Plant-Human Embodied Biofeedback (pheB): A Soft Robotic Surface for Emotion Regulation in Confined Physical Space

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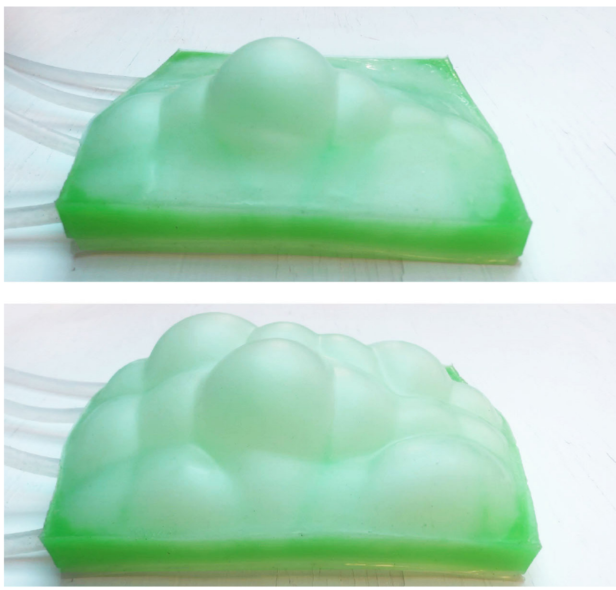

[A] Two states of pheB (plant-human embodied biofeedback).

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ABSTRACT

"pheB," is a robotic "plant-human, embodied, biofeedback" system to support the wellbeing of human inhabitants in confined, physical spaces. This surface aims to increase users' emotion regulation and foster connections with nature by visualizing the internal states of plants through tactile, expressive movement. Unlike 2D biofeedback visualization models currently in use, our research explores mindfulness practices through immersive, tangible interactions to increase therapeutic effectiveness. This pictorial traces the development of our design (to-date) and presents results from an early user study conducted to (a) assess the prototype at leading breathing exercises, (b) evaluate preferences for different design features, and (c) refine the design of a questionnaire for future user testing. Findings suggest pheB was perceived positively and as an embodied extension of self during guided breathing exercises. This work contributes knowledge toward developing novel biofeedback modalities and offers a design exemplar for interactive artifacts that nurture meaningful relationships with nature.

Authors Keywords

biofeedback; mindfulness; wellbeing; biophilia; soft robots; bioinspired design; human-robot interaction

INTRODUCTION

This paper discusses the design of a "plant-human, embodied, biofeedback" robotic surface ("pheB") that supports the wellbeing of human inhabitants in confined, physical spaces. pheB provides inhabitants with therapeutic support manifested as gentle, responsive behaviors of the soft robot, shaped by computational transformations of electrical signals emitted by plants and humans. This robotic interface is designed to increase the inhabitant's ability to regulate emotions through biofeedback, whereby the robot behavior and physiological states of the *plant-human dyad* synchronize.

Our key research questions are two: (1) Do tangible, embodied interaction modalities increase the effectiveness of mindful breathing practices and biofeedback?; and (2) Do tangible, embodied representations of a plant's internal states amplify the restorative effects of nature and foster meaningful plant-human relationships through a more expressive interaction?

CSS CONCEPTS

•Human-centered computing~Interaction design~Interaction design process and methods~Interface design prototyping •Human-centered computing~Interaction design~Empirical studies in interaction design **•Human-centered computing~Visualization~Visualization design and evaluation methods**

MOTIVATIONS & FRAMEWORK

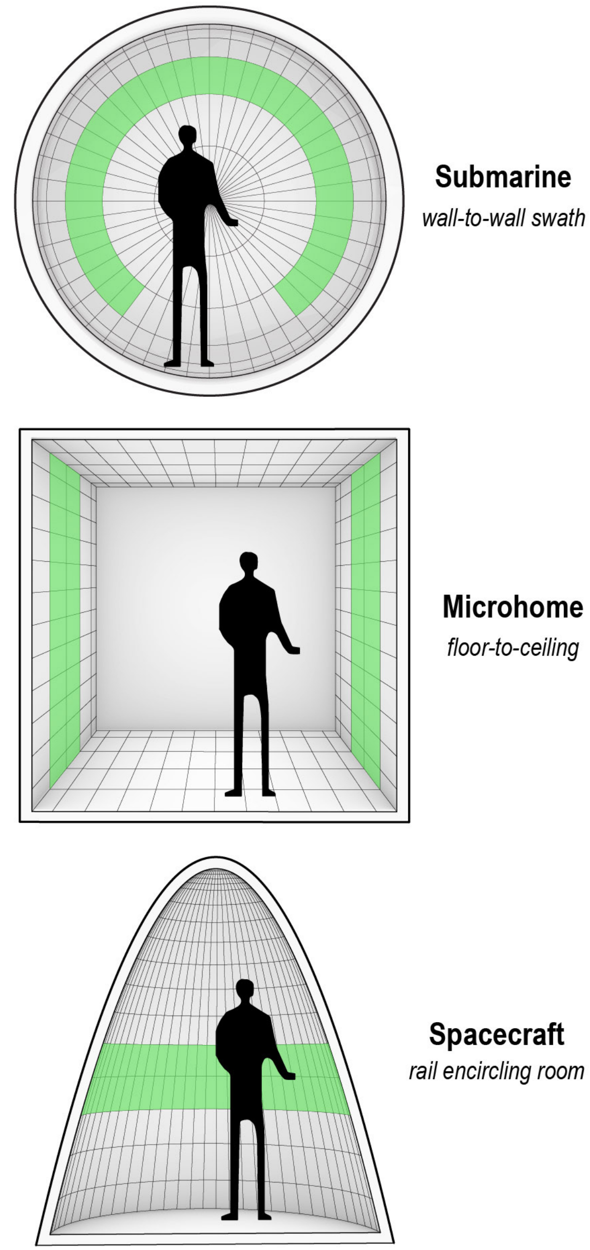
There is an urgent need to rethink the design of domestic settings, prompted by climate change, a growing population, rapid urbanization, global pandemics, and limited access to nature. Humans are spending considerably less time outdoors [19] and residing in crowded urban areas. Looking to the future, society is preparing for the possibility of living in extreme environments on Earth and other planets. Such “homes” may be spatially confined (capsule habitats, like submarines or spacecrafts), or microhomes (dwellings less than 200 square feet). To prevent the spread of infectious disease, stay-at-home measures further compel the need to find ways to sustain mental health during long periods spent in tighter confines. Evidence shows [4, 28] that confined spaces can stress inhabitants due to separation from nature and prolonged social isolation which negatively impacts emotional wellbeing. Embedding ecologically-rich, interactive [13] biofeedback interfaces into domestic architecture can enrich the experience of living in a confined, isolated space.

The efficacy of biofeedback for therapeutic purposes has been widely studied [7, 12, 25] as a behavioral treatment for mental health disorders and overall benefit to emotional wellbeing. The choice to design with biofeedback elements is supported by the framework of *Interoception*, the ability to sense one’s own internal states, and suggests new modalities of human-robot interaction grounded in cognitive neuroscience [10]. pheB increases awareness of one’s internal physical states to mediate emotion regulation. The surface performs embodied heartbeat visualizations, guided breathing exercises, and movement that simulates soothing patterns of nature. Unlike many 2D biofeedback visualization models currently in use, our research explores mindfulness practices through immersive, tangible interactions. Previous spatial biofeedback designs [27] have required users to enter structures designed solely for biofeedback purposes. pheB’s design embeds the biofeedback device into pre-existing habitats, facilitating a more seamless interaction to adopt spatial, tangible biofeedback into daily life.

