# With Every Breath: Testing the Effects of Soft Robotic Surfaces on Attention and Stress

Elena Sabinson
Environmental Design
University of Colorado
Boulder, CO, USA
elena.sabinson@colorado.com

Jack Neiberg
Human Centered Design
Cornell University
Ithaca, NY, USA
jack@neiberg.com

Keith Evan Green
Human Centered Design
Cornell University
Ithaca, NY, USA
keg95@cornell.com

## ABSTRACT

We report on the effects of a novel soft robot of our design on emotional wellbeing. Participants (*N*=94) engaged with our soft robotic surface designed to simulate the benefits of nature and provide a therapeutic behavioral intervention. The study assessed group differences in attention, perceived restorativeness, and self-reported stress between three groups: a group that performed a breathing exercise with the robot, a group that watched the robot perform an ocean-inspired movement designed to capture involuntary attention, and a control where the robot was static. The Breathing Group had a significant reduction in self-reported stress compared to the Control Group. Significant differences in attention and perceived restoration were not found. Qualitative feedback suggested the robot did provide a positive distraction in the environment and participants were generally favorable to the robot, characterizing it as *soothing* and *fascinating*. Feedback on the sensory qualities showed that people who did not initially enjoy the texture or sound often acclimated to the novelty of the surface with improved perceptions over time. These findings suggest the promise of soft robots to support mental wellbeing.

## CCS CONCEPTS

**•Human-centered computing~Interaction design~Empirical studies in interaction design**

## KEYWORDS

Soft Robotics, Emotional Wellbeing, Bio-inspired

**ACM Reference format:**
Elena Sabinson, Jack Neiberg, and Keith Evan Green. 2024. With Every Breath: Testing the Effects of Soft Robotic Surfaces on Attention and Stress. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction (HRI '24), March 11–14, 2024.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3610977.3635004



*HRI '24, March 11–14, 2024, Boulder, CO, USA.*

ACM ISBN 979-8-4007-0322-5/24/03.
https://doi.org/10.1145/3610977.3635004

## 1 INTRODUCTION

People are increasingly living in urban settings without convenient access to the natural environment. Additionally, the pace and speed of urban living can stress urbanites due to experiences of environmental overload from auditory and visual stimuli, pedestrian density [12, 26], and the activities of daily life. To buffer these negative effects of urban living, we developed several novel soft robotic surfaces (Figure 1) that can be embedded in small interior living spaces to prompt behavioral interventions and offer positive distractions for stress reduction. The surfaces aim to provide some of the psychological benefits of nature [15, 16], through interactions with nature-inspired behaviors [34]. This paper investigates the effectiveness of the system through a user study to determine if the behavior of our soft-robotic surfaces can provide beneficial outcomes for mental wellbeing through stress reduction and improved attentional cognitive performance.

**Figure 1. Soft Robotic Surface Panel (18 x 33 inches)**

Human robot interaction (HRI) research with soft elastomer robots is a growing area of interest due to their flexible, stretchy materiality, making silicone an ideal medium for bio-inspired robots with life-like movement [30, 32, 40]. These pneumatically driven soft robots are deformable and compliant, reducing safety concerns caused by rigid-body robots [42], and making them well-suited for therapeutic purposes to support wellbeing [5, 37].

Researchers have previously studied how soft robots can provide calming interactions [4, 35] and communicate emotions through their expressive movement [15, 20]; however, many HRI studies focus on social interactions with human-scale soft robots. This study investigates a large, non-anthropomorphic robot embedded in the environment. To understand how the environment influences wellbeing, we looked to environmental psychology theories that seek to explain the restorative power of natural environments. The Attention Restoration Theory (ART) suggests that nature has a restorative effect on our attention [1, 16, 17, 28] through experiences of "soft fascination" [3] that capture involuntary attention through mesmerizing stimuli without requiring a cognitive load that might deplete attentional capacity. Looking at soothing stimuli found in nature, we modeled the inflation for our robot (Figure 2) using real ocean wave movement datasets, to produce a "softly fascinating" behavior that swells like ocean waves to promote restoration [36]. The Stress Reduction Theory (SRT) posits that nature has a positive effect on health [41] and mental wellbeing by reducing stress levels [45]. The SRT suggests that nature provides positive distractions, thereby reducing stress provoking thoughts. This study explored whether our robot's representation of ocean waves can reduce stress by providing experiences of soft fascination and a positive distraction, which has not been previously tested.

