AirCraft: Exploring Air as a Design Medium

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Figure 1: Presenting AirCraft along with its use in a workshop. (a) rendering of initial AirCraft concepts as a set, (b) brainstorming wheel, (c) elemental discovery cards, (d) prototyping blocks, (e) participant blowing the brainstorming wheel, (f) participant explaining idea with the cards, (g) participants trying different air movements through prototyping blocks.

Abstract

Air is essential for all living things and is felt through wind, our breath, and artificial air currents from fans. Current research surrounding air in interactive systems is limited to pneumatic haptic technologies, which can result in barriers to creative experimentation by designers with limited technical expertise which traditionally associated with STEM fields. Additionally, harnessing air as a design material needs deeper investigation, including the elemental and instinctive aspects of air that make it an integral part of our sensory existence and lived experience. In response to these gaps, we created AirCraft, a toolkit to explore the use of air as an expressive design medium. We deploy and assess this toolkit through generative design workshops involving designers and makers from diverse backgrounds. Outcomes showcasing various ideas and shifting perspectives on using air as a design element. We emphasize the importance of incorporating air into interaction design and advocate for further exploration of this overlooked material for design interactions.

CCS Concepts

• **Human-centered computing** → **User interface toolkits**; **User studies**.

Keywords

Air, Toolkits, Research through Design, Haptic Interactions, Embodied Interaction Design, Design Workshop, Tangible Artifacts

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1 Introduction

Air is a critical component for the existence of all living organisms, including humans. Air is also ubiquitous and omnipresent. Humans, in particular, reside within the constant flow of air, whether it's the natural winds created by nature, the breaths we take, or artificially generated currents from building systems, such as HVAC. As we observe the various ways in which air is harnessed, used, and experienced, it is natural to wonder if these interactions truly capture the essence of air. Although these applications use specific characteristics of air, such as lightness [84], buoyancy [9, 74], transparency [7, 9], and abundance, they may not evoke more familiar facets closely tied to human experience, such as how people feel the wind brushing against their skin or how they actively engage with air through activities such as surfing, walking, or skydiving.

It is essential to consider air as a design medium because it enables users to interact with systems without physically touching a surface, fostering more intuitive and natural experiences that mirror our interactions with real-world objects [29]. Furthermore, integrating air with touch and other input methods creates a richer and more flexible interaction paradigm, enhancing multimodal systems that improve accessibility and user satisfaction [16, 23, 38]. Engaging with air also allows for the freeing up of valuable screen-based interactions, facilitating larger-scale and more complex interactions without cluttering the interface[43, 54].

Designing active engagements with air has been previously explored. For example, pneumatic systems have been widely used in Human-Computer Interaction (HCI) because of their ability to provide tactile feedback and enhance user interaction through the contained air, such as inflatables. These approaches simulate physical sensations like pressing buttons or feeling resistance, enabling the creation of soft and deformable interfaces [24, 26, 36, 67, 81, 88]. Although pneumatic systems rely on additional devices such as compressors and pumps, they offer extra benefits such as space efficiency with diverse material combinations. These include increased storage capacity, accessible mobility, and adaptation to various scenarios while providing safe and flexible material properties [7, 17]. However, current pneumatic systems heavily rely on being enclosed with secondary materials, limiting direct interactions between people and the air. Furthermore, we identified a need for a design approach suitable for designers with less technical expertise but a stronger focus on interactions and its narratives, to explore multifaceted aspects of air beyond current technical approaches.

Using a Research through Design approach, this paper iteratively investigates air as a design material and the opportunities to realize approachable designerly toolkits to design sensorial experiences and interactions with air. Based on these investigations, we describe the implementation of a toolkit, AirCraft. Our toolkit works to foster a designer's sense of air's potential to extend beyond utilitarian applications and supports the design of both direct and indirect encounters with an uncontained flow of air. To examine how it helps designers view air as a design medium, we deployed AirCraft in generative design workshops with 12 designers from various backgrounds. The outcomes illustrate the potential of the toolkit to inform design practices and how conventions of designed interactions with air can expand to include elemental, instinctive aspects integral to our sensory existence of air flows.

This paper contributes to an ongoing exploration of air in three main ways. Firstly, it further illustrates and characterizes opportunities to design direct interactions with uncontained air. In particular, our work highlights air as a somaesthetic design material [22, 30, 69] and its sensorial intimacy, intuitive nature, and intrinsic relevance to human existence. This contrasts with most applications of air within HCI where it is most often a secondary consideration in input-output mechanisms. Secondly, we demonstrate the value of our toolkit in expanding interaction design practices to the medium of air flows. Our approach familiarizes designers and makers with air's applications in design, and empowers designers of varying technical backgrounds, to explore a wide range of design concepts that can leverage and prioritize air's unique properties in interaction design. The workshop outcomes showcase innovative design concepts with Aircraft and how designers imagined the versatile potential of air as a creative and interactive medium, introducing innovative design concepts created while utilizing AirCraft. Demonstrating this work and the designerly approaches to air, AirCraft serves as a catalyst for further design-oriented inquiry into air. We hope that both the toolkit and the sensorial exploration in this paper invite further investigation into air as a compelling design material for interactions.

2 Related Work

2.1 Phenomenology of Air

While air is invisible it is a complex element that can be experienced, felt, and perceived in multiple and important ways. These experiences stem from variations in its fundamental properties: humidity [51], and temperature [83, 89]. These can affect our perception of an environment and its comfort. Studies have shown that most people will find temperatures above 26.1°C and relative humidity of 70-80% uncomfortable, and increased humidity negatively affects thermal acceptability [87]. High ambient air temperature can also decrease wellbeing [56] and affect perception and emotional response [11, 18]. In addition to temperature and humidity, air can flow. The direction and speed of flow (or the absence of flow) are also important properties of air. Air flows contribute to our perception of space. In particular, and as air flow helps the body to regulate temperature, air flows have been demonstrated to increase perceived coolness in hot conditions [91]. Although wind speed and direction can contribute to heat transfer, it is a complex process with many other contributing variables including metabolism, humidity, and body temperature [71].

Additionally, air flows are a medium by which chemical compounds, including for example volatile organic compounds (VOCs), pollutants and fragrances, are conveyed. The presence of these compounds can affect the body in a range of ways. VOCs, dust, pollen and other allergens are carried in air flows and can produce coughing, irritation, and diminished wellbeing. Air flows, as with

perceived coolness, can also increase perceived air quality, especially if air flow is directed towards the face and when the air is hot, humid and contains high levels of pollutants [50].

Importantly, air is also a medium that enables two of our primary senses: hearing and smelling. Sound waves can move through the air as vibrations that may reach the body and be felt by the skin as touch or heard by ears. Similarly, air is responsible for carrying fragrances and smells to the nose. In turn this can provoke strong emotional responses from pleasant to disgusting. Depending on air flows, smells may linger or fade. Smells, too, can trigger memory [41, 86] and transport you to an experience, place, or time in your life. Smells are "located with reference to source, air currents, and direction and distance from source" and thus site-specific [60]. Conveyed by the local microclimates of air and air flow, smells help to define and enrich the character of a place [60]. This is a partial overview of the features and effects of air and air flow. Other qualities include air's lightness [84], buoyancy [9, 74], transparency [7, 9], and abundance [5]. These aspects layer and interact with one another in ways that both enhance air's interactive potential and make the design of air-based experience challenging.

2.2 Air in Creative Expression

Some creative works have already experimented with leveraging the different properties and features of air. For example, architectural research has explored temperature regulation within air by using Shape Memory Alloys (SMAs) to create dynamic and responsive installations [52, 89]. Projects like LOTUS 7.0 [65] demonstrate this approach. Artists like Berndnaut Smilde [6] use humidity to create indoor artificial clouds, visually representing the presence of air in space. Within mixed reality technology, incorporating scents into the air has been used for immersion and sensory experiences of virtual environments [13, 37]. Scents have also been deployed to evoke memories [37, 53] and to facilitate communication between participants. Also, there have been projects involving air quality, such as creating a visual display of air quality that is interpretable in different cultural backgrounds [25]. Notably, artists like Michael Pinsky with his Pollution Pods [59] have pushed these boundaries further, offering a sensory exploration where visual and olfactory cues enable people to perceive and interpret air quality in new ways.

Moreover, people's lived experiences are also explored by drawing inspiration from cultural traditions involving air manipulation, such as flying kites, blowing bubbles [15, 39, 68], and launching paper planes, can enrich emotional experiences. By tapping into familiar interaction cues and evoking nostalgic emotions associated with these experiences, engagement can be heightened in interaction design.

Some artists have improved their sources of air by utilizing natural airflow driven by winds or pressure differentials in the environment, such as in a power source or architectural design. For instance, Alexander Calder's mobiles [12] and windmills use small amounts of air to create movement, while Theo Jansen's moving sculptures [32] use large-scale air flow, such as sea breeze, to move larger art pieces. Besides the creative works, wind turbines have been generating massive energy through natural air flow, and ventilation systems in architecture are another way of leveraging the air in people's lives. The others have highlighted the practical deployment aspects of air in their large-scale installation. For example, [7] and [17] demonstrate the use of inflatable architecture as large as people could visit inside, offering people an immersive experience of air's volumetric and invisible characteristics. This architectural approach is favored for its ability to minimize sculpture weight while maximizing volume, enabling ease of shipping, reproduction, deployment, and retraction in various locations. This approach can be achieved relatively less reliant on digital technology by leveraging the abundance of air, and most importantly, tapping into people's intuitive understanding gained from their daily experiences with air. Although utilizing the air from the body and environment is instinctively easy to use, its application has been predominantly restricted to initiating feedback loops and simplifying the process.