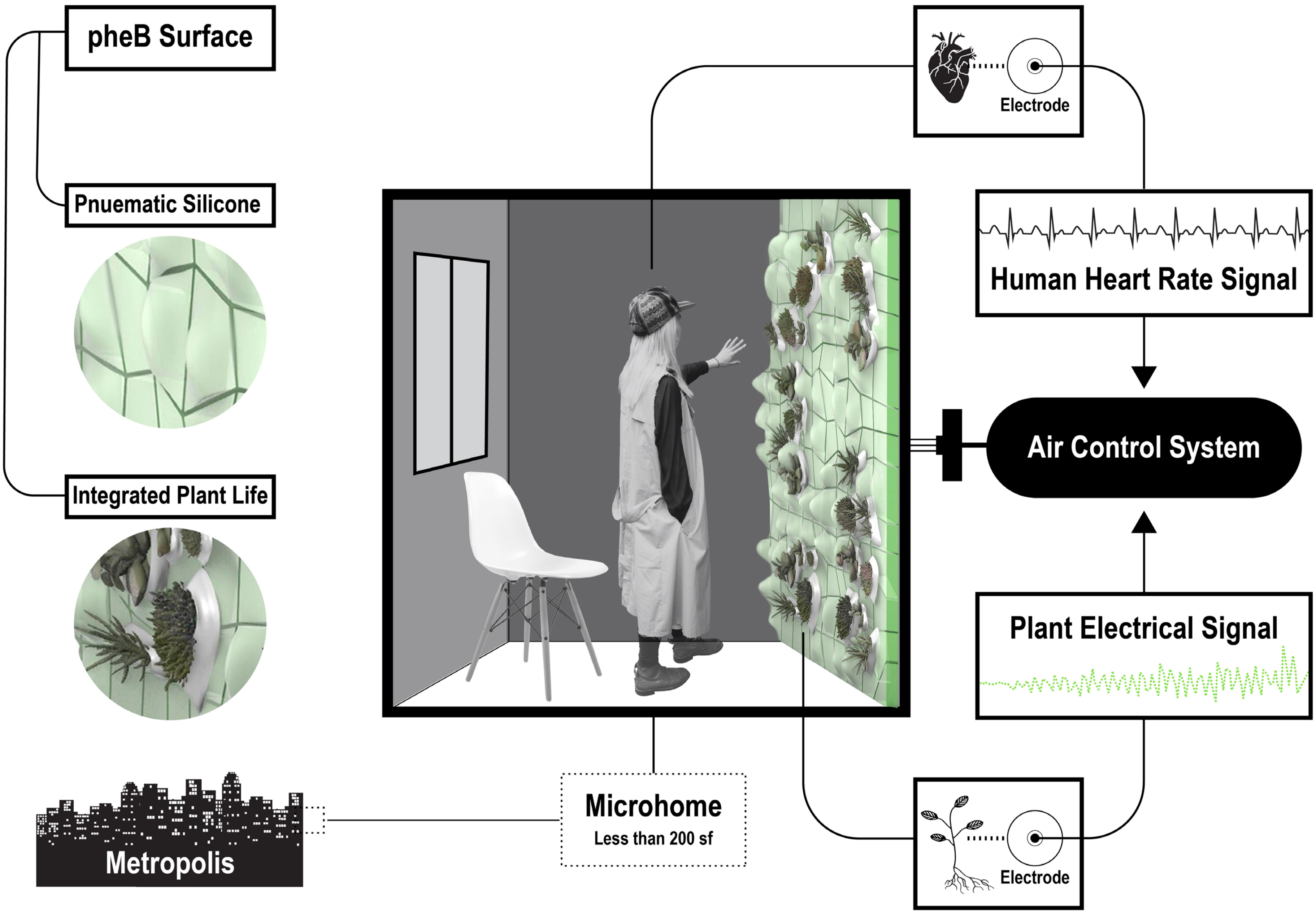
The design of pheB is informed by *Biophilia*, which posits an intrinsic human attraction and attachment to nature [18]. Human-environment researchers have found that exposure to nature is vital to human wellbeing [17]. Plant life and patterns of nature, or *nature analogues*, can produce a restorative effect through *soft fascination*, an involuntary attention to pleasing stimuli [26]. pheB translates sensory data from the plant-human dyad into an experience of soft fascination through the behavior of the surface, which is both familiar and mysterious: familiar, in that pheB’s robotic behavior follows the algorithm of familiar phenomenon (e.g., the soothing patterns of ocean wave forms); mysterious, in that pheB’s behavior is trans-mediated from the familiar to a novel mode of expression. Applied to walls and ceilings in compact environments, we envision pheB as a rail encircling the room, a floor-to-ceiling or wall-to-wall swath, and an object on a wall [B]. pheB amplifies the unseen experiences of plants through embodied representation, providing tangible visualization of plant behavior not typically visible to humans.

DESIGN OVERVIEW

The pattern and movement of pheB is determined by discrete physiological outputs from the plant-human dyad [C]. Two types of bio-signals are used to drive the device, human heart rate and electrical impulses expressed by plants, that are modulated by shifts in the plant’s environmental stimuli and resources [e.g., light, 6]. The plant-human bio-signals are translated into distinct inflation patterns: air pressure is delivered by numerically controlled regulators to the silicone surface with air chambers of various volumes and shapes. When a human user has an elevated heart rate, the surface inflates at a rhythm that encourages the user to slow their respiratory rate. State shifts in the plants' physiology initiate an inflation pattern that mimics natural phenomena (e.g., the rhythm of ocean waves) evoking the biological [21]. Biomimetic design can create an emotional response in human users while fostering a deeper connection to the biological world [20]. pheB captures the physiological state of the plant-human dyad as one coherent biofeedback index in real time.



[B] pheB embedded in different interior spatial arrangements.



[C] System diagram of the human-plant dyad interacting with the pheB soft robotic biofeedback surface in a microhome setting.