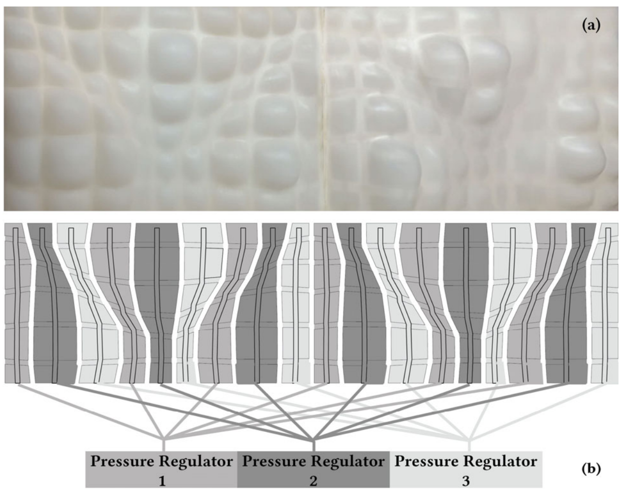


**Figure 2. (a) Two soft robotic surface panels performing ocean inspired movement, (b) diagram of air tubing setup.**

In addition to the nature-based strategies we deployed in the design of our surfaces, our system also guides users through relaxing breathing exercises, which are an effective tool for stress management [24] and can lead to improvements in sustained attention [11]. Our surfaces inflate and deflate in a pre-determined timing pattern designed to activate the parasympathetic nervous system through a long, slow exhale, helping the body to relax [27]. The use of pneumatic robots to influence users' respiratory patterns is an area of growing interest. An existing study [2] explored whether synchronized breathing could be induced by soft robots. Participants in the study were not explicitly instructed to match their respiration to the inflation of a soft robot that they touched while performing a task. The study found an effect on the depth of breathing through the interactions, but synchronization was not passively induced by the tactile feedback alone. We previously conducted a study online that explored synchronized guided breathing exercises with soft robots where participants were directly instructed to follow the pace of the inflation [33]. Participants reported decreased stress levels after viewing videos of the pneumatic surfaces. The study reported here expands upon our earlier work and the existing studies by testing the effects of synchronized robot-led breathing exercises in comparison with a nature-inspired movement. Moreover, this study is the first to test our novel custom prototype through in-person interactions. This allowed people to physically touch the surface and hear it operating while it inflates and deflates, giving further insights into user perceptions of the sensory qualities of the system. Responses to the tactile quality of the robotic surface were of particular interest, given that most electronic devices used for guided breathing exercises utilize 2D screen-based graphics. Our system provides a tangible interaction, which provides respite from the ubiquitous use of digital screens, and a multi-sensory (visual and tactile) experience, to offer a haptic modality for people with visual disabilities [18, 43].

We included both behaviors (i.e., ocean wave movement and timed breathing pattern) in our study to determine which was more restorative, and which was better at reducing stress levels. The ocean wave movement behavior exemplified a more passive interaction with the surface, as participants in the Ocean Group were not required to modify their behavior, offering an ambient experience with the soft robotic surface. This enabled us to assess whether the ocean wave movement was engaging enough to evoke soft fascination in the same way someone might experience mental wandering when looking at a natural scene. The breathing exercise interaction was more active, as it gave clear instructions to the Breathing Group for how to interact with the surface. Both behaviors were aimed at improving mental wellbeing, the breathing exercises were developed to directly support emotion regulation, whereas the ocean wave movement was aimed at restoring cognitive attentional capacity. We also included a Control Group, where the robotic surface remained static in front of participants to determine if interactions with the moving surfaces had an effect compared to the control. Based on the existing literature, we hypothesized the following:

**H1. (a)** Participants who interact with the moving robotic surfaces will perform better on the attention task than participants in the Control Group; **(b)** the Ocean Group will perform better on the attention task than the Breathing Group.

**H2. (a)** Participants who interact with the moving robotic surfaces will have a greater reduction in self-reported stress than the Control Group; **(b)** the Breathing Group will have a greater reduction in self-reported stress than the Ocean Group.

**H3. (a)** Participants who interact with the moving robotic surfaces will perceive the environment to be more restorative than the Control Group; **(b)** the Ocean Group will perceive the environment to be more restorative than the Breathing Group.

## 2 MEASURES

### 2.1 Sustained Attention to Response Task

To determine whether interactions with our prototype were effective at restoring attentional capacity, we utilized the computerized Sustained Attention to Response Task (SART) [8, 22, 31, 46], which measures attentional performance while reducing other necessary cognitive operations (e.g., memory). The SART [38, 39] asks participants to press the spacebar on a keyboard for frequent "Go" non-targets (a set of numerical digits) and withhold pressing the spacebar for infrequent "No-Go" targets (a specific digit). The task measures attention by habituating users to a motor response (pressing a button many times in succession for "Go" targets), and then requiring them to override their impulse to hit the button for the "No-Go" targets.

For each trial, a digit is presented for 250 msec followed by a duration mask (a graphic circle with an "x") for 900 msec. Digits were presented in pseudo-random order at five varying font points (48, 72, 94, 100, and 120 pt). The instructions stated that speed and accuracy were equally important to performance. The task started with a training of 18 practice trials. Participants were shown the results of their performance (error percentage) giving them the opportunity to modify their strategy prior to starting the real task. After the training, the real 225-trial test began. The SART was repeated as a pre-post measure. To minimize practice effects from repeated testing, the No-Go target was the digit "3" in the pre-test and "4" for the post-test.

### 2.2 Self-Reported Stress Measure

We included a scale item to evaluate perceived stress, that asked participants to rate their current level of stress. The 10-point rating scale ranged from *0=Not Stressed* to *10=Very Stressed*. Given that the other measures included in the study required considerable time for data collection, the quick self-reported measure was used to reduce the overall experiment duration.