2.3 Air in the I/O Interfaces

There is much potential to leverage air as both input and output for interactive experiences. Air flows produced by breathing have been most extensively explored as an input. Breath, a biologically generated air flow, is symbolic of life, and it has unique poetic elements. Moreover, as an innate product of the body, breath creates universal potential for participation in interactive experiences and installations. For example, in gaming, modified gas masks have been used to monitor breathing flows and interactively control a series of games [77]. It has also been used to increase the feeling of connection, awareness, and empathy between participants and with nature through breathing synchronization [76]. Additionally, various projects use breath to craft different modalities of experiential modalities, such as illuminations [1, 62] and atmospheric effects like mist [51], scaled haptic experiences like Blow Up [8], and Into the wind [35].

Alternatively, air is also often to create haptic feedback. Haptic feedback and the embodied sensations it creates, is an important aspect of many interactive technologies, such as mixed reality, as they enhance immersion and add realism to immersive experiences. Multiple haptic systems examine air flow for feedback, for example, in I/O interfaces [24, 81, 88], fluidic channel embedded wearables [26, 36, 67], and soft robotics [46, 66, 89]. Current research on air-induced haptics focuses primarily on pneumatic systems that use contained or compressed air in sealed pockets, membranes, or inflatable materials. These systems often require additional materials like elastomers and textiles to allow for the expansion and contraction. However, these materials also create a barrier between air flow and direct contact, often shifting the focus of interaction toward the encapsulating materials rather than the enabling air flow itself.

Alternatively, mid-air haptic systems have been gaining popularity. This approach does not require the user's hand to physically contact with a surface or material to create interactive feedback. For example, AiReal created a controllable device that generates air vortexes and directs them toward a person to create sensations of virtual objects or to provide interactive feedback. AiReal also examines the potential to distribute air-based haptic feedback into the environment [75]. Similarly, other research has demonstrated the potential for ultrasonic speakers to create more varied patterns of haptic feedback in mid-air haptic experiences [14, 34, 42, 70]. Some researchers have explored the replication of haptic sensation

using air as an alternative medium. For example, simulating the sensation of water flow through air flow enables the creation of immersive experiences without confining the environment to wet conditions [64]. However, such haptic experiences are typically limited to small areas of focus, limiting the interactive potential.

Alternative approaches to harnessing the effects of air for interaction have been explored in fans. Wearable devices [63, 85] simulate the environmental winds and the temperature of the air, and create imaginary movement like teleport by creating the airdrag [78] to offer rich haptic feedback of Virtual Reality (VR) experiences. Additionally, other projects have used pressure that is created by air flow to expand possibilities beyond direct interaction with the air itself, tapping into its inherent impact. For example, wearable devices such as WindBlaster [33] incorporate propellors to create force feedback. This overcomes spatial limitations of current mounted devices, allowing users freedom of movement and increasing portability. However, while on-body devices have potential in immersive interactions, they also pose limitations. In Extended Reality (XR) scenarios, achieving comprehensive sensory engagement may require wearing multiple devices too, resulting in added weight and ergonomic challenges. These considerations underscore the importance of balancing innovation with usability in designing immersive experiences.

Additionally, while these approaches expand our relationship to air in designed interactions, they require significant expertise to customize and adapt or are cost-prohibitive for broader use. As a result, these approaches remain largely inaccessible to artists and designers to experiment with air as novel material for interactive systems. Consequently, air as a design material needs additional investigation.

2.4 Toolkits for Democratizing Design

There are already a small number of toolkits that focus on integrating air into interactive systems [82, 90], streamlining prototyping processes [34, 48, 55, 73], and reducing physical module volumes while maximizing air flow efficiency. Most have focused on enabling interactions with contained or compressed air through pneumatic or inflatable systems. For example, FlowIO [72] and Pneuduino [28, 57] offer portable, modular pneumatic solutions that simplify prototyping, which is particularly beneficial for designers focusing on pneumatic system dynamics. In contrast, the Soft Circuits Toolkit [80] introduces analog pneumatic systems to aid designers with limited technical expertise, emphasizing soft robotics and programmable materials over direct air flow interactions. However, these toolkits were primarily developed for soft robotics and optimizing pneumatic systems. Notably, they do not specifically focus on designing direct interaction with air, but rather on developing technology with the assistance of air.

More broadly within HCI, there is a growing interest in creating toolkits to improve user interaction through versatile and customizable interfaces that cater to diverse creative needs and preferences. These approaches can offer insights into addressing the constraints of technology-driven design methods and enhancing accessibility for designers with limited technical knowledge. Examples of such toolkits include ThermoPixel [79], which empowers novice participants to imagine and design personalized affective interfaces, and 'It Puts Life into My Creations' which reduces technological barriers by creating a toolkit that easily controls the fluids to explore emerging material, fluid fibers, in expressive display [44]. These toolkits typically use modular components, frameworks, and material libraries, allowing designers and researchers to quickly prototype and iterate a range of applications [28, 57, 72]. They also foster participation and collaboration to explore how collaborative design processes can enhance affordance and accessibility in HCI.

Despite advancements of toolkits in technological supporting roles, there is also a focus on toolkits designed to support the design process outside of prototyping sessions. Analog tools like cards have been widely used because of their cost-efficient, visually comprehensive, and portability. Some toolkits like MakerCards [47] assist electronic educational components by allowing remote access to information and personalization of learning. Other tools like Method Cards [3, 92] offer a variety of design methods, activities, and strategies in concise formats, the Design with Intent Toolkit [45] incorporates the principles of behavioral psychology and human behavior into their design processes easily. Also, there is The Thing From The Future Cards [40], which is designed to stimulate future scenarios and possibilities in design thinking. The IoT Inventor Toolkit [4, 49] and IoT Service toolkit [21] also utilize the form of boardgame supporting people to experience the design process step by step. These analog toolkits are used primarily in workshops and brainstorming sessions. Common to these approaches is how the toolkits actively encourage new design concepts and stimulate creativity with unfamiliar subjects and scenarios.

Our work bridges these areas by developing a toolkit that encourages brainstorming ideas for interacting with air, supports prototyping sessions, and expands the creative potential for designing with direct air interactions.

3 Approach and Early Explorations: Research through Design

While there have been technical explorations of air in interaction design, we note a lack of design-focused exploration. To better understand air as a design medium, we used a Research through Design (RtD) approach [20, 93] to build an understanding of the complex nature of air. We did this for three reasons. Firstly to help identify unexplored aspects of air as inspirational resources; to involve hands-on design action in order to build engagement with air as a material. Specifically we aimed to materialize the invisible aspects and abstract perceptions of air. During the creation of artifacts, a RtD appproach also encouraged experimentation with air itself. Finally, these resulting artifacts helped act as tangible conversation pieces with other researchers, facilitating discussions

Code	Background
EP1	Interaction Design, UX Research, Business Consulting
EP2	Computational Design, Architecture
EP3	Interaction Design, Landscape Architecture
EP4	Computational Design, Architecture
EP5	Computational Design, Physics

Figure 2: Five early exploration participants table including assigned code, and background.

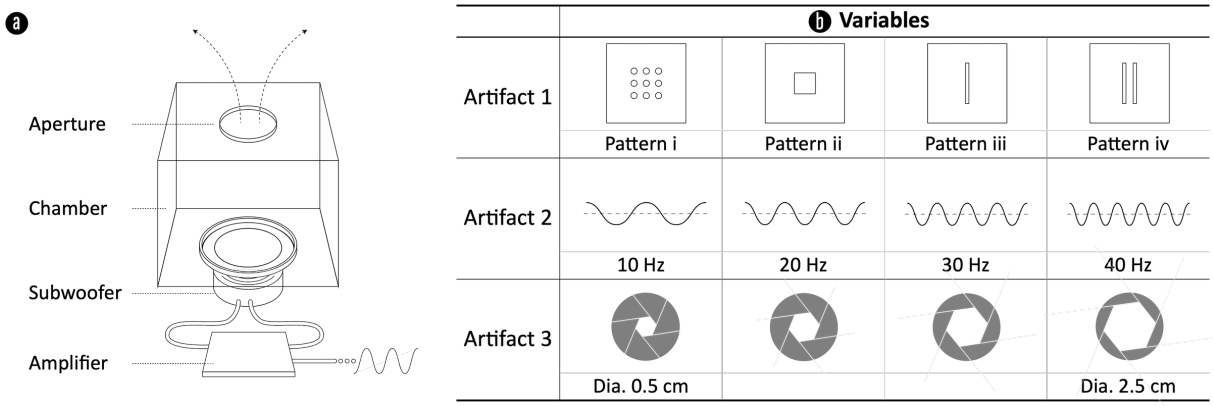


Figure 3: Image of Artifacts in Research through Design Inquiry in early exploration. (a) Basic structure of artifacts (b) Controllable variables in each artifact: Artifact 1 can change the aperture shape in four different patterns. Artifact 2 can control the frequency of the sound wave from 10Hz to 40Hz. Artifact 3 has a camera aperture that opens from a diameter of 0.5cm to 2.5cm.

on both the opportunities and challenges of designing with and for air. This section describes this journey and the insights and how they informed the design of the *AirCraft* toolkit.