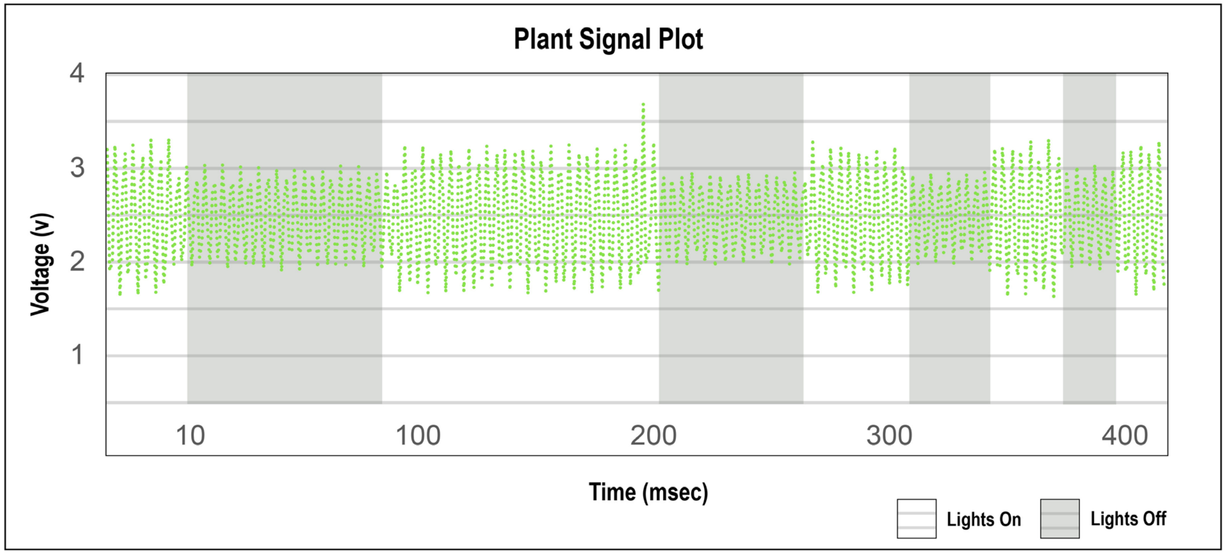
PLANT ELECTRICAL SIGNAL

pheB is a surface comprised of both robot and plant life. The plant aspect of pheB represents an index of the human's wellbeing, as the state of the plant's health reflects the human's own emotional wellbeing. This conclusion follows from evidence that a human that cares well for a plant is a well human [3, 22]. The robot aspect of pheB promotes connection to nature by magnifying the unseen experiences of plants and encourages the human to better care for the plant by visualizing changes in its health status [1, 5]. This is achieved using electrodes that measure shifts in the electrical signals emitted by plants in response to environmental stimuli [9]. These shifts are fed into a control algorithm that initiates movement of the robotic surface. We are working towards designing a set of behaviors that represent different physiological states of the plant (e.g., a plant needs water) with real-time feedback. The behaviors also reinforce attachment to nature, as the behaviors are designed to translate and simulate calming natural phenomena (e.g., the ebb and flow of the ocean surface, leaves swaying in a gentle wind). Through this interactive surface, the human sees a more animated expression of the plant's experience, which has been demonstrated to engage neurological mechanisms of social cognition [29]. As the human develops a relationship with both the plant and the robotic surface as an embodied extension of the plant, they are more likely to anthropomorphize the plant, thereby increasing empathy and attachment.

To date, we have established proof of concept for the plant signal, using low-cost surface-mounted electrodes and the electromyography (EMG) detector from Seeed Studio with Arduino, we recorded the electrical signals by attaching the electrodes to the leaves of different plants [D]. We performed several experiments to see what stimuli created a shift in the electrical signal output from the plant. We repeatedly observed the voltage measured from the plant's signal shift in response to light detection, human touch, and the presence of water. For example, when the lights are turned on, the voltage output from the plant increases. The design of pheB represents these state shifts through its biomorphic design and harnesses the patterns of nature for expressive means.

Surface-mounted electrodes on plant

Variations in plant signal in response to stimuli measured

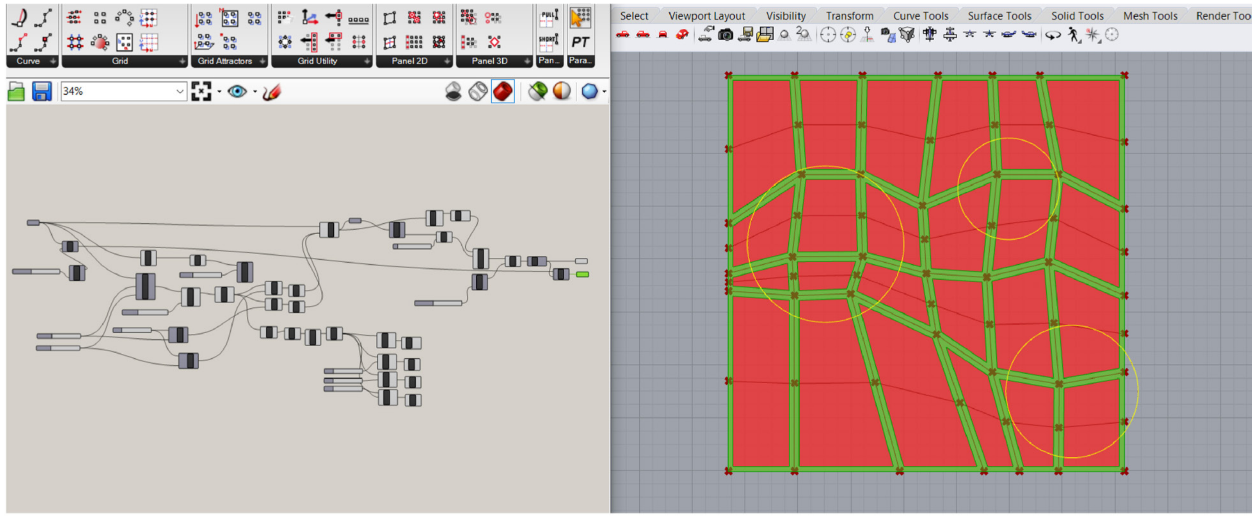


[D] Surface-mounted electrodes record the electrical signals emitted by plants in response to environmental stimuli (light).

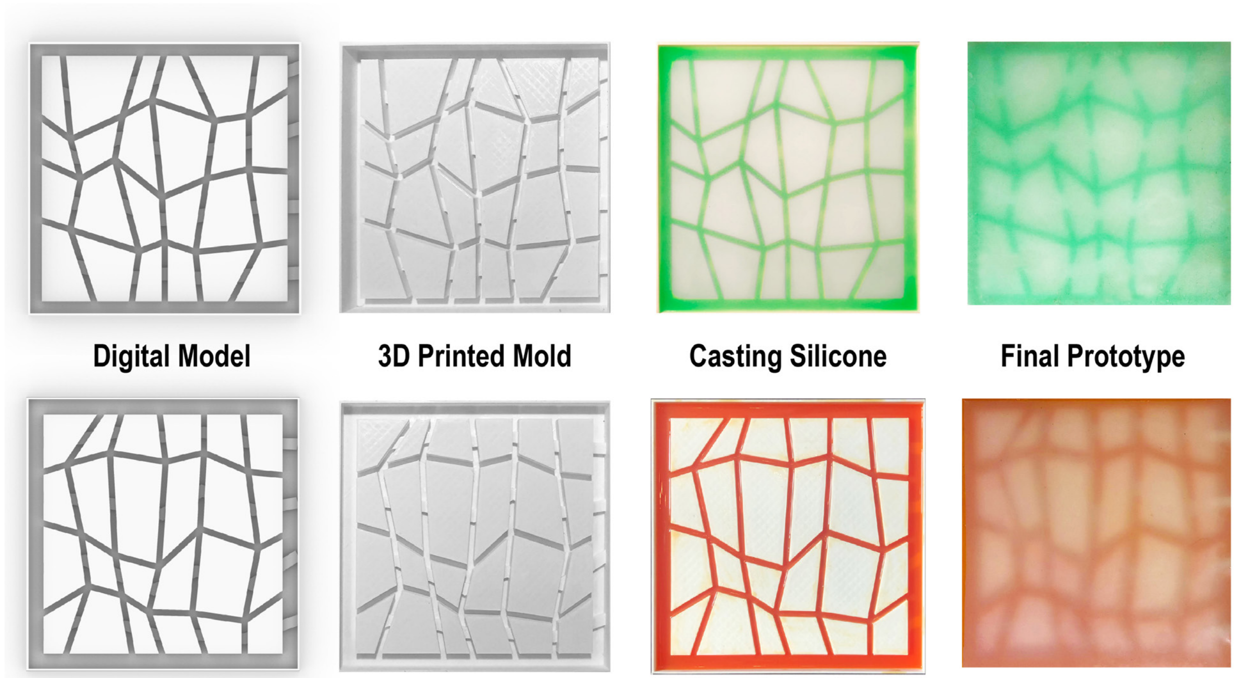
DESIGN & FABRICATION

There is a growing interest in soft robotics in the field of interaction design due to their compliant, flexible nature [14]. Soft robots (or soft actuators) are typically fabricated using a set of molds to cast silicone, an elastomer material. The mold forms a series of interior cells with connecting channels to move the air throughout the robot [24]. The behavior of the robot is controlled in part by the shape and volume of the pre-determined cells, as defined by the mold as well as by the amount of air that is fed into the pneumatic device. As our research is interested in exploring soft robotic surfaces for their expressive qualities [15, 16] we wanted to develop an easy way to quickly iterate different surface typologies to test their respective potentials for our biofeedback surface. We were interested in designing surfaces with irregularly shaped grid cells to incorporate visual intrigue, capable of evoking *soft fascination* [17]. Additionally, we sought to evoke a biological sensibility by using a pattern that resembled *natural analogues* through biomorphic geometry (e.g., cracks found in the desert earth, the scales of a reptile, or the texture of a cephalopod's skin).