### 2.3 Perceived Restorativeness Scale

The Perceived Restorativeness Scale (PRS) [13] was also included in the study as a subjective measure of restoration. The PRS is a 7-point scale (1=*Strongly Disagree*, 7=*Strongly Agree*) with 26 items that ask about descriptions of an environment. The items are grouped into subscales. The four subscales developed from the ART of nature are: 1) *Being Away:* escape from directed attention, 2) *Fascination:* effortless attention, 3) *Coherence:* legibility of a setting, and 4) *Compatibility:* level of correspondence between one's personal inclinations and the environment [29]. As our research is aimed at learning whether soft robotic surfaces can improve mental wellbeing for occupants of a confined interior space devoid of nature, we wanted to learn if interactions with our system affected perceptions of the lab environment (a room with no nature views). The PRS evaluated whether participants perceived the laboratory setting as more restorative after interactions with the robotic surfaces, but the PRS was not used to measure the restorativeness of the robot directly.

### 2.4 Evaluation of the Prototype

The evaluation included 10 Likert items (1=*Strongly Disagree*, 7=*Strongly Agree*) about experiences with the robotic surface on several themes: if the movement was soothing (Q1, Q7); if the surface was fascinating (Q3, Q5); experiences of co-embodied breathing (Q4); the desired frequency and duration of use (Q2, Q5); perceptions of the sound produced by the system when inflating (Q6); if the surface had a natural sensibility (Q8); if the appearance was appealing (Q9); and experiences of discomfort (Q10). The items were developed to address our research questions using insights from our previous user studies on soft robots [33, 34] and informed by the standard usability scale [7].

## 3 METHODS

A sample of 94 participants was recruited from a university in the United States using SONA Systems (sona-systems.com) and convenience sampling. The study took approximately 30 minutes to complete, and participants were given extra credit or a gift card as compensation. The study was conducted in a cluttered lab space of approximately 300 square feet, with a few tables, computers, and shelves with prototyping tools. Compressed air lines fed into three electro-pneumatic pressure regulators controlled by an Arduino microcontroller. Two of our robotic surface panels (18" x 33") were used in the study, placed side-by-side on a large white table to form an 18" x 66" soft robot. The same laptop was used for all participants, positioned on the table in front of the surfaces where they completed the experimental protocol (Figure 3).


**Figure 3. (a) The experimental setup; (b) a participant in the breathing group; (c) a participant in the ocean group.**

The study employed a between-subject design with three groups: 1) a Control Group (CG), where participants sat in front of the static surface placed on the tables in front of them; 2) an Ocean Group (OG), where participants watched the surface perform the ocean wave behavior; and 3) a Breathing Group (BG), where participants performed a breathing exercise led by the robotic surface. The participants were randomly assigned to a group. Subjects were given a consent form and then asked to sit at a table with the experimental setup. The study was conducted using PsyToolkit [38, 39] and included the following sections: 1) demographics, 2) baseline self-reported stress measure, 3) baseline SART task, 4) post-intervention self-reported stress measure, 5) post-intervention SART task, 6) the perceived restorativeness scale, and 7) prototype evaluation of users' interactions with the robotic surfaces. Participants completed all sections, except for Section 7, which was not completed by the CG who did not have an active interaction with the robotic surfaces. After the baseline SART measure, the laptop was removed, and the assigned intervention was administered for three minutes. Participants in the OG were informed that the surface in front of them was going to inflate with air and they could interact with the robot, including touching the surface while it was moving. Participants in the BG were instructed to perform a guided breathing exercise following the rhythm of the surface. They were instructed to inhale when the surface was inflating and exhale when the surface was deflating. Participants in the CG were instructed to take a break sitting in front of the static robotic surfaces. They were told that they could look around the room or interact with the objects in the environment, but to abstain from using their electronic devices. Once the study was completed, participants who were in the BG and OG were asked, "Do you have any comments or feedback about the prototype?" As a follow up they were asked, "How did you feel about the texture and sound?" Researchers recorded comments provided by the participants and their intervention condition.

## 4 RESULTS

The 94 participants in our sample ($M_{Age}$=19.7 years, $SD_{Age}$=1.49; *Women*= 61, *Men*=32, *Non-Binary*=1) completed the study over several weeks. All 94 responses were included in the analysis of the survey data; however, one participant fell asleep during the post-intervention attention task and their response was excluded from the analysis of the SART measure. The survey portion of the study took on average 22.69 (*SD*=2.05) minutes to complete. Analysis was performed using R Software (r-project.org).

### 4.1 Sustained Attention to Response Task

The SART task was analyzed to determine the effects of the intervention conditions on accuracy. For the No-Go trials, box plots demonstrated that participants in the BG had the greatest improvement between tests, and participants in the OG performed slightly better at the post-test task than the CG. For the Go trials, there was very little difference across the groups (Figure 4). The general pattern showed that most participants across groups performed better on the post-test compared to pre-test scores. The CG had the smallest improvement in accuracy.