3.1 Exploration through Artifacts

Within our early work, we sought to move away from the long traditional of wind-based experiences and realized the need for new methods beyond conventional fans. During a user study and expert interviews, participants shared their previous experiences with air-based projects. Their feedback highlighted that the noise and mechanical sounds from fans greatly impacted user perception and emotional responses to air interactions. This line of inquiry led to the development of artifacts inspired by Aireal's principles [19] and operated as mid-air haptic devices. We created three different prototypes using subwoofers to make the air vibrate (depicted in Figure 3, Figure 4). The first artifact explores different aperture formats from a grid of small openings, a small single central opening, and one or more slits. The second artifact focused on studying the effect of subwoofer sound frequency, from 10Hz to 40Hz, on air flow and vibration. The third artifact investigates the use of an aperture that can be adjusted from 0.5cm in diameter to 2.5cm in diameter. These artifacts represent our exploration of subwoofer technology combined with surface forms to manipulate air vibrations, aimed at enhancing user interaction through controlled sensory stimuli and customizable tactile feedback.

3.2 Conversation with Artifacts

We conducted a conversational session with five participants (see Figure 2). Our aim was to understand the relationship between the patterns controlled by artifacts for two key reasons. First, since these artifacts allow users to control sensory stimuli that is unconventional and without a specific context, we hypothesized that different airflow patterns could evoke distinct emotional responses, potentially serving as a parameter for utilizing air. Second, we wanted to gather users' insights rather than merely replicating sensations based on our own interpretations. The study took place in a quiet room, allowing participants to fully immerse themselves in the tactile experience for about an hour. Ear protection was available for those who preferred it; however, only one participant (EP1) initially tried it but ultimately decided not to continue using it.

Each participant received four emotion cards — happy, relaxed, angry, and sad — representing the extreme ends of the arousal and valence spectrum. They were also given blank *Emotional Circumplex Maps* based on Russell's theory [61] and asked to define each emotion based on their own subjective experience. After mapping their emotions, participants engaged with three different artifacts and were encouraged to think aloud as they mapped the four emotions with each variation in the artifacts using the emotional map as reference (see Figure 4).

3.3 Findings

Participants were free to associate prototypes and their varied airflow patterns with emotions. For artifact 2, we observed that subwoofer frequency often correlated with the arousal level participants associated with the arousal on the circumplex map. For instance, participants who identified anger as the highest arousal matched this emotion with the highest frequency (40Hz) on the map. Similarly, participants who mapped happiness as the highest arousal also associated it with the highest frequency. The aperture size and frequency showed similar trends in arousal. Smaller apertures were associated with higher arousal, but defining the valence of the emotion was difficult. An intriguing discovery emerged with this particular artifact 3, as it proved to be continuously adjustable, unlike the others with fixed elements. We identified a transition method that facilitates a digitized and uninterrupted shift between states, offering insights into valence relationships.

In exploring artifact 1's various opening patterns, participants showed a clear preference for two patterns (pattern ii and pattern iii, depicted in Figure 3), which evoked strong feelings of arousal. Participants described similar air flows in these patterns based on their personal experiences. Another notable aspect was that participants attributed an emotional response to artifacts 2 & 3, for

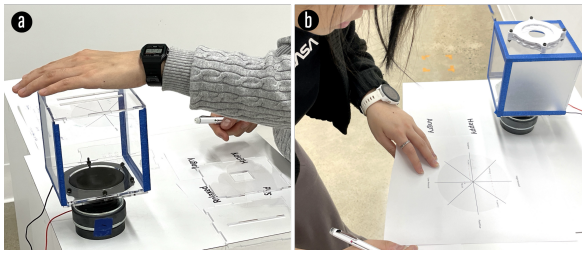


Figure 4: Images from the early exploration of three artifacts with the participant: (a) the participant trying different patterns of air on their hands, (b) the participant mapping their emotional response to each air pattern on the circumplex map.

example, by describing the prototype as "angry." In contrast, the responses to artifact 1 were more personal and reflective, with participants expressing their own emotions and making associations to other experiences, for example, "It reminds me of this...". This indicates the potential of shaped air flows and crafted mid-air haptics to evoke bodily experiences and personal associations. However, these associations are deeply personal so a challenge lies in crafting apertures and shaped air flows that provide a generally agreeable experience while allowing room for personalization. Observing the participants, we saw that the modular opening patterns appeared easy to interchange. Further, several participants stacked the modular openings to create an array that crafted unique sensations and sculpted air flows to their liking. This showed potential to layer apertures on each other, like building blocks, to create more complex effects and increased customization.

3.4 Reflection with Experts

To supplement the findings from the user study, we extended the conversation by gathering input from five professionals and educators in various design fields. We presented the artifacts and the user study to the experts and discussed their responses. Initially, our goal was to measure artifacts and related user study criteria, focusing on interactivity, embodiment, empowerment, and engagement. However, the discussions naturally evolved into open conversations about air as a design medium, allowing experts to share their own perspectives in general. These conversations helped us critically review and assess the design approach and artifacts and generate ideas about the toolkit. All interviews were recorded and coded and we used affinity mapping to organize the data into pre-prepared categories and new ones, which were then axially coded to explore relationships and insights. We distilled the conversation and organized feedback around three keywords: interactivity, embodiment, and inspiration.

3.4.1 Interactivity. We define interactivity as fostering inherent curiosity and willingness to experiment. E1 and E2 specifically noted that while the relationship between air and humans is fundamental, it evolves into a more complex personal relationship. *"The feeling of air caused by someone blowing in my face is entirely different from the natural breeze flowing from the hill. But you could say in a physiological sense, the sensation can be very similar, but the story behind it is incredibly different. (E3)", "Different people represent the same thing in the same way. (E5)"*

Code	Design Background
E1	Industrial Design, Interaction Design, Transition Design,
E2	Industrial Design, Product Design
E3	Industrial Design, Design and Technology
E4	Human-Machine Interaction in Architecture, Design based on Cybernetic Epistemology
E5	Architecture

Figure 5: Design background information of five experts along with their assigned code.

The previous associations can be used to play with the expectations that are observable in everyday scenarios. For instance, the subtle shift in air flow before a sneeze allows individuals to anticipate this forthcoming event. *"I always find that quite interesting that a sudden movement in the air signals that something is about to happen. ... the wind is evidence of something happening; it's like that, a clue. ... the way that air connects you to the future. (E1)"* This predictive nature of air can serve as a connective clue, bridging individuals to coming occurrences. On the other hand, deviations from established relationships could reduce the experimental quality. *"Everybody coming into this interaction already has a pre-existing relationship with air, which is helpful and unhelpful... (E1)"* Therefore, balancing this association can provide a unique experience that inspires diverse approaches to spark curiosity. This highlights the significance of the design approach in the development of air as a design medium.

3.4.2 Embodiment. As air transitions from intangible to tangible, opportunities arise to manipulate its characteristics, enhancing the embodied experience. However, the sensory experience facilitated by air is often overlooked. Since our bodies act as both input and output devices, the embodiment's control dynamically changes based on the engaged elements. Participants noted that the artifacts, particularly, prompted them to imagine various air textures.

Many attempts in the entertainment industry have added multiple modalities and they have often failed to meet expectations. This was noted as something to avoid. *"At movie theaters that, coupled with some haptic technology, the vibrations are meant to make you feel (immersed)... but it takes your imagination out of the movie... these things are to make you feel more authentic, but you're much more present in your own body in there... the intention is totally different. (E2)"* This embodiment is also crucial, particularly because it integrates real-time elements and fosters a sense of immediate co-presence in the moment. *"When you are adjusting your breath, you're responding to its state of change in real-time, taking more breaths and blowing harder, softer... (E2)"*

3.4.3 Inspiration. During both early explorations and expert interviews, various ideas that diverged from the original intended use of the prototyped artifacts were uncovered and shared. *"I am curious whether immersive applications offer a more unique experience compared to movies. Unlike movies, which are pre-recorded and can be fast-forwarded or rewound, immersive applications provide a real-time performance that allows both performers and audiences to participate in the environment together. (E2)", "What if there is a way*

to make people perceive air visually? (E4, E3)", "... using your breath is an exciting thing because you have to get more intimate with the object, and you have to build a rapport with it to understand how sensitive it is or how much you want it to change the environmental effect and to do it without your hands or a screen sort of interesting. (E1)" This highlights the opportunity to develop a toolkit that can inspire other designers to explore air as a design medium. Such a toolkit can broaden and solidify our understanding of air's characteristics while also fostering curiosity and experimentation. Some of the ideas and quotes from early exploration, such as humidity, mist, smoke, memory, and future, are directly utilized in Elemental Discovery Cards.

4 Design of AirCraft

During user studies and expert interviews, participants enthusiastically shared their thoughts, but many struggled to envision practical implementations of their ideas, particularly when it comes to unconventional uses of air such as those demonstrated by the artifacts. Here, we identified opportunities to support the designers throughout the design process, such as scoping and brainstorming, and develop the concepts using air as a design medium in an ideation in the early design process. Also, providing accessible technical support for harnessing airflow through physical computing can empower designers to prototype effectively, even without advanced computational skills. Based on feedback from the early prototypes, we refined our toolkit goals: to empower designers to experiment freely with air as a dynamic and expressive design material. In this, we used the early artifacts as groundwork for a toolkit, but developed other complimentary materials to help guide effective brainstorming and prototyping sessions for those unfamiliar with air. In particular, we focused on a set of materials that would help a designer identify and expand the creative possibilities of direct air interactions. The final toolkit comprises three elements: a brainstorming wheel, elemental discovery cards, and prototyping blocks. These are next described.

4.1 Brainstorming Wheel

Previously, all participants mentioned that designing with air is wildly abstract, and that they need help figuring out where to start.