We created an algorithm using Rhinoceros 3D/ Grasshopper (www.rhino3d.com) computer-aided design (CAD) software that enables us to produce a wide range of digital models to cast different surface designs [E]. In addition to a variety of pattern typologies, the algorithm made it so that as the prototype continues to develop, we can easily change the size and shape of the overall surface. The algorithm also allowed us to manipulate the underlying grid to produce desired inflation patterns, through areas of compression and expansion. One technique we explored was the use of "curve attractors," which allows one to draw vectors in the workspace and apply a magnitude of attraction/repulsion. Based on the placement of the curve attractors, the number of sub-divisions in the grid cells, and the magnitude of the attraction, we are able to control where the larger grid cells are placed to shape the behavior of the surface. The algorithm also creates a set of corresponding air channel pathways to connect the air chambers along the array of



Grasshopper script to build custom mold patterns with curve attractors to control size of surface cells



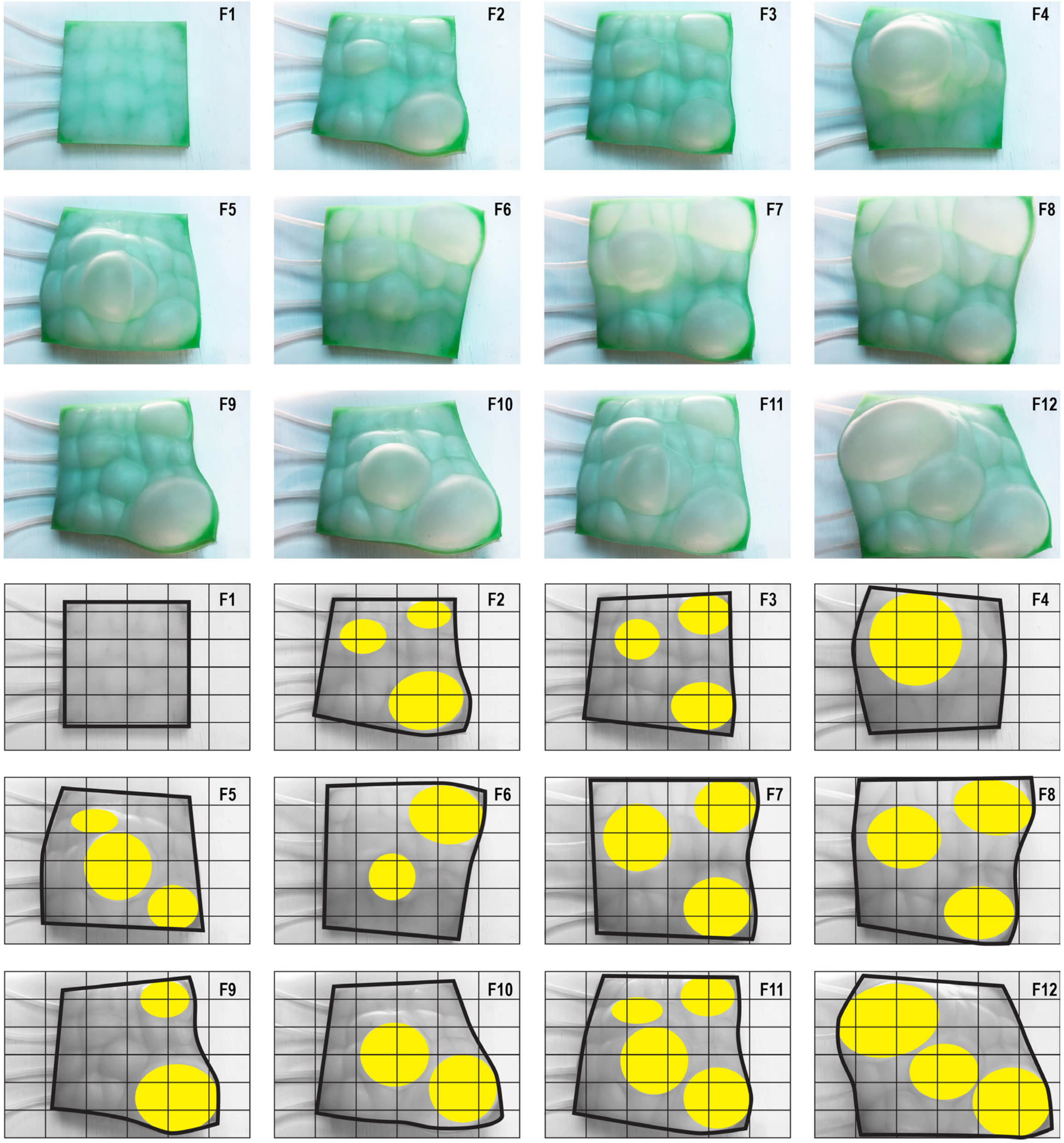
[E] Computational algorithm used to generate molds of pneumatic silicone pheB surface for quick iterative prototyping.

cells. The current algorithm uses the midpoint of neighboring grid cells to generate a channel along the shortest path.

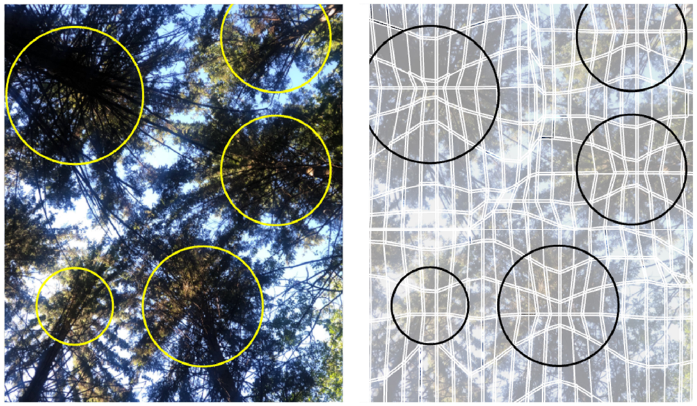
After the initial prototypes were fabricated, still images of the inflated surface in different positions were taken in top view. The images were used to analyze how the initial grid pattern of the chambers influenced the prototype's range of behavior. A rectangular grid of lines and a series of closed ellipses were manually overlaid onto the images to evaluate the nominal area of different inflation swells [F]. This exercise provided valuable insights into the relationship between the air chambers designed in the digital model and the corresponding performance of the physical surface.

We also reinforced the biophilic nature of the surface by using images from nature as a generative tool for the design of the inflation patterns. We made bitmap images of natural features (e.g., trees in the forest) and imported them into our CAD software [G]. We then overlaid the images with a series of vectors. We applied an attraction force towards these curves using our Grasshopper script to generate a pattern that loosely corresponds to the identified features. This creates a pattern with variations that resemble shapes and forms seen in nature. The resulting design has a biomorphic effect that is familiar in its organic appearance, yet also mysterious.