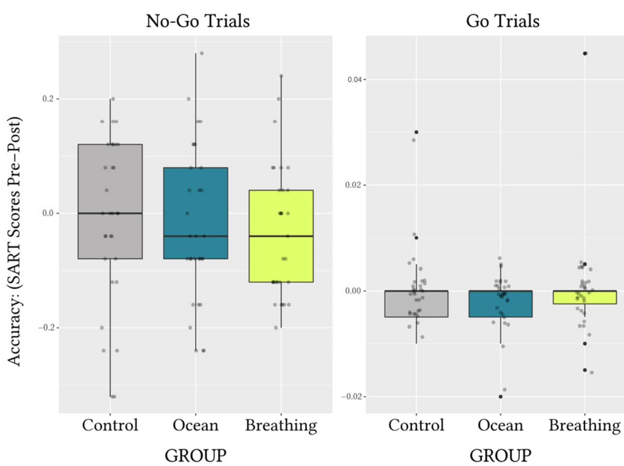


**Figure 4. Boxplots of accuracy (SART score pre-post) for No-Go and Go trials by group.**

We performed regression analysis using a linear mixed model that modeled accuracy by condition, accounting for order with a random effect to account for the repeated measures of each subject. Analysis was performed separately for the No-Go and Go Trials and was conducted with the lmer package [21]; post-hoc analyses were evaluated with emmeans [23]. Histograms of the residuals for the No-Go and Go trials were used to check if variance was normally distributed, demonstrating a normal distribution for the No-Go trials and a severely left-skewed distribution for the Go-Trials. Our analysis therefore focused on the No-Go trials to evaluate performance. The estimated mean accuracies for the No-Go trials indicated that participants had improved accuracy for the second test, with very minor differences across groups (Table 2). The estimated mean differences showed the smallest pre-post difference for the CG, followed by the OG, with the greatest difference in the BG; however, the contrasts were not statistically significant (Table 3).

**Table 2. Estimated mean pre-post scores for No-Go trials.**

| *Estimated Mean Accuracy (df = 113)* | | Estimate | SE | Lower CL | Upper CL |
|---|---|---|---|---|---|
| *Control Group* | *Pre* | 0.697 | 0.035 | 0.628 | 0.766 |
| | *Post* | 0.707 | 0.035 | 0.638 | 0.776 |
| *Ocean Group* | *Pre* | 0.692 | 0.035 | 0.622 | 0.761 |
| | *Post* | 0.715 | 0.035 | 0.646 | 0.784 |
| *Breathing Group* | *Pre* | 0.716 | 0.035 | 0.647 | 0.785 |
| | *Post* | 0.748 | 0.035 | 0.679 | 0.818 |

**Table 3. Estimated mean differences of accuracy (pre-post scores for No-Go trials.)**

(* = $\alpha < 0.05$, *df* = 113)

| *Estimated Mean Differences* | *Estimate* | *SE* | *t-ratio* | *p.value* | *Cohen's d* |
|---|---|---|---|---|---|
| *Control (pre-post)* | -0.0103 | 0.0238 | -0.434 | 0.6653 | -0.08 |
| *Ocean (pre-post)* | -0.0232 | 0.0238 | -0.977 | 0.3314 | -0.18 |
| *Breathing (pre-post)* | -0.0323 | 0.0238 | -1.356 | 0.1784 | -0.26 |

### 4.2 Self-Reported Stress Measure

The pre and post self-reported stress measures were analyzed to evaluate effects of the interventions on perceived stress. Observed means (Table 4) demonstrated the smallest mean difference was in the CG (*M*=0.10, *SD*=1.45), followed by OG (*M*=0.61, *SD*=1.73), with the greatest difference in the BG (*M*=1.41, *SD*=1.41). Box plots of pre-post stress ratings exhibited the same pattern (Figure 5).

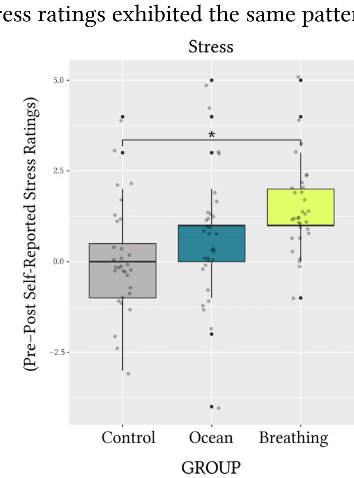


**Figure 5. Pre-post stress ratings by interaction group.**

Linear regression and analysis of variance were also used to examine pre-post stress. The estimated mean differences from the model (Table 5) corresponded closely to the observed means, with the smallest decrease in stress found in the CG, followed by the OG, with the greatest decrease in the BG. The conditions were significantly different ($F[2, 91] = 6.38$, $p = 0.002$), with a medium effect size, $\eta 2 = 0.12$, $\omega 2 = 0.10$. Post-hoc tests on the between group contrasts with a Bonferroni correction (Table 6) found the group differences were statistically significant between the CG and the BG ($p$=0.002, $d$=-0.74), and marginally significant between the BG and the OG ($p$=0.104 $d$=-0.45).