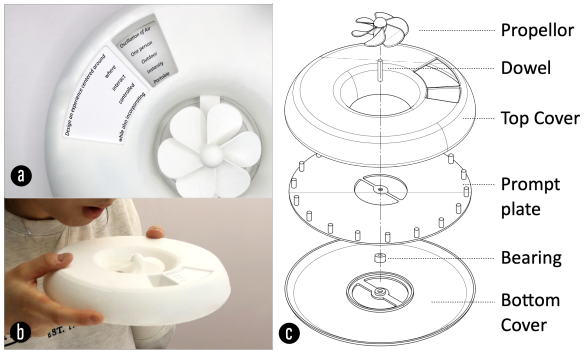


Figure 6: Brainstorming wheel: (a) design prompts example, (b) image of a user trying the wheel, blowing breath into it, (c) structure of the brainstorming wheel.

To help them with the early stages of design, we created the brainstorming wheel (see Figure 6) as a tool to guide exploration in air-centric design thinking. Designers must use their own breath to initiate brainstorming. The wheel contains a propeller, powered by breath or other air flows, that causes the wheel to spin. The wheel can land on one of 18 prompts covering various aspects of air. Each prompt includes the types and transitions of air, users, locations, and characteristics of air that they should initially design with (ex. Design an experience centered around 'Flow of air' where 'Two people' interact 'Outdoor' controlled 'Gently' while also incorporating 'Heat'). The goal with this approach is to reduce the complexity of the design space by introducing some up-front constraints. Each blow of the wheel allows a designer to iteratively become familiar with a subset of the features of designing with air. By constraining the design space in this way, our goal is to offer designers familiar requirements in the design process so they can adapt systematic thinking while navigating the complexities of air as a design medium.

4.2 Elemental Discovery Cards

Understanding the nature and complexities of materials is crucial for any design process to provide insight into what is possible and what limitations exist. The unique properties of materials often guide design and inspire concepts. Consequently, we prepared Elemental Discovery Cards (see Figure 7, Appendix A.2) to provide this insight. Each card summarizes a specific design factor for air and the cards are organized into eight distinct categories:

- Source type: Flow, Oscillation
- Transition: Digital, Analog
- Direction: Rotation, North-East-West-South, Transfer
- Movement: Mount, Wheel, Wearable, Portable
- Magnitude: Breath, Breeze, Moderate, Fresh, Strong
- Repeatability: Count, Time
- Period: Second, Minutes, Hours, Irregular
- Mediation: Humidity, Scent, Heat, Mobility, Future, Memory

Individually and collectively, the cards offer insights into conceptual aspects of air and inform considerations for designing devices

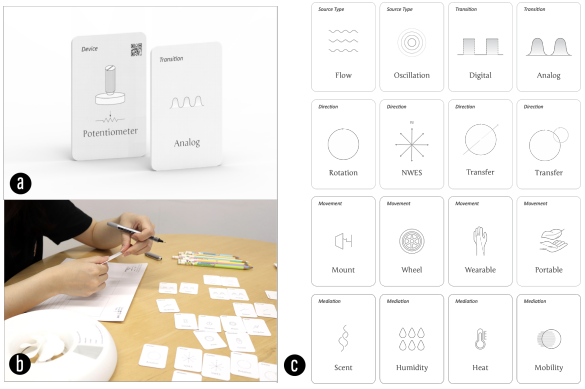


Figure 7: Elemental discovery cards: (a) example of cards front and back side, (b) user looking at the card, (c) example of cards



Figure 8: Prototyping blocks: (a) overview of modular block units, (b) interchangeable opening patterns, (c) magnetic connection for easy assembly, (d) photo from the generative design workshop showcasing the direct use of prototypes

that leverage air interactions. The details of the cards can be found in the appendix A. These cards serve as educational tools to enhance designers' understanding for air's potential. For example, the cards pair with the prompts on the brainstorming wheel, and provide context to interpret the prompts. In this way, they also work to inspire creativity and guide exploration by presenting possibilities beyond conventional notions of air.

4.3 Prototyping Blocks

Using the previous two elements of the toolkit, end users can arrive at a concept for air-based interactions. The final element of the toolkit, the prototyping blocks, allows rapid enactments of these concepts. While air interactions can be enacted with a range of materials — from waving paper or sheets to create air flows or mocking up pin wheels or kites to capture air, concepts that require electromechanical control can pose significant challenges and barriers for designerly engagement.

Our prototyping blocks (see Figure 8, Figure 9) address these challenges and cater to a broader audience who might be unfamiliar with physical computing or have low technical expertise. Our prototyping blocks offer six fundamental physical computing elements for prototyping with air that can be quickly related to one another, recomposed, and organized into a working prototype. The six elements are comprised of:

- Main (core): A block containing a SEEED Studio XIAO SAMD21 board used for control and coordination between components.
- Battery (power): A power pack to provide DC current to all components.
- Subwoofer (output): A subwoofer speaker to create mid-air haptic sensations through varied frequency ranges. The block comes with interchangeable apertures that can be placed on top to change and shape air flows. The subwoofer block includes a dial to adjust the frequency range.
- Fan (output): A 5V DC motor with custom 3D printed fan blades.
- Dial (control): A 10k Ohm rotary potentiometer to adjust the amplitude of the subwoofer and/or the speed of the fan.
- Button (control): Turn on and off power to the outputs.

These blocks are connected using snap-fit magnetic connectors, which transfer power and signals between blocks. This design allows air interactions to be prototyped without requiring additional code or computing. Thus, these blocks allow for easy experimentation with different air sources and control mechanisms. The initial version of the blocks focuses on designing air flows as outputs, but it provides an extensible platform that can be adapted to include breath sensing, anemometers to monitor wind and other air flows, and other forms of output.

5 Generative Design Workshop

In the interaction design research [2, 27, 31], the generative design phase encourages participants to produce a broad range of ideas while emphasizing creative exploration. In our study, we employed storyboarding and prototyping techniques during this generative design process. As noted above, the goal for our toolkit was to empower designers to experiment with air as a design material. To evaluate how the toolkit operated in design activities and towards these goals, we organized a generative design workshop. Our research questions are as follows:

(1) How can design workshops, that use the accompanying toolkit, foster the understanding of air as a design material and help participants generate diverse ideas and possibilities for interaction with air?
(2) How can individuals, and in particular designers with diverse backgrounds, including limited technical expertise, comprehend and utilize the toolkit for manipulating air?

Additionally, we sought to evaluate participants' perceptions of the toolkit's ease of use, efficiency, intuitiveness, and overall experience to improve the current version of AirCraft. We conducted debriefing interviews to identify any challenges or pain points encountered by users and to explore opportunities for refining the toolkit.

5.1 Workshop Procedure

The workshop was structured to generate and prototype air-based interactions and was organized into two phases: conceptualization through storyboarding, and prototyping interactions. Before the workshop, participants were informed that their task was to generate design interaction ideas centered around air as the main theme. Activities took place over a 90-minute session, during which participants worked in pairs to help foster collaborative conversations about air as a design medium and to facilitate cooperative sensemaking. The toolkit was presented at the assigned session to ensure that their use did not bias the original ideas, but fostering creativity without influencing their initial concepts.

During the first phase, participants were introduced to the brainstorming wheel. They were also provided with storyboard templates (see appendix and Figure 12 a) to capture generated ideas. Each participant was invited to sketch out one or more ideas using the storyboard templates. As they developed these concepts, participants were encouraged to think aloud and discuss their ideas with the other participants. In the second phase, they were introduced to the prototyping blocks and given prototype templates (see appendix and Figure 12 b) as well as basic art supplies — such as hot

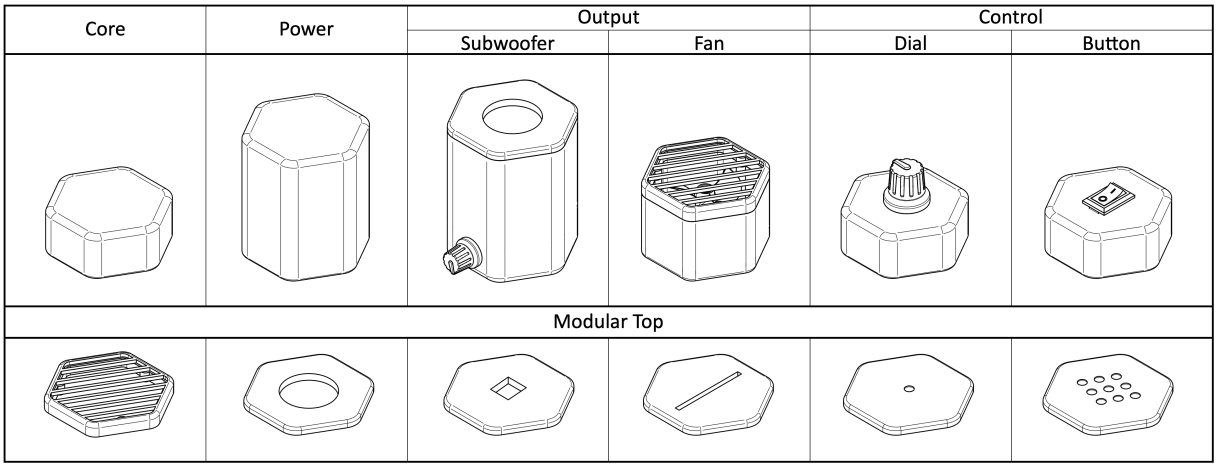


Figure 9: The table presents six elements of prototyping blocks: 1 Core, 1 Power, 2 Output, 2 Control, and modular tops.

glue, cardboard, colored pencils, masking tape, scissors, knives, and cutting mats — to create physical models and mockups. The elemental discovery cards were introduced at different phases. They were presented during the first batch of participants during the first phase and later participants in the second phase. This change was made in response to feedback from earlier participants, who found the introduction of cards overwhelmed the amount of information they conveyed.

