we suggest classifying different environmental sensors to explore their possibilities for human-atmospheric interaction. We also suggest that an advanced toolkit be developed that includes the preliminary taxonomy, electronic components, and different materials for inspiration and fast prototyping (e.g., swatch books, cardboard, pencils, scissors, and glue). Finally, an evaluation of a participatory workshop could provide promising results about participants' needs and concerns, the most preferred inputs and outputs, and the usage of the preliminary taxonomy. In summary, this study introduced important steps for future research implications that encompass the development of interfaces to perceive the state of the air in the physical environment and to empower interdisciplinary knowledge transfer.

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