**Table 4. Observed mean stress ratings by group.**

| ***Stress Rating*** (0 = Not Stressed, 10 = Very Stressed) | ***Control*** Mean (SD) | ***Ocean*** Mean (SD) | ***Breathing*** Mean (SD) |
|---|---|---|---|
| ***Pre-Test*** | 5.19 *(2.47)* | 5.16 *(2.60)* | 5.75 *(2.20)* |
| ***Post-Test*** | 5.10 *(2.33)* | 4.55 *(2.11)* | 4.34 *(2.16)* |

**Table 5. Estimated mean stress ratings (pre-post) by group.**

| *Estimated Mean Difference Stress Measure (df = 91)* | *Estimate* | *SE* | *Lower CL* | *Upper CL* |
|---|---|---|---|---|
| *Control Group (pre-post)* | 0.0968 | 0.263 | -0.43 | 0.62 |
| *Ocean Group (pre-post)* | 0.6129 | 0.263 | 0.09 | 1.14 |
| *Breathing Group (pre-post)* | 1.4062 | 0.259 | 0.89 | 1.92 |

**Table 6. Contrasts of estimated mean differences of pre-post stress ratings between groups with Bonferroni correction.**

| *Stress Measure (* = α < 0 .05, df = 91)* | *Estimate* | *SE* | *t-ratio* | *p.value* | *Cohen's d* |
|---|---|---|---|---|---|
| *Control - Ocean* | -0.516 | 0.373 | -1.385 | 0.508 | -0.29 |
| *Control - Breathing* | -1.309 | 0.370 | -3.543 | **0.002*** | -0.74 |
| *Ocean - Breathing* | -0.793 | 0.370 | -2.146 | 0.104 | -0.45 |

## 4.3 Perceived Restorativeness Scale

The 26 items were first analyzed individually to determine group differences. The OG had the highest mean ratings for 38.46% of the items, followed by the BG (30.77%) and CG (26.92%). For Item 21 (I can find ways to enjoy myself here), the highest mean rating was tied between the BG and OG (3.85%, $M$=4.8). Linear regression and analysis of variance was used to examine the relationship between groups, but most items were not significantly different.

Next, analysis was conducted for the four subscales: *Being Away*, *Fascination*, *Coherence*, and *Compatibility*. For *Being Away*, the observed mean ratings were higher in the BG ($M$=4.26, $SD$=1.69) and the OG ($M$=4.26, $SD$=1.41) than the CG ($M$=3.86, $SD$=1.71). For *Fascination*, the observed mean ratings were highest in the OG ($M$=5.37, $SD$=1.21), compared to BG ($M$=5.10, $SD$=1.60) and CG ($M$=5.02, $SD$=1.35). For *Coherence*, observed mean ratings were highest in the BG ($M$=4.77, $SD$=1.62), compared to OG ($M$=4.19, $SD$=1.47) and CG ($M$=4.42, $SD$=1.40). For *Compatibility*, observed mean ratings were highest in the CG ($M$=4.19, $SD$=1.45), compared to OG ($M$=4.03, $SD$=1.42) and BG ($M$=3.80, $SD$=1.64). Linear regression and analysis of variance was performed to model the relationship between the groups and the subscale ratings; there were no significant differences across groups.

## 4.4 Evaluation of the Prototype

The 10 items from the prototype evaluation were analyzed by condition to determine if ratings differed between the OG and BG. Observed means showed that generally participants felt the surface was soothing, somewhat appealing and fascinating, and something they would want to interact with frequently (Table 7). Linear regression and analysis of variance did not find significant differences between groups.

**Table 7. Mean ratings for the prototype evaluation of the robotic surface (RS) by group.**

| ***Mean Ratings by Condition*** (1 = Strongly Disagree, 7 = Strongly Agree) | ***OG*** Mean (SD) | ***BG*** Mean (SD) |
|---|---|---|
| *I found the movement of the RS soothing.* | 5.68 *(1.42)* | 5.41 *(1.32)* |
| *I would like to interact with the RS frequently.* | 5.06 *(1.59)* | 4.91 *(1.59)* |
| *I DID NOT find the movement fascinating.* | 2.10 *(0.91)* | 2.16 *(1.22)* |
| *I felt like the RS was breathing with me.* | 5.16 *(1.53)* | 4.47 *(1.61)* |
| *I could watch the RS inflate for hours.* | 4.26 *(1.90)* | 4.03 *(1.67)* |
| *I enjoyed the sound made by the RS.* | 4.48 *(1.86)* | 4.38 *(1.83)* |
| *Watching the RS inflate DID NOT make me feel more relaxed.* | 2.45 *(1.26)* | 2.50 *(1.30)* |
| *The movement reminded me of something I might see in nature.* | 4.52 *(1.67)* | 4.03 *(1.84)* |
| *The RS appearance was appealing to me.* | 4.84 *(1.44)* | 5.06 *(1.22)* |
| *I found the RS creepy.* | 3.71 *(1.72)* | 3.09 *(1.57)* |