The workshop included facilitated sharing and reflection periods after each phase. This also allowed for participants to discuss and provide feedback on each other's ideas, and contribute to the development of additional design possibilities. Finally, post-workshop surveys and interviews were conducted to gather insights for improvement.

5.2 Participants

Twelve participants in their late twenties to thirties (ten female and two male) were recruited (see Figure 11). Recruitment was conducted through campus bulletin board posters and email distribution lists. Participants worked in pairs during the workshop; six two-person workshops were held. In pairing participants, we balanced random assignment with creating pairs with different design and technical backgrounds; adjusting initial random assignments as needed. Participants received a 15-dollar gift card as a reward. The study's objectives and tasks were briefly explained upon enrollment, however, the details of the toolkit were not introduced initially, until pre-study activities were completed. At the beginning and end of the workshop, participants were asked to provide their thoughts on using air as a design medium. This was used for comparison.

5.3 Data Analysis

Storyboards were collected and prototypes documented. To examine and assess the variety of ideas generated, outcomes were annotated using five described categories: forms of input and output; purpose; scale; modality; and how the air was created (or employed) in the system. Additionally, we analyzed the audio recordings from workshop discussions and reflections, as well as the final interviews. This analysis focused on understanding if and how participants changed their perception and understanding of designing with air as a result of the AirCraft. We then coded the data openly and axially to identify categories of insight. Two recurrent and key concepts identified were: *access*, which refers to allowing users with limited technical literacy to design easily; *playfulness*, often closely associated with people's perceptions of difficulty and showing the reduction of their mental obstacles. Finally, the System Usability Scale [10] was administered during workshop sessions to evaluate the toolkit's usability. We used this survey to gauge user perceptions of ease of use, efficiency, intuitiveness, and overall experience with the toolkit. This was used, in combination with the debriefing interview to identify challenges or pain points, explore avenues for enhancing the toolkit, and uncover opportunities for iteration and improvement in user experience.

6 Findings

6.1 Workshop Outcomes: Approaching Air In Interactive Scenarios

During the workshop, a diverse range of ideas emerged. These are provided in detail in Appendix B and summarized in Figure 13. Participants created a total of 31 storyboards (2-3 per person) and at least one interactive prototype based on the storyboards (with 2 participants creating two prototypes). The ideas showcasing uses of air not limited to the electrical pneumatic systems. For example, P5 designed an electric-free sensor system that collects information about people passing through a door by sensing the magnitude and direction of air movement caused by the doors' opening and closing. P11's concept enabled two people connecting through scents. They blow air into the device to create a sensory experience that encourages memory recall and conversation. The design of P3 aims to simulate a breeze by tapping the curtains, using sound and visuals, without actual weather conditions. Ten participants (P1, P2, P3, P6, P7, P8, P9, P10, P11, P12) thought of using air as a part of the output system such as puffing the air to draw patterns on the surface of water (P8), or creating tactile weather information (P6). There

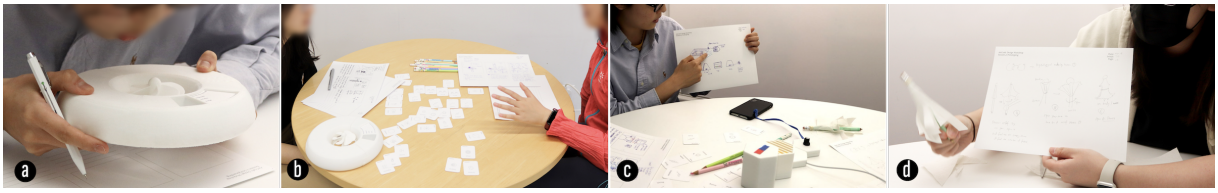


Figure 10: Images from the generative design workshop: (a) a participant using a brainstorming wheel to receive the design prompt. (b) Participants engaged in active discussion during the workshop. (c, d) a Participant explaining the final prototype.

Code	Design Experience	Design Background	Level of Physical Computing
P1	8 - 12 yrs	Architecture, Computational Design	Beginner
P2	5 - 7 yrs	Architecture, Interaction Design, UI/UX	Intermediate
P3	0 - 4 yrs	Computational Design	Intermediate
P4	0 - 4 yrs	Interaction Design, UI/UX, Graphic Design, Photography, Installation, Fine Arts	Novice
P5	> 13 yrs	Architecture, Computational Design	Novice
P6	8 - 12 yrs	Computational Design	Advanced
P7	0 - 4 yrs	Interaction, Design, UI/UX, Graphic Design	Beginner
P8	8 - 12 yrs	Interaction Design, Industrial Design	Intermediate
P9	0 - 4 yrs	Interaction Design, UI/UX, UX Research	Novice
P10	5 - 7 yrs	Architecture, Computational Design	Beginer
P11	8 - 12 yrs	Interaction Design, UI/UX, Industrial Design, Graphic Design	Novice
P12	5 - 7 yrs	Interaction Design, UI/UX, Architecture, Computational Design, Photography	Beginner

Figure 11: Twelve generative design workshop participants table including assigned code, design experience, background, and physical computing skill level.

were six different ways of utilizing air in input sensor, for example utilizing their breath to transmit the emotional states and presence (P9), or leveraging the direction of air flow from the motion of a door opening or closing to get the information of visitors who pass through the door, indicating whether they are coming in or going out, and how many visitors are passing (P5).

Furthermore, there were concepts where air served as both input and output. For example, P1 imagined capturing air movement and bubbles through body movement, and P11 utilized the blowing air to initiate an air puff of a scent to encourage memory recall and conversation. P3 designed a device that replicates sensations perceived through the air, providing a similar experience for designers without actual air, and P5 made a sensor to detect the number and direction of people to pass through the gate.

In terms of purpose, these concepts ranged from practical applications, pure enjoyment of the air itself, to exploring new and alternative ways of communicating their emotions or current states to others. Some ideas aimed to enhance existing interactive systems, while others focused on reveling in the elemental qualities of air. Notably, participants leveraged not only tactile sensory feedback but also incorporated sounds and visual information to amplify the impact of air. Participants, also started exploring ways to evoke memories and build emotional connections between people. Interestingly, the power sources utilized to harness air varied among the ideas. Some relied on physical computing elements, while others explored alternative methods, such as environmental wind or bodily movement.

6.2 Perception Change Towards Air

"Design using air. That's really abstract. I have no idea how should I start with when hearing that kind of idea.(P1)" While the concept of using air as a design element fascinated participants, it was also a new concept to them. Our survey indicated that prior to the workshop, more than nine participants felt unsure or unclear how to design for air (P1, P2, P3, P6, P7, P9, P10, P11, P12). They additionally had no preliminary ideas about what or how they would create air-based interactions, even with knowledge of the focus of the workshop. Analysis of the workshop transcripts and debriefing interviews characterized how their perception of air's potential as a design material developed through engagements with AirCraft. This evolved positively, shifting from initial feelings of uncertainty of how to design with air (P6, P9, P10, P11) or air as abstract material (P1, P2, P3, P7, P12) to a newfound appreciation for its nature and opportunities for design. P1, P2, and P9 reflected on these changes: *"I never really considered air as a design medium, but after the workshop, I realized how important it is as an element surrounding us and how it affects our experience and interaction. I also think there are challenges arising from this unfamiliarity, such as understanding the flow and rhythm, as well as finding materials that work well with air. (P9)".*

Participants also appreciated the ability to engage air as it is a natural material and readily available in their surroundings. They also recognized the need for considering related factors, weather, and environmental conditions like humidity, heat, scent, and seasonal changes (P3, P6, P7, P9, P11). In addition, several participants

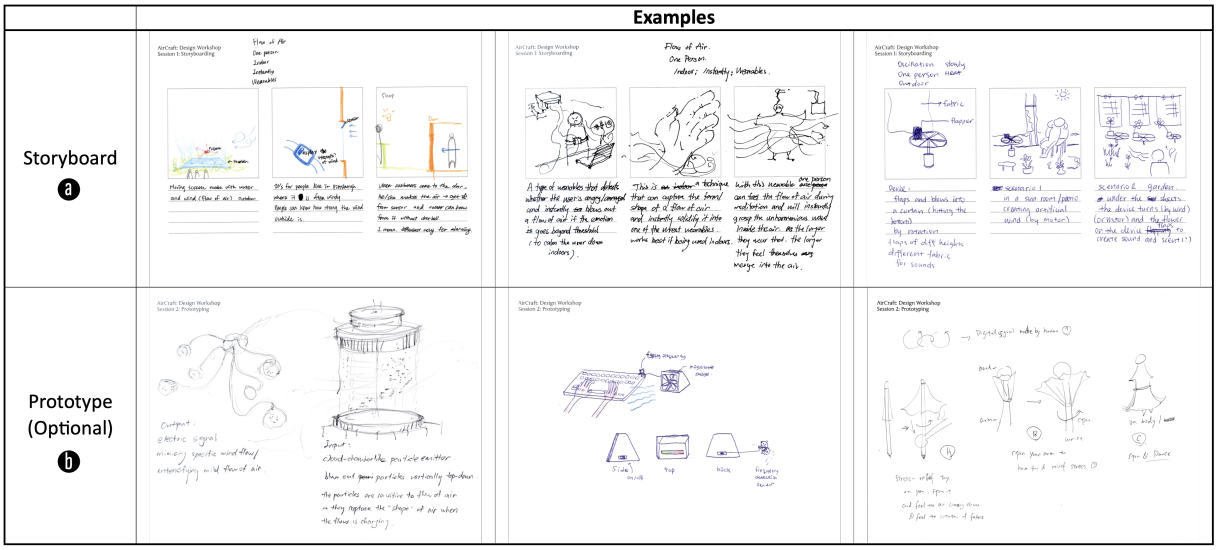


Figure 12: Storyboard and prototype example works from the generative design workshop. Storyboard from left to right (P5, P10, P3), and prototype from left to right (P10, P1, P2). see Figure 18 in appendix.