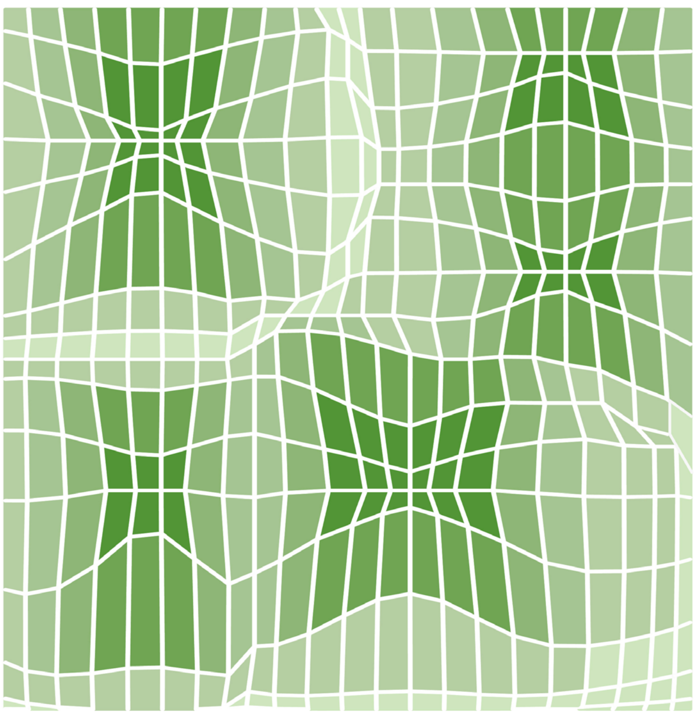
The current prototype has four distinct air channel pathways with unique inputs that run horizontally across the surface. Moving forward, our goal is to develop a physical prototype that is capable of inflating in patterns that simulate soothing natural phenomena. While the biophilic inflation pattern will be determined largely by a control algorithm that drives a series of electronic pressure regulators, the underlying surface also needs to be able to facilitate the movement. To explore how we might change the behavior of the prototype through the design of the surface, we produced a series of diagrams to evaluate strategies to inflate the device through different air channel typologies. This series of diagrams [H] helped us to consider many inflation permutations of possible behavior using the same underlying grid. Future work will also consider a heterogenous approach to the design of the air channels, where multiple strategies are integrated into one surface to produce a variety of possible inflation behaviors representing different facets of the biofeedback loop. For example, pheB might use distinct inflation types to represent whether the visual feedback is related to the physiology of the plant or human.



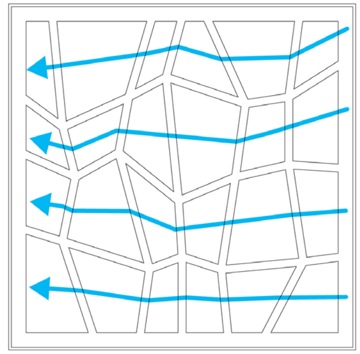
[F] Diagrammatic analysis of pheB prototype in different positions to evaluate different inflation swells.



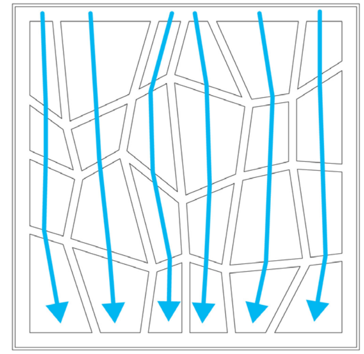
Biophilic Surface Development
Bitmap image of nature is brought into CAD software and traced.
Curves are drawn over natural features which determines the pattern of the surface.



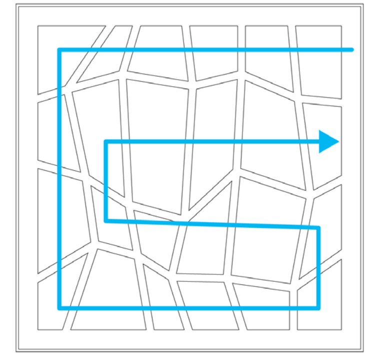
[G] Bitmap image used to create biophilic surface.