## 4.5 Qualitative Feedback

An open-ended thematic analysis was performed to identify meaningful themes from the feedback collected during the exit interviews [6]. Researchers coded the interviews with ATLAS.ti (atlasti.com) in consideration of the research goals of the study. First the researchers reviewed the transcripts and counted which descriptors of the prototype were frequently repeated to determine important patterns. Preliminary codes were assigned to the transcripts, and then iteratively reviewed by two of the authors to confirm the interpretations fit with the content of the data. This section provides an inventory of quotations drawn from the transcripts organized by the three most salient themes identified during the analysis, including: 1) Associations to Breathing and Influence on Respiration, 2) Sensory Qualities of the Surface, 3) Soft Fascination and Positive Distractions. Quotes were also organized by intervention group and identified as being positive (+), negative (-), or neutral/mixed (±).

### *4.5.1. Associations to Breathing and Influence on Respiration: Pace, Depth, and Awareness.*

Many comments were related to breath and how the interaction influenced the participants' respiration. Participants in the BG were the only ones instructed to match their breath with the surface; however, participants in the OG also stated that they attempted to synchronize their breath to the robot. This suggests watching the surface inflate might influence users' respiration behavior, even without explicit instructions. Several comments compared the inflation to human breathing, offering further support for **an intrinsic association with the movement of respiration**. Some participants found the association to human breathing comforting *("[it] was human-like…but it was a soothing sound"),* while others found it unsettling, suggesting experiences related to the uncanny valley ("*its non-humanness was a little unnerving*"). **The robot influenced participants' respiration in three ways: 1) pace** *("looking at the surface made me want to follow the rhythm*" and "*I tried to match my breath*"), **2) depth** *("it was hard to breathe that deeply but touching it while breathing helped*"), and **3) awareness** *("I could chill out enough to actually focus on my breathing because normally I can't…*").

**OG**: *[I] think I could chill out enough to actually focus on my breathing because normally I can't pay attention to my breath.* **(+)**
**OG**: *Oooh what is this?... I'm kind of obsessed with this thing…I felt like it going up and down helped me with breathing.* **(+)**
**OG**: *Made me think of breathing and I tried to match my breath to it.* **(+)**
**OG**: *[The robot] sounded like labored breathing…It felt like an alien.* **(±)**
**OG**: *[F]ound it soothing, but its non-humanness was a little unnerving… felt like it was breathing.* **(-)**
**BG:** *[I'm] not used to breathing that deeply or that level of awareness. [It was] nice to have a visual for how much you are supposed to breathe.* **(+)**
**BG:** *I liked the sound, it sounded like a person breathing deep, [it] was human-like…but it was a soothing sound.* **(+)**
**BG:** *[I] kept my hand on the surface because it helped me to pace my breathing and breathe deeply. At first it was hard to breathe that deeply but touching it while breathing helped.* **(+)**
**BG:** *[L]ooking at the surface made me want to follow the rhythm.* **(±)**

#### *4.5.2. Sensory Qualities of the Surface: Acclimation to the Sound and Texture, and Squishy vs. Sticky*

Participants were asked about their sensory experiences to evaluate reactions to the sound and texture of the robotic surface. Feedback on sound was mixed, with both positive and negative comments. **Perceptions on sound changed over the course of the interaction when participants acclimated to the system.** More than one participant stated that initially the sound was disruptive or caused discomfort, but they appreciated the sound by the end of the interaction ("*At first the sound…was disruptive, but [I] liked it by the end").* Interestingly, two participants in the BG compared the sound to sounds of the ocean ("*reminded me of the sound of ocean waves*" and "*[like] hearing the waves in a seashell*"). The association was surprising given that ocean waves were not mentioned to either interaction group and suggests that **some people had intrinsic associations to ocean sounds from the sound of the air inflating the surface.**

The texture also elicited both positive and negative reactions. Many comments used the descriptors "sticky" ($x$=9) and "squishy" ($x$=5). After reviewing the coded transcripts, the co-occurrence of descriptors "sticky" and "squishy" was associated with the desire or repulsion to touch the surface (Table 8). **When participants found the surface "sticky," they were more inclined toward negative perceptions** *("[it] was tacky and sticky so I did not want to touch it").* **Conversely, when the surface was perceived as being "squishy" feedback was more positive** *(Woah that's squishy! [I] really liked the texture*"). Several participants enjoyed "poking" or "tapping" the surface, and compared it to stress balls, fidgets, and other sensory tools used for emotion regulation. One participant felt touching the surface helped them relax, suggesting that squishing and poking could help to release emotions ("*being able to poke it was relaxing").* Similar to sound, there was an adjustment period to the tactile quality ("*At first, I was like what the [heck], but then I found it soothing")* where **initial experiences of discomfort subsided after people adjusted to the texture.**

***Sound qualities.***

**OG:** *[I] was distracted by the wheezing sound.* **(-)**
**OG:** *[A] little creepy at first because [it] sounded like Darth Vader, but [I] got used to it.* **(±)**
**BG:** *At first the sound…was disruptive, but [I] liked it by the end.* **(±)**
**BG:** *[I] didn't really like the sound, but it was relaxing overall.* **(±)**
**BG:** *[Like] hearing the waves in a seashell.* **(+)**
**BG:** *[It was] rhythmic and reminded me of the sound of ocean waves.* **(+)**