explored how air might evoke memories, and simulate recalled experiences (P2, P3, P5, P6, P11). They noted how these concepts added increased depth to air interactions, making some prototypes more culturally-relevant and intimate. *"[Air] is always everywhere and related to many situations, but there are still not many design ideas compared to other natural sources. (P5)", "The air contains lots of information that we didn't even realize. If we have more approaches that capture different attributes of air, then there is much more potential. (P10)", "I tried to echo a lot in my memory about when I can feel the air when I can interact with the air, and when I have a really strong connection with the seasons. Also, about some romantic or interesting moments in your daily life and how we can feel in the air. So as more about memory. (P2)"*

6.3 Time Matters

In addition to exploring the ways the tools inspired understanding of air, we explored how and when the tools were introduced to participants. We were interested in the sequencing of activities, design materials and the implications for how they guided design directions. As noted earlier, in early workshop sessions, a few participants mentioned the challenge of effectively using the cards, citing two specific issues. Firstly, two participants expressed feeling overwhelmed by the sheer volume of cards, even though they found the categorized structure more helpful than individual cards. *"It's a little bit difficult to work with because there are so many things. I feel like I have no idea where to start with picking the ideas, because there are so many combinations here. (P6)"*

Alternatively, two participants mentioned that it could have been preferable if the cards had been introduced in the earlier session, brainstorming, and storyboarding. *"I feel like this should be introduced at the very beginning. So we can get a good understanding of the characteristics that this media has. (P4)" "When I selected which prototype to create, I already had some ideas. So, when I saw the cards afterward, I felt that maybe they didn't really help me. (P5)"*

This perspective is important because it addresses the challenge of participants feeling overwhelmed by too much information early in the design process. Conversely, introducing the cards too late can make it seem irrelevant, as participants may be already too commited to a design direction for the cards to inform and guide ideation. To examine this issue, we altered the timing of when the cards were introduced in the workshop. From feedback, we determined that the optimal moment to introduce the cards is midway through the brainstorming session, rather than with the brainstorming wheel or in the prototyping session. This moment allowed participants to begin brainstorming with the prompts from the wheel, and then use the cards when they encounter difficulties expanding their ideas on the storyboard. Feedback from later workshop participants indicated that this adjustment eliminated any sense of disconnect between the tool and the brainstorming process. *"I think the cards were introduced at the right time. It was after the prompt, so it wasn't all at once. It was nice to get started just with the prompt. As I started thinking, I got stuck a little bit, and then you introduced the cards. So the words in the cards, again, helped to get out of that being stuck a little bit. (P2)".*

The participant (P2) presented the card labeled 'transfer' under direction category and described how the diagram of two interacting circles inspired her/him to envision people dancing together, with the air moving around them as they spin. Additionally, the participant developed three different scales of interaction, ranging from a hand-held object to full-body size clothing, emphasizing the concept of transferring experiences across these varying scales. This shows that the visual information on the elemental discovery cards allowed the improvisational ability beyond original intention.

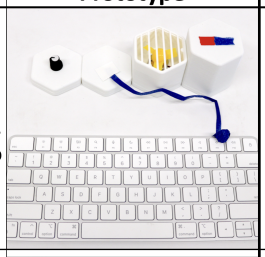
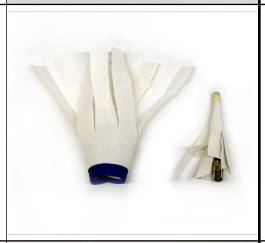
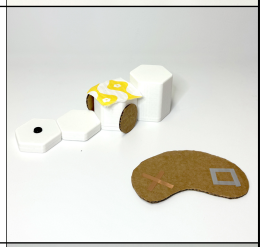
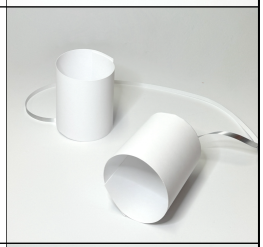
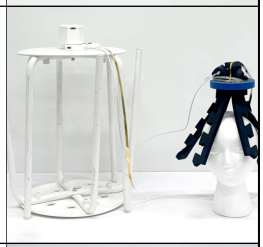
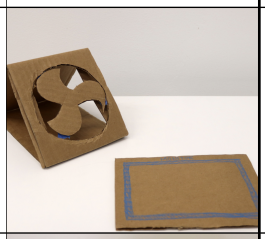
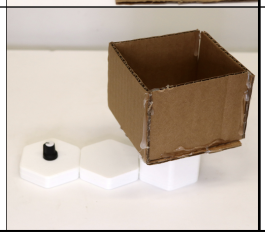
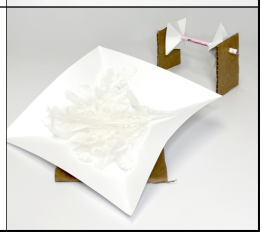
Code	Concept		Prototype	Code	Concept		Prototype
P1	Input/ Output Utilitarian Small Touch Electricity	A device that monitors users' stress levels and body temperature while they work on a computer. It gently activates a fan to signal when it is time for the user to take a break.		P7	Output Utilitarian Large Scent, Vision Electricity	A room with airflow-guiding features, dynamic color-changing lighting, and scented air that adjusts temperature based on occupants' movements for personalized comfort.	
P2	Output Recreational Small-Medium Touch, Vision Bodily Movement	The idea involves users generating airflow through body movement, particularly dancing, which is visually and tangibly expressed through the fabric.		P8	Output Recreational Small-Large Vision Electricity	The a mini-car game with a wheel and controller to generate air puffs that keep a fabric afloat. Additionally it features a giant upside-down water tank for creating water patterns, or colored dye for vibrant fabric crafts.	
P3	Output Recreational Small-Medium Sound, Vision -	It aims to enhance the perception of indoor winds by simulating the effects of outdoor breezes: locates beneath a curtain and produces a sound of wind rustling through an open window.		P9	Input/ Output Communicational Small Touch Electricity	The device transmits breathing rhythms, enabling individuals to sense each other's presence and emotions. It supports mindfulness and connection, inspired by a can telephone.	
P4	Input Communicational Small Touch Wind, Movement	The device can store winds patterns and serve as a memory aid for individuals, which can help with tactile memory and facilitate remote, shared experiences.		P10	Input/ Output Recreational Small Touch Electricity	The input observes air patterns as data, while the output generates intensified sensations via electric signals to the body. This can utilize EEG to capture or transmit brain signals.	
P5	Input Utilitarian Large - Movement	The idea utilizes air movement during door openings and closing to gently notify individuals inside stores without disruptive sounds. movements.		P11	Input/ Output Recreational Medium - Large Scent Bodily Movement	The idea connects two people through scents, with one blowing air to release a scent at the other end. Scents can be customized to enhance sensory experiences and encourage conversation.	
P6	Output Recreational Small - Large Touch, Vision Electricity	This device visualizes air conditions by generating fog or frost based on humidity levels, effectively representing the weather of the location it's positioned on the map.		P12	Output Recreational Large Touch, Vision Bodily Movement	Interactive installations use a rotating propeller to lift feathers, creating a captivating visual effect, especially for children.	

Figure 13: Table of participants' final prototype concepts from the generative design workshop and its analysis under five categories: input/output, purpose, scale, modality, and source of air.

6.4 Toolkits Usability Evaluation

All items in the toolkit scored above 68 on the System Usability Scale, indicating good usability, but with room for improvement.

6.4.1 Brainstorming Wheel. The brainstorming wheel scored 76.59 and it was generally found to be helpful in grasping abstract ideas related to designing with air and served as a good starting point for ideation. Its playful nature fostered an exploratory atmosphere during workshops, promoting, on occasion, both laughter and bodily movement. *"It's interesting as it adds some kind of randomness based on my own body interaction. It's like a lottery to get something to brainstorm with. (P3)", "The initial five words when we spin a wheel, and also all those cards that provide extra attributes on how we think of air...(P10)", "Getting the prompt was helpful in starting to think about it. (P11)".*

6.4.2 Elemental Discovery Cards. The elemental discovery cards scored 76.79, which was the highest score among all the tools. The information on the cards was key to both building insight around the designing for air and sparking creative approaches among participants: *"When you showed these cards, I said wow. Air can have many different characteristics, and there are so many directions that designers can take. It really expands my imagination and my understanding of the air, because I never thought of there being so many different categories and different aspects of air. (P2)", "I read some words on the cards and that helped trigger ideas. (P11)", "The cards help me understand the elements I'm working with. (P9)"* Additionally, some participants referenced the elemental discovery cards to develop their concepts after completing their storyboards. P4 discussed this relative to the addition of ideas for wearable interventions inspired by information from the cards. *"This transfer card really helped me, actually the diagram of it. I interpreted this diagram as two people spinning their bodies. ... I don't think I could come up with this concept without the card. This was super helpful. (P2)", "I am more of a visual person, so I am definitely sensitive to visuals and rely on images when brainstorming. Icons also help me with brainstorming. The cards were really helpful for me to consider the type of interactions or experiences I want to create. (P4)"*

6.4.3 Prototyping Blocks. The prototyping blocks just met the criteria for usable systems, with a score of 69.77, indicating a significant need for improvement. While there were shortcomings, nevertheless, participants saw valued in the blocks ability to quickly mock up air interactions. They valued the prototype blocks' modular and expandable nature, which facilitated the quick creation of sketch models and experimentation with effects. *"I really enjoyed the modular and expandable architecture of the prototype. (P1)", "It just inspires me to think, 'Hey, what can I build with this?' in different ways. (P7)"* Similarly, other participants also pointed out that translating concepts into prototyped sensory experiences was important to their understanding. They talked about how exploring air-related concepts through rapid prototyping can have a transformative impact on how the interpret the concepts. Participants shared also how directly engaging with air through block-based prototyping expanded their imagination, and helped them to develop their own conceptual frameworks for working with air. *"I never saw the block like this. I could do something creative with these that could potentially change the way we experience and interact with air. So it definitely helped me to open up my imagination about air. (P4)", "[Because of the blocks,] It was easy to understand the different texture of air and to get inspiration about air. (P5)"*

7 Discussion

We identified two distinct ways in which participants interact with AirCraft. First, they use it as intended, leveraging AirCraft to guide their design processes. Second, participants used it as a communication tool. This not only influenced design practices but also inspired perspectives resulting in diverse design concepts from the generative design workshop. We recognized this achievement by embracing the Research through Design approaches in both earlier exploration and designing of the workshops.