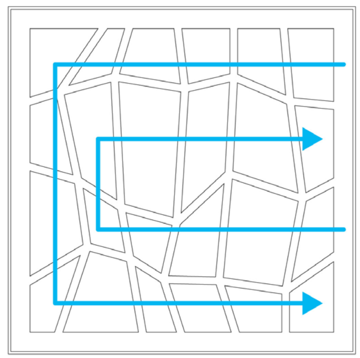
H1] By Row: horizontal air channels



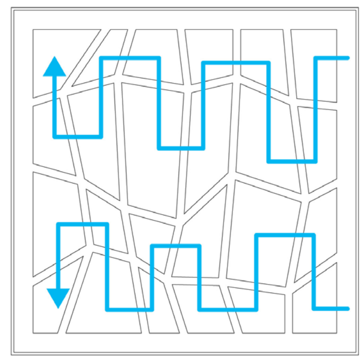
H2] By Column: vertical air channels



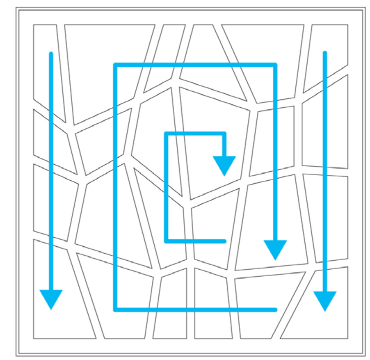
H3] Single Input: continuous channel



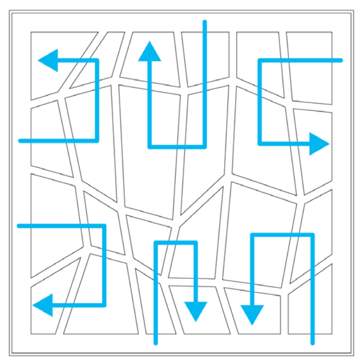
H4] Two Inputs: c-shape channels



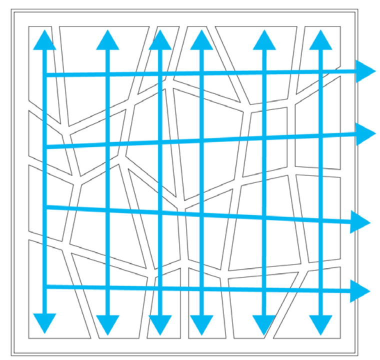
H5] Two Inputs: zig-zag channels



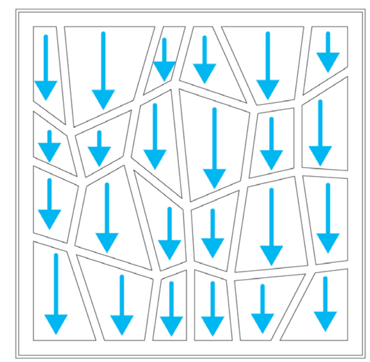
H6] Multiple Inputs: spiral channels



H7] Multiple Inputs: c-shape channels



H8] Interlocking: air channel matrix



H9] Individual: unique input for each cell

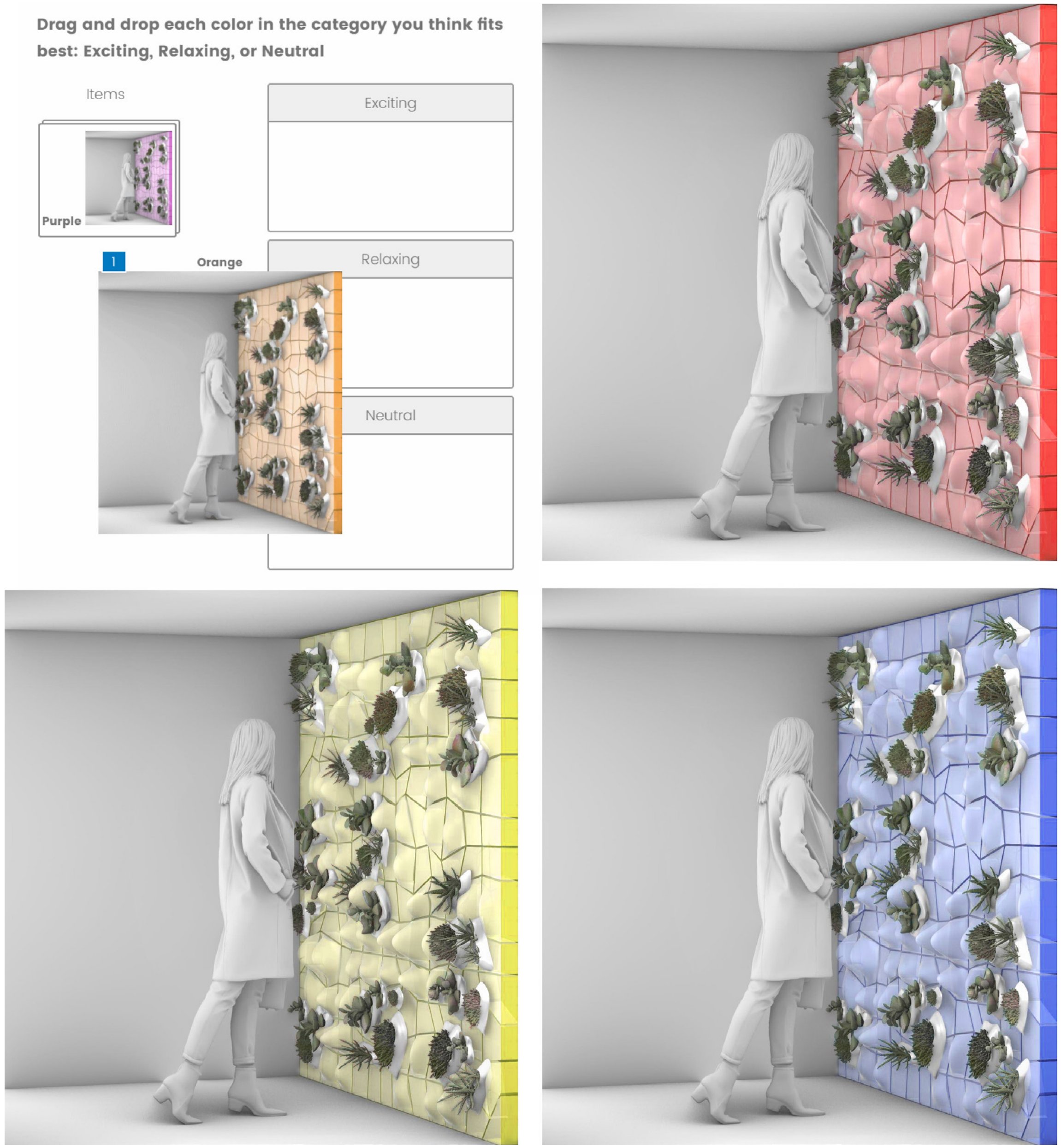
[H] Strategies for different air channels pathways to control the behavior of the pneumatic surface.

QUESTIONNAIRE DESIGN

Our early prototypes have established proof of concept for the bio-electrical control systems and started to test different inflation patterns. We continue to refine the early prototypes. To guide our process, we developed an online questionnaire to discover user preferences for different design features: color, size, scale, and orientation. While the fabrication process was designed to make it easy to produce a variety of different designs for the pheB surface, the cost of materials and labor demands for prototyping with silicone are quite high. Therefore, digital images can provide important insights during our user testing process without investing the time and money to build a physical prototype. We produced a series of animated gifs depicting the pheB surface embedded in the wall of a small, confined space. Two renderings were made to construct each animated gif: the first rendering shows pheB uninflated, and the second, inflated [J]. This was done so respondents could evaluate the prototype in both an active and resting position. Additionally, we believed that seeing the surface subtly inflating in the gif will help respondents associate the digital drawings with the prototype seen in the breathing exercise videos. A 3D model of a person was placed in the scene to help the participants imagine themselves within the room, standing in front of the surface.

Participants were asked to assign a series of gifs depicting pheB in different colorways into three categories: 1) exciting; 2) relaxing; and 3) neutral. Six hues were used to cover the whole range of the spectrum (i.e., red, orange, yellow, green, blue, and purple); the images were otherwise identical [I]. As color has been demonstrated to be associated with emotional perception and affective meaning [2], we wanted to assess how different colors of the pheB surface might be perceived by users. Insights from the user evaluations will guide our developing work as we add complexity to the prototype. Based on prior research, we hypothesized that cool colors (blue and green) would be more highly associated with relaxation, warm colors (red and orange) would be more frequently associated with excitement, while the colors purple and yellow would be more frequently assigned to the neutral category.

The questionnaire also asked respondents for their preferences for the size of the overall pheB surface, the scale of the air chambers, and the orientation in the environment (i.e., horizontal/vertical). Three questions were asked, with three design options per question:



[I] Gifs of pheB in different colors are grouped in three categories: exciting, relaxing, and neutral.

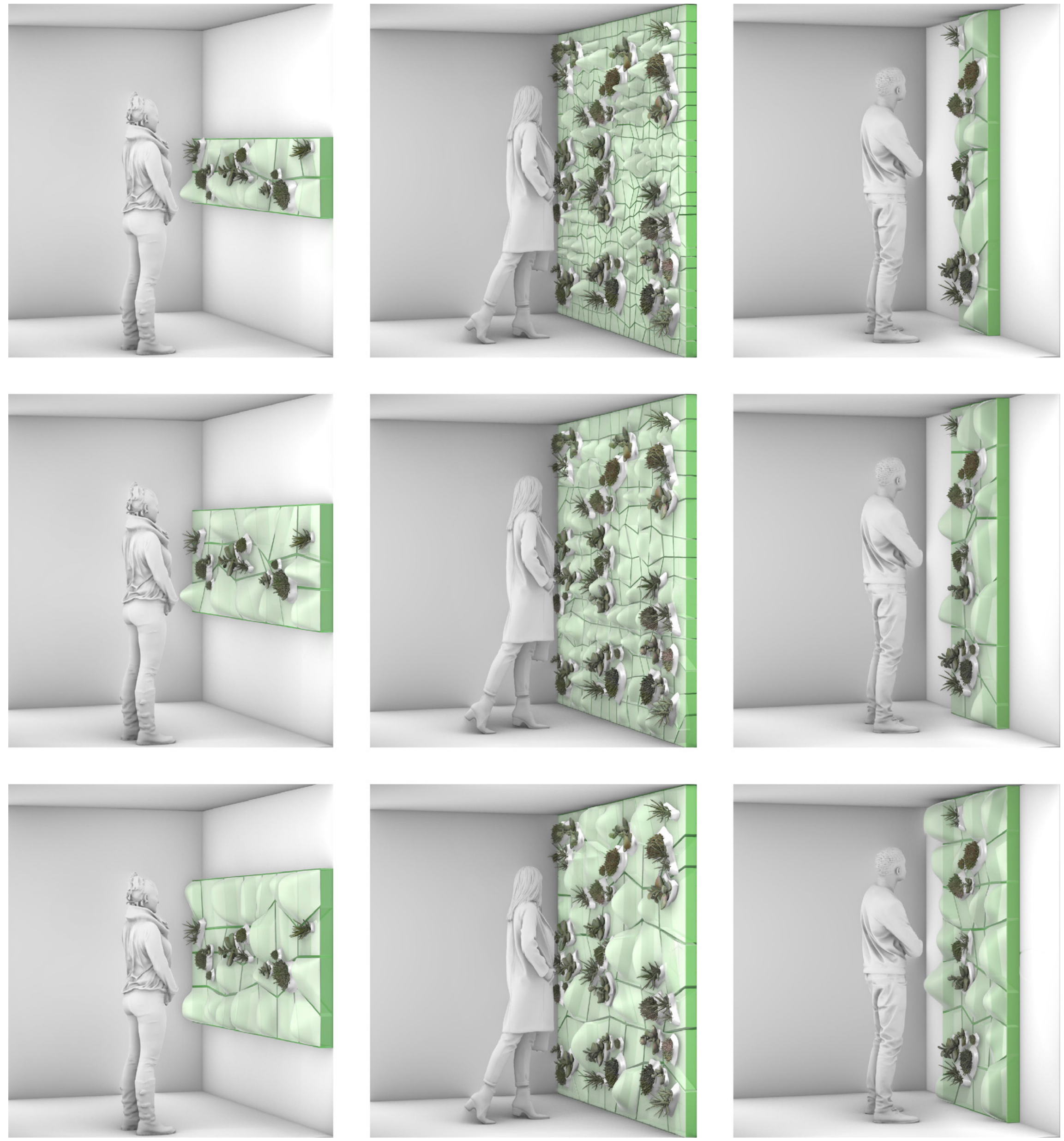
1) pheB surface covering the entire wall with air chambers at three different scales; 2) pheB surface shown in a vertical orientation at three different widths; and 3) pheB surface shown in a horizontal orientation at three different widths [K]. We did not form a hypothesis on which features would be preferred, as there was little precedent to inform our reasoning.