***Tactile qualities.***

**OG**: *[B]eing able to poke it was relaxing…[it] reminded me of a de-stress tool like a fidget.* **(+)**
**OG**: *[It] was tacky and sticky so I did not want to touch it.* **(-)**
**OG**: *Why is it so sticky? At first, I was like what the [heck], but then I found it soothing [and] felt de-stressed.* **(±)**
**BG:** *Woah that's squishy! [I] really liked the texture.* **(+)**
**BG:** *[I was] not too interested in touching it, it was too sticky to have a quality that's tactilely enjoyable.* **(-)**
**BG:** *It scared me when I first touched it because it was sticky.* **(-)**

**Table 8. Co-occurrence of codes for tactile qualities associated with desire to touch the robotic surface (RS)**

| | *Did NOT want to touch* | *Did want to touch* |
|---|---|---|
| *Squishy* | 0 | 5 |
| *Sticky* | 3 | 1 |

#### *4.5.3. Soft Fascination and Positive Distractions: Capturing Involuntary Attention and Giving People Something to Do.*

Many participants made comments that suggested experiences of soft fascination, where the movement of the surface helped people "get in the zone," and several participants described it as "mesmerizing" or "fascinating." Feedback suggested **the robot's behavior successfully captured involuntary attention and many people found the movement soothing to watch** *("I found that I was fully in the zone watching it, it was soothing").* Participants described the surface as "oddly satisfying" and stated that interacting with **the surface "gave [them] something to do" suggesting the surface was a positive distraction in the environment.** The novelty of the surface again led to initial experiences of surprise at the robot, with **improved perceptions after users acclimated to watching the robotic surface.**

**OG**: *First, it was unexpected but then I fell into a rhythm watching it.* **(+)**
**OG**: *Oddly satisfying…Why do I enjoy this?!* **(+)**
**OG**: *[I] didn't know what it was going to do so it was really surprising at first when you turned it on, but then I found that I was fully in the zone watching it, it was soothing, I was so in the zone that I was startled when you came over to tell me the break was done.* **(+)**

**OG**: *Weird. [I] didn't really like it…found myself zoning out and felt more relaxed, [but I] wasn't sure if [I was] relaxed because of [the surface] or because of zoning out."* **(-)**
**BG:** *[It gave me] something to do* **(+)**
**BG:** *[It was] mesmerizing, and I liked the squishiness. I wasn't sure if it was really relaxing because it was so interesting, I was paying attention to it and not focusing on my breathing as much.* **(+)**
**BG:** *[I found the surface] fascinating… fun to watch.* **(+)**

## 5 DISCUSSION

The present study investigated the effects of soft robotic surfaces on three measures: sustained attention, self-reported stress, and perceived restorativeness of the laboratory setting. The study also included a prototype evaluation questionnaire and exit interviews to collect qualitative feedback on the robot. In this section, we further elaborate on the results. We did not find the significant differences we hypothesized for the effect of the interventions on sustained attention (**H1**). This might be due to the relatively small sample size (*N*=94); based on the results, we estimate we would need 237 participants to reach a 0.8 power at 0.05 alpha level.

The results of the pre-post stress measure (Table 5-6) found a significant stress reduction in the BG compared to the CG, and a marginally significant difference between the BG and the OG, supporting our hypothesis that the breathing intervention would be most effective at reducing stress (**H2b**). The difference between the OG and the CG was not significant. The results therefore did not establish that the CG had the least amount of stress reduction compared to the intervention groups (**H2a**). The ocean wave movement did not have an effect on stress, which suggests the passive nature-inspired positive distraction was not as effective as the active breathing interaction. However, qualitative feedback did highlight experiences of soft fascination and an effective positive distraction provided by the system, with several participant's stating the rhythmic movement of the surface was "soothing" and "oddly satisfying" allowing users to "zone out."

One concern that arose from our previous user studies [33, 34] on soft robots was that discomfort or an uncanny-valley effect caused by the appearance of the robot surface could counteract the soothing, therapeutic effects. While feedback did point to some initial discomfort to the novel system, interviews also seemed to suggest that these experiences did not prevent the robot from providing an effective, soothing interaction overall *("[F]ound it soothing, but its non-humanness was a little unnerving").*

Interestingly, several participants in the OG commented on how the surface helped them focus on their breathing, including participants who tried to match their respiration to the rhythm of the surface without being instructed. The silicone materiality of the surface, which expands during inflation, seems to have an intrinsic, embodied connection to the way the human body swells during inhalation, which may play a role in the effectiveness of soft robotic surfaces for breath-related interactions [2, 20]. Feedback from the OG suggested there was some stress-relieving qualities of the surface *("reminded me of a stress ball. [I] had a lot of fun squishing it")*, but linear regression of the pre-post stress ratings (Table 5-6) showed the ocean-wave behavior was not effective at reducing stress. Several participants noted an acclimation period, stating they were initially unnerved by the robot, but by the end of the interaction had adjusted to the surface *("[A] little creepy at first…but [I] got used to it")*, making it more effective as time passed. Given the novelty of our custom soft robotic surface, interactions longer than three minutes might be optimal to achieve a restorative effect. Moreover, participants in the OG were not given formal instructions on how to interact with the surface during the break. Having no instructions might have increased experiences of surprise that prevented participants from experiencing soft fascination long enough to elicit restoration. Conversely, the BG was given concrete instructions for their activity, likely making it a more effective intervention for the short duration of the interaction.