7.1 Toolkit that prioritizes Designing Interactions

AirCraft prioritizes its interactive potential and explores the role of air in interactions from designerly perspectives. This contrasts with the majority of existing toolkits that focus on adopting, learning and utilizing technical approaches, and specifically pneumatic systems [28, 57, 72, 80]. While these toolkits facilitate engagement with underlying technologies and simplify complex systems that enable interactions, the current toolkits' main emphasis has been on soft robotics and activating inflatables with air, offering convenient ways to manipulate air flow using pumps and valves, considering air as a secondary material.

Previous HCI research suggested developing the technology before considering the applications [19, 72]. However, AirCraft users engage with the tool through a design approach that deeply explores the characteristics of air and its interaction with humans in the early stages of the design process. As illustrated by our findings, AirCraft cultivates designerly exploration of air and the possibilities for interaction through approachable formats for both conceptualization of interactive possibilities and rapid prototyping. The former sensitizes a designer to the possibilities for air while the latter affords a designer a direct sensorial encounter with their concept. By bridging the gap between creative and technical approaches, AirCraft encourages a wider range of ideas and concepts that extend beyond technical skills.

7.2 Expanding The Role Of Toolkits From Guidance To Communication

We noticed that participants used the toolkit to facilitate conversations about air-based interactions. It is not atypical for toolkits to promote conversations and many other toolkits have fostered conversations between different stakeholders towards new insights [31, 58]. We noticed that participants use AirCraft in a slightly different way. For example, the brainstorming wheel, which involves embodied interaction through breath, added a playful element and helped participants recognize and reflect on the differences in their breathing activities. This led to an exchange of thoughts and personal experiences related to breathing or other similar activities that produced or circulated air. Additionally, the abstract and broad terminology of the elemental discovery cards allowed for diverse interpretations and encouraged open conversation and sensemaking among participants. This was the distinctive role of the elemental

discovery cards in the design process compared to some existing toolkit cards that were more focused on guiding the design process [3, 45]. We were also surprised to find that prototyping blocks, despite not initially being considered a communication tool, were used by some participants to illustrate their ideas, even though they did not integrate them directly into their designs. These observations suggest future developments for AirCraft and ways to broaden its audience and functionality.

7.3 Toolkit Evaluation and Future Improvement

We created a toolkit to aid the designerly engagement with air, through scaffolded brainstorming and prototyping, and exploration of the potential of air as a design medium. In the future, the AirCraft could be further refined, in particular, the prototyping blocks. While participants acknowledged the potential of the prototyping blocks, the usability score was in the borderline range, highlighting the need for improvements. Contributing factors included insufficient airflow strength and control. Additionally, the lack of input sensors for air and missing features from the elemental discovery cards, such as scent and humidity, may have lowered user expectations. Expanding the blocks to incorporate input sensors and additional functionalities could enhance their applicability and scalability, facilitating a broader exploration of air's unique properties in both prototyping and exploratory design phases.

Similarly, the addition of a graphical interface for programming the block prototypes would help toolkit users explore and customize a greater range of scenarios and experiences. Building on the feedback from the generative design workshop, we created the concept for a computational tool (Figure 14) that caters to advanced users allowing them to create advanced immersive experiences with the physical blocks. The tool has a user interface that resembles a familiar turntable, making navigation intuitive. Each element's shape signifies the type of air source, and its size denotes magnitude. Additionally, the duration of air interactions is adjustable via a slider, providing further customization. Users can simply drop elements onto the turntable-like circle within the tool's interface, where they rotate to reveal the repetition period of multiple interactions. Rings can be added to accommodate multiple blocks, facilitating complex designs. As elements pass the needle, they trigger the programmed air interactions, seamlessly connecting the digital and analog aspects of the interaction. We plan to integrate this tool into the toolkit in the next phase.

Furthermore, we recognize that the small sample size of 12 participants in the generative design workshop, along with the short duration of the study, limits the findings and restricts generalizability within a controlled environment. Increasing the sample size and monitoring longer-term, real-world design projects would enhance the measurement of the AirCraft's effectiveness.

7.4 Exploring Overlooked Mediums

In our early exploration and generative design workshops, conducted under a Research through Design (RtD) approach [20, 93, 94], conversation and discussion played a crucial role in sharing the idea of designing with air. For instance, a landscape architect discussed windbreak design, while an air quality researcher offered perspectives on managing air pollution. Others also shared their

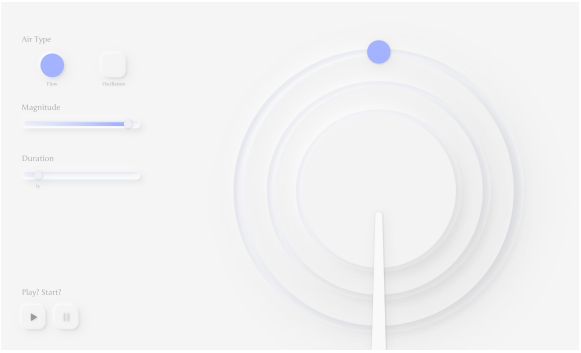


Figure 14: User interface of automating computational tools.

cultural and climatic backgrounds, enriching the discussion with varied perceptions of air. This interdisciplinary dialogue aligns with Christopher Frayling's view that RtD can profoundly connect design with culture and society [20]. Even the word 'air' itself can convey a sense of tension in the environment, as it is used in various ways in our daily lives. By observing these discussions and outcomes of workshops, these already established profound connections with people and society with air make it a unique and meaningful design medium.

One participant even noted that these materials could extend beyond the design domain, inviting a broader audience to engage in exploration and innovation in various formats. *"As a designer, I often find myself trying to imagine what kind of product or concept... I did the same with the prompts. However, I believe that my five-year-old brother would likely come up with a beautiful story instead. I wonder if my role as a designer sometimes hinders my ability to create beyond my professional boundaries. Perhaps people who are not designers can come up with more diverse ideas that are not design-oriented. (P10)"* This dialogue highlights the designers' further responsibility beyond creating a toolkit, which involves pushing the boundaries of conventional thinking. Our approach and study revealed that, while the concept of air is often under-explored, it presents numerous possibilities to explore as a design material. It prompts us to think about the potential of other materials that we may overlook in our daily lives. Basic elements like humidity, scent, and weight are often disregarded as possible media for design, yet they can be incredibly useful for creative purposes. By expanding the focus beyond familiar materials, we can uncover untapped resources, like air. In fact, the abundance and ubiquity of overlooked materials suggest that they may be rich resources for design. Their universality provides a common foundation for shared experiences, facilitating the creation of cohesive design language. At the same time, their versatility allows for diverse interpretations and personalization. Our approach and investigation demonstrate the value of exploring materials beyond the traditional, examining their inherent properties beyond their physical attributes.

8 Conclusion

We created AirCraft, a toolkit comprises of a brainstorming wheel, elemental discovery cards, and prototyping blocks to empower designers to explore, design, and prototype air-based interactions.

During our generative design workshops, which involved 12 participants with diverse design backgrounds and technical skills, we evaluated the effectiveness of the toolkit and identified areas for improvement. Our findings show that the toolkit effectively supports the creation of diverse interactive design concepts that leverage differing I/O approaches and modalities. Findings also suggest that it changes participants' perceptions of air and enhances recognition of air as a design material. For participants, the availability of the toolkit also made air seem more tangible, accessible to them for design prototyping, and approachable regardless of their limited technical expertise. We urge design researchers to further investigate the potential of air in interaction design and cultivate designerly supports for further exploration of this often overlooked material for interaction.