METHOD

Our initial user testing focused on our first primary research question: Do tangible, embodied interaction modalities increase the effectiveness of mindful breathing practices and biofeedback? Given the current global pandemic which requires research methods that can be conducted remotely, we chose to focus primarily on developing mindful breathing practices,which can be administered online and in-person. Therefore our aim for the initial user study was to (a) assess how successful the pheB prototype was at leading guided breathing exercises, (b) evaluate preferences for different design features, and (c) refine the design of the questionnaire before disseminating it widely. To begin user testing, we conducted a small pilot study to observe people’s response to the current prototype as well as evaluate the early version of the questionnaire. The in-person pilot study had five participants from a convenience sample who were asked to complete exercises from the questionnaire and provide feedback on pheB through unstructured interviews.

Participants were asked to perform a series of four guided breathing exercises demonstrated to have a calming effect [8, 23]. Two distinct

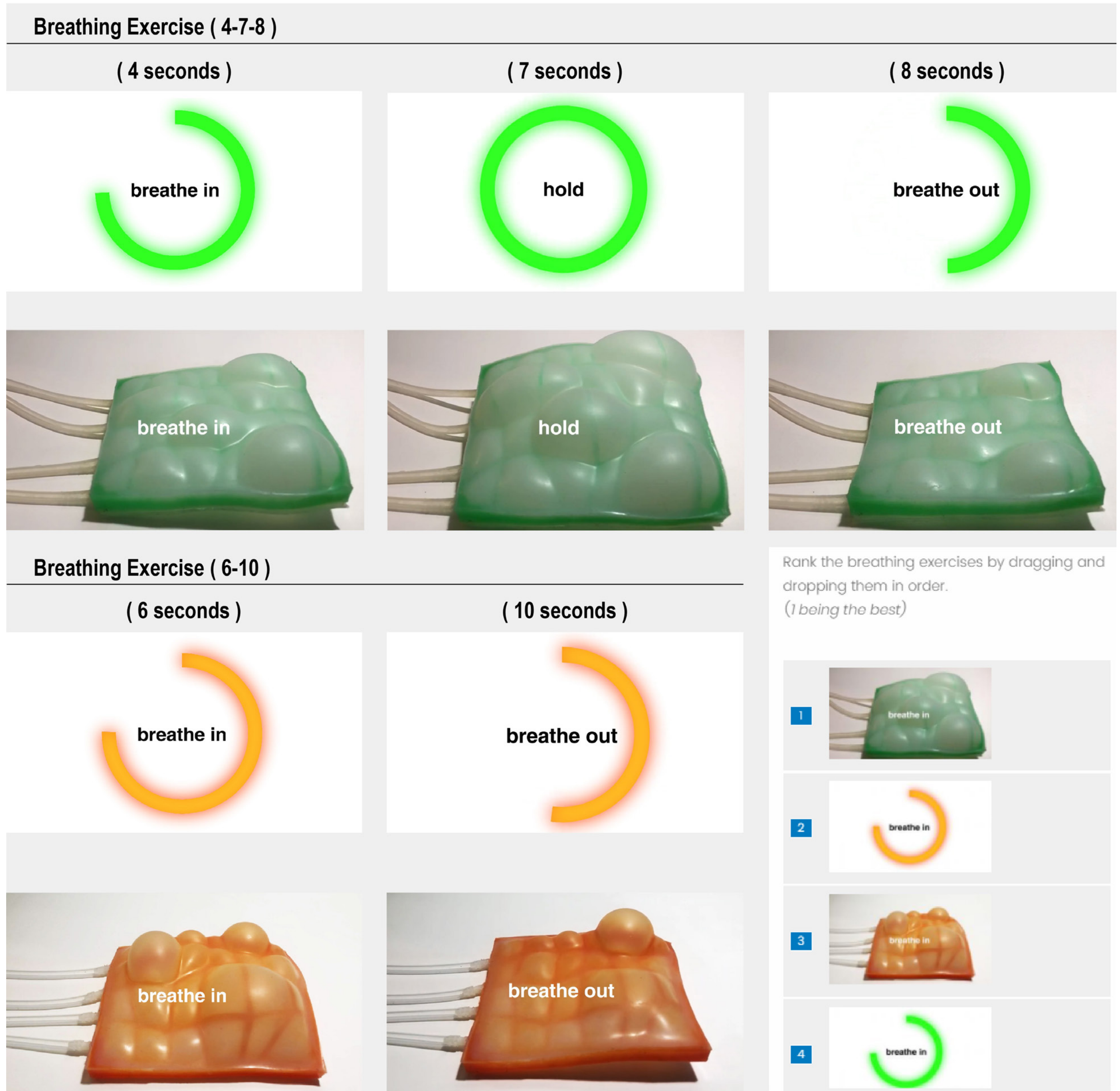
[J] Animated gifs depict pheB surface in resting and inflated positions.



[K] Images of pheB in confined space shown in different orientations, scales, and widths for user testing.

breathing patterns were used for four exercises and were presented to the participants in a series of videos lasting one minute and thirty seconds each [L]. The 4-7-8 exercise directed a person to inhale for four seconds, hold their breathe for seven seconds, exhale for eight seconds, and is associated with relaxation. The 6-10 exercise directed a person to inhale for six seconds and exhale for ten. Evidence has shown that exhaling longer than inhaling can stimulate the vagus nerve and activate the parasympathetic nervous system [11], which is responsible for activities such as digestion and rest. Both breathing exercises were visualized in two ways: 1) through a simple 2D animation of a line that moves towards becoming a complete circle while the participant is breathing in, a complete circle when holding, and reverses when breathing out; and 2) a video of the pheB surface that inflates, holds, and deflates in the rhythm of the breathing exercises. Using a within-person research design, all participants were asked the same survey questions, allowing participants to compare and rank the different visualization modalities.