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A Elemental Discovery Cards

A.1 Double Sided Cards

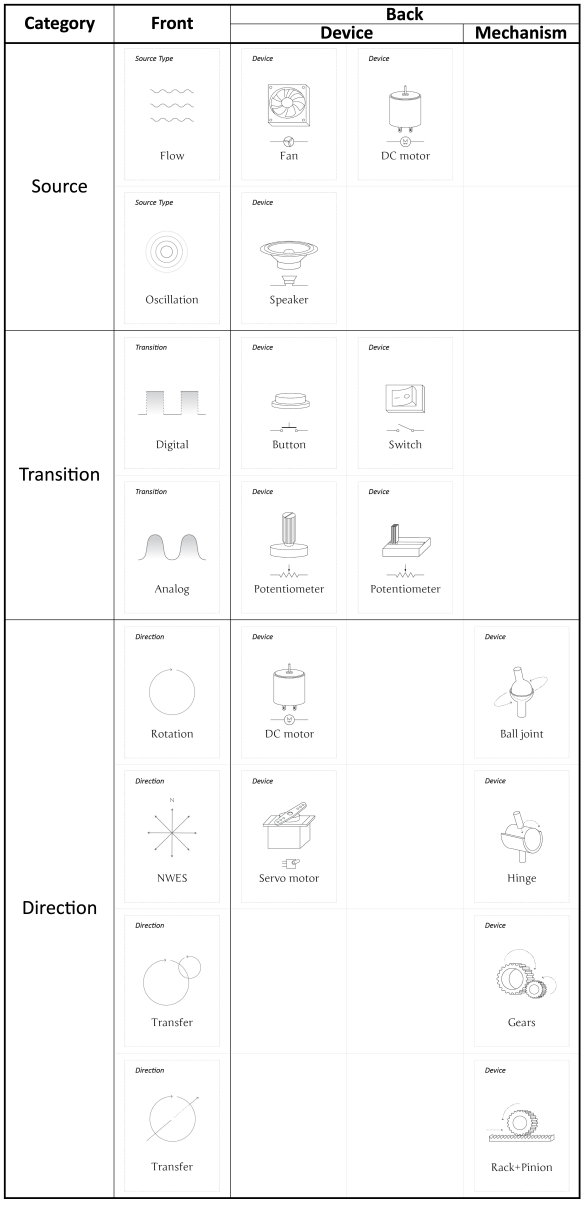


Figure 15: Table of double-sided cards

A.2 Single Sided Cards

Category	Single Sided Cards			
Movement	Movement: Mount	Movement: Wheel	Movement: Wearable	Movement: Portable
Magnitude	Magnitude: Breath	Magnitude: Breeze	Magnitude: Moderate	Magnitude: Fresh
	Magnitude: Strong			
Repeatability	Repeatability: Time	Repeatability: Count		
Period	Period: Seconds	Period: Minutes	Period: Hours	Period: Irregular
Mediation	Mediation: Scent	Mediation: Humidity	Mediation: Heat	Mediation: Mobility
	Mediation: Memory	Mediation: Future		

Figure 16: Table single-sided cards

B Templates for Storyboards and Prototypes from the Generative Design Workshop

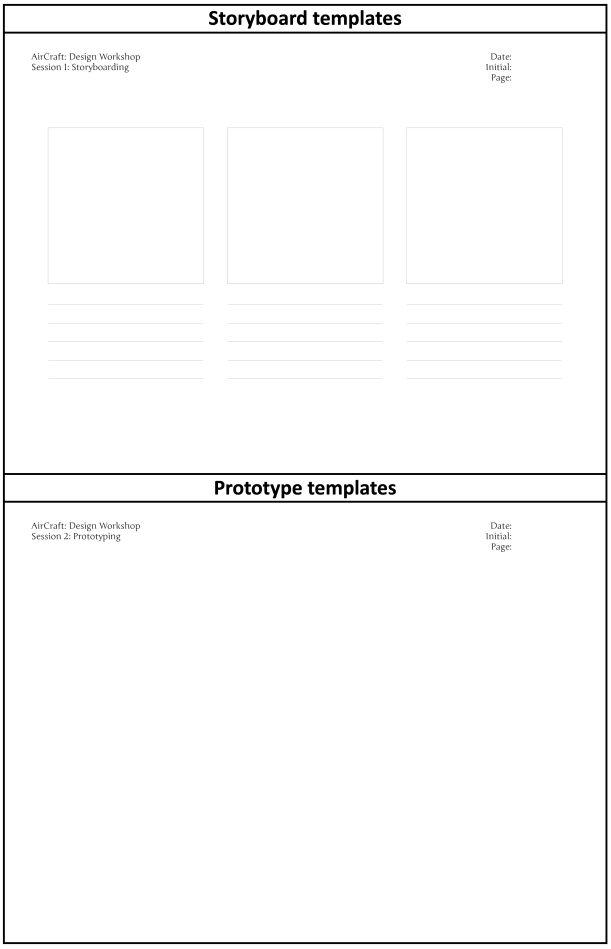


Figure 17: Templates for storyboarding and prototyping

C Storyboards from the Generative Design Workshop

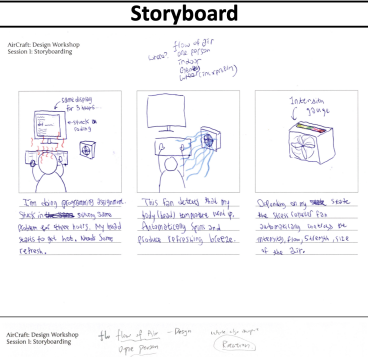
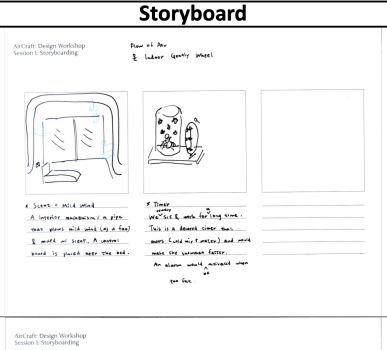
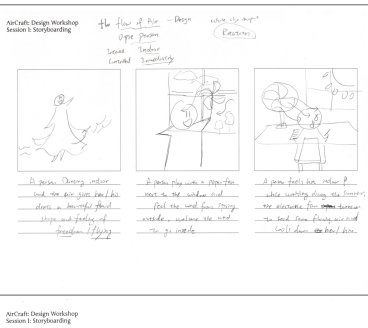
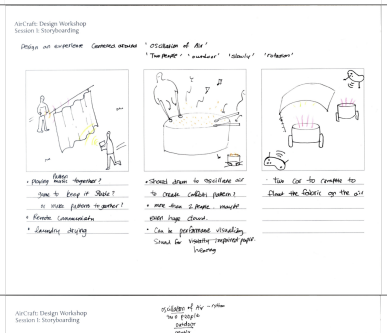
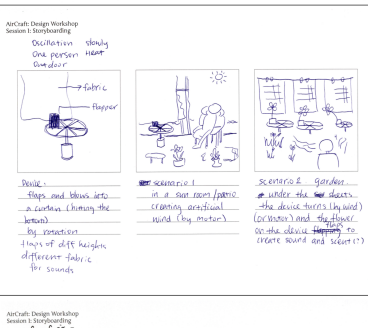
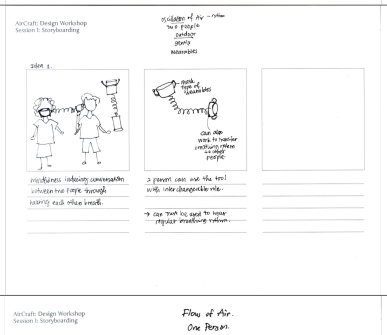
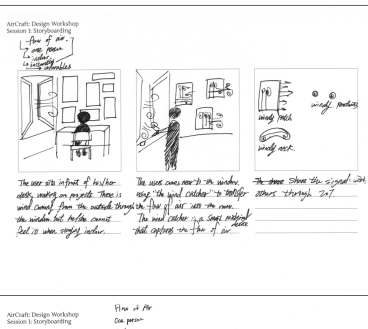
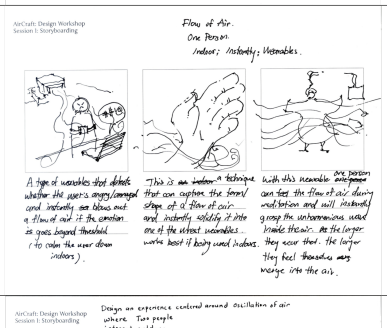
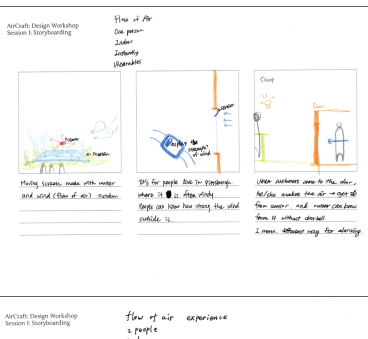
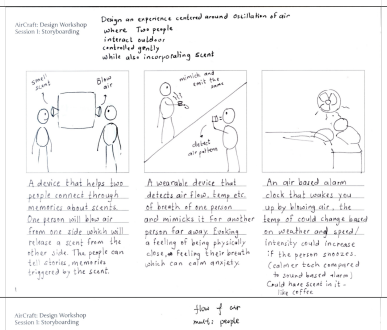
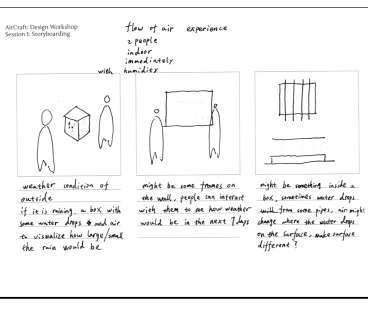
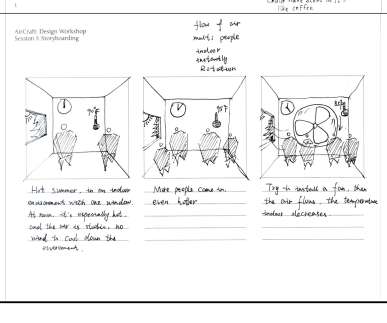
Code	Storyboard	Code	Storyboard
P1		P7	
P2		P8	
P3		P9	
P4		P10	
P5		P11	
P6		P12	

Figure 18: Storyboards from the generative design workshop