To control for participant fatigue, we randomized the order of the exercises. For the breathing exercise videos, we controlled for color as a confounding variable by matching the color of the 2D animation with the corresponding pheB (i.e., orange and green). The lines in the 2D animation are presented with a feathered edge, to create a more soft, tactile visualization, and establish some visual interest. Text was used to help the participants follow the timing of the exercise. The text had the same font, size, and placement across all four conditions; however, white text was used for the pheB breathing exercises to increase contrast and legibility. After each breathing exercise, participants were asked to evaluate their experience. In the questionnaire, participants were asked if they agree or disagree with three Likert-style scale statements: 1) This breathing exercise was relaxing; 2) I enjoyed this breathing exercise; 3) I thought this video was an effective tool for the breathing exercise. Then the participants ranked the breathing exercises from best to worst. An open-ended



[L] Images from four breathing exercises used to evaluate the effectiveness of the pheB surface.

follow-up question asked them to explain their reasoning. After the four breathing exercises were completed, the participants were asked to rate their current stress level again. Our research aims to understand whether a tangible, embodied visualization technique will be more effective than the 2D animation. While both exercises were viewed through a screen and have tactile features, we hypothesized that the breathing exercises with the tangible pheB surface would be ranked higher by participants as an effective guide and increase experiences of shared embodiment.

RESULTS

During the in-person study, participants performed the same breathing exercises developed for the questionnaire, but qualitative feedback was given through informal interviews. We also elicited feedback on pheB through a live demonstration of the working prototype and asked participants to evaluate the questionnaire so that it could be improved upon before we administered the final version on Amazon's Mechanical Turk.

For the most part participants responded positively to the questionnaire but provided some valuable feedback that will be implemented in the final version. Many comments on the questionnaire were directed at the animated gifs used to evaluate design features. Some participants preferred the images to be organized side-by-side so they could be easily compared, while another wanted to view each image individually so they could be assessed independently and then compared after. There was no overarching consensus as opinions varied greatly among participants.

For the breathing exercises, we were interested in learning how participants felt about the pace and duration. We also wanted to determine if people preferred the 4-7-8 or 6-10 breathing exercise. Most participants felt that the pace and duration was comfortable; however, one participant felt that it was "tedious" to perform all four exercises in succession. Generally, the 4-7-8 exercise was preferred over the 6-10 sequence. When comparing the 2D animated visualization with the pheB visualization, participants felt that the 2D animation was "less distracting" but it

[M] User explores the tactile nature of the pheB surface while inflated.

was also described as "less interesting." One participant felt that the 2D visualization made it easier to pace their inhalations because they could more easily follow the progress of the circle. Yet another participant felt that they had to pay close attention during the 2D animation and stare directly at the computer, whereas with the pheB surface they felt that could follow along using just their peripheral vision. They enjoyed that they could use the surface to indirectly guide their breathing with less focused attention. This aligns with the theoretical frameworks behind biophilic design [18] and soft fascination [17], which suggest that involuntary attention can be restorative, as well as encourage reflection and the exploration of ideas through mental wandering.

There were several comments that addressed experiences of embodiment during the pheB exercises. One person in the study stated that they were more aware of their lungs when following the pheB surface because they felt the surface was "metaphorically related to lungs" and a "visual index of what breathing looks like." This description was supported by additional comments about breathing with pheB, as one participant described, they felt "like they were in it together" and had a "connection because [pheB] was doing what I was feeling." Another described pheB as something "critter-like I was breathing with." Participants largely expressed that the breathing exercises were relaxing.

When asked to describe the pheB surface, participants used the following descriptors: *tactile, soft, friendly, amorphous, futuristic, alien, bulbous, organic, blob-like,* and *fantastical*. One participant thought it reminded them of an anatomical organ, they stated that the surface was "a little disturbing but strangely calming." This was supported by another comment which described it as "familiar but strange." Almost all the participants made comparisons between pheB and biological analogues. It was compared to "a jellyfish or invertebrate," "a turtle shell," "craters on Mars," "plant cells," "slime," "fruit pods," and a "membrane." None of the participants expressed fear, and most felt that they wanted to touch the surface. Overall, participants found pheB intriguing and indicated they wanted to interact further with the surface. Findings from our early study suggest that pheB was successful at guiding embodied mindfulness interactions, and that the tangible surface can induce feelings of shared experience with the soft robot during breathing exercises. pheB's design was associated with biological entities and patterns of nature, which may increase the biophilic sensibility of the system. Feedback demonstrated that pheB was perceived as calming and intriguing; this suggests the movement of the surface might induce soft fascination which allows the mind to wander and can alleviate stress. pheB provides a design exemplar of a novel biofeedback surface that enacts a set of behaviors reflecting a hybrid biofeedback loop that visualizes the internal experiences of both plants and humans. This research contributes an exploration of inter-species biofeedback, which cultivates a connection to the natural world, mediated through the bio-cyber-physical system.

LIMITATIONS & FUTURE WORK

The research team is mindful of the limitations of our initial results given that the pheB prototype is in its early stages. The current prototype has established proof of concept for the use of plant electrical signals as a control system, yet more work must be done to integrate the plant biofeedback into the interactive system. Future studies will focus on our second primary research question: Do tangible, embodied representations of a plant's internal states amplify the restorative effects of nature and foster meaningful plant-human relationships through a more expressive interaction? We plan to demonstrate the validity of our results with more quantitative analysis, but early discussions with the convenience sample suggested that visualizing the internal states of plants was a compelling way to engage with plant life and participants seemed to perceive the expressive plant-human interaction as meaningful.

Future work will assess if pheB is perceived as biophilic and restorative. The current questionnaire focuses on aesthetic design features and breathing exercises. We are developing an additional questionnaire for the next phase of user testing that will be used to evaluate user perceptions of visual representations of real natural phenomenon compared to pheB's representations.

Toward this goal, we are developing a bioinspired algorithm that translates the movement of natural phenomena into a corresponding inflation pattern. Applying a math model of a sinusoidal function, we are translating the amplitude and periodicity of ocean waves into a control system for the air pressure regulators. The prototype's new grid pattern has nine air channel inputs. Using Matlab (www.mathworks.com) to simulate inflation patterns, the model uses nine columns to represent each air channel. Grey values correspond with the amount of pressure the regulators use to inflate the column; lighter values represent more pressure [N]. This resulting inflation behavior can be tested for its restorative effect and perception of biophilic design. More broadly, pheB suggests the kind of tangible, embodied system that we hope will improve emotional wellbeing during periods of isolation in confined spaces and foster a connection with nature that is both restorative and meaningful.

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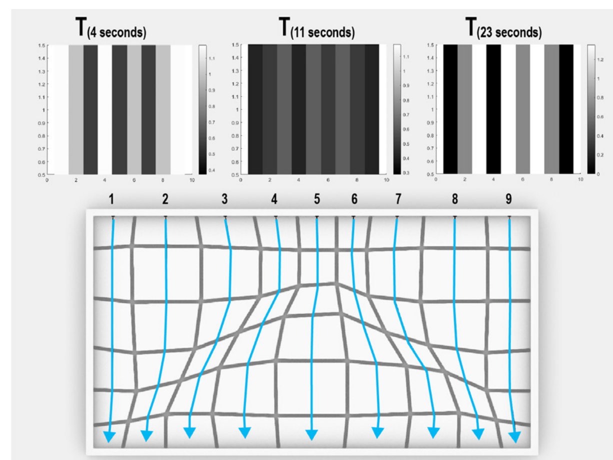

[N] Model simulates the inflation pattern of ocean waves.

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