The responses to the PRS found that the OG and BG rated the setting as more restorative than the CG for the subscales: *Being Away*, *Fascination*, and *Coherence*. While the estimated marginal mean ratings were not statistically different between groups, the observed means were higher for groups that interacted with the robot (**H3**). For *Being Away*, the observed mean ratings were the same for the OG and BG, suggesting both robot interactions might have provided an experience of escape through a positive distraction. Given that confined spaces limit the possible activities in the setting, cultivating a perception of escape is an important aim. For *Fascination*, the OG had the highest mean ratings, suggesting that the nature-inspired movement of the surface might have been perceived as softly fascinating (**H3b**). The BG had the highest mean rating for *Coherence*, suggesting that the soothing nature of the breathing exercises might have made the setting seem less disorganized. Notably, the item with the largest mean difference across groups was Item 17 (which was reverse coded), where the BG (*M*=5.2, *SD*=1.6) rated the environment as less chaotic than the OG (*M*=4.1, *SD*=1.6), perhaps supporting the notion that performing the beathing exercises improved perceptions of the laboratory and promoted relaxation for participants in the small, cluttered room. Another possible interpretation is that the participants in the BG were very focused on the breathing activity and had less time to look around the room to observe the visual clutter. This might also explain why the CG had the highest ratings for the subscale *Compatibility*, since the participants had the most time to observe the room during the three-minute break, providing opportunity to better understand their relationship to the environment.

The prototype evaluation showed that, overall, people had positive perceptions of the system (Table 7). Observed means indicated agreement for the statement, "I found the movement of the soft robotic surface soothing" and disagreement for the statement, "Watching the surface inflate DID NOT make me feel more relaxed." Thus, the results revealed that interactions were perceived as relaxing, offering some support for **H2.** There was mild agreement for the statements, "I would like to interact with the robotic surface frequently," and people were somewhat neutral towards the statement, "I could watch the robotic surface inflate for hours." One possibility for this finding is that the language was quite strong, and while participants might have enjoyed their experience, it might be hard to imagine the desire for much longer interactions. Both groups disagreed with the statement, "I DID NOT find the movement of the robotic surface fascinating," suggesting the surface had fascinating qualities.

The OG had higher mean ratings for the statement, "The movement reminded me of something that I might see in nature," corresponding with our prediction, since the interaction for that group was nature-inspired. Quantitative feedback on the sound was fairly neutral. Qualitative data suggested the sound was not appreciated by all participants, but tolerated by most, and appreciated by some. After some participants acclimated to the sound, negative perceptions subsided. Regarding experiences of discomfort, or an uncanny valley-like effect, observed in previous user studies of soft robots [33], the prototype evaluation showed there was mild disagreement to the statement, "I found the robotic surface creepy," and participants found the appearance of the surface mildly appealing overall (Table 7).

People were somewhat polarized in their reactions to the tactile qualities of the surface. When people perceived the surface as "sticky," they were less positive about the texture; conversely, when the prototype was perceived as "squishy" the feedback was positive. This is an important design consideration for soft robots, and effort should be made to increase perceptions of squishiness and decrease perceptions of stickiness. The silicone used to fabricate our robotic surfaces has excellent material properties for pneumatics due to its ability to elongate and return to its original form, the tradeoff being that softer silicones tend to be stickier. Surface treatments can be applied to the silicone to reduce the stickiness, which we plan to explore for future prototypes. Positive comments related to squishiness suggest that it reminded people of "stress balls" and "fidget toys." Given our research objective is to induce positive distractions and alleviate stress, these comparisons are encouraging, and highlight the promising potentials for soft robots to provide a tactile outlet for stress relief.

## 6 CONCLUSION & FUTURE WORK

This study tested the restorative effects of a soft robotic surface installed in a confined space to investigate if the system could be used for therapeutic purposes to support mental wellbeing. The study did not find significant differences in the accuracy of the SART measure of sustained attention between groups, nor for the ratings of the PRS, but did find a significant effect on self-reported stress for participants in the Breathing Group. One possibility for the lack of significance was the use of the SART to measure sustained attention. While some studies have found significant effects using the SART [8, 22], others have failed to find an effect of their interventions [9] and argue the SART does not measure sustained attention [10] but rather a person's decision to respond quickly *or* accurately. While response time was recorded for our study, we found no significant effects of time on our outcome variables, and therefore did not include it in our analysis. However, given that instructions asked participants to treat speed and accuracy as equally important, it is unclear if different strategies (i.e., prioritizing speed over accuracy *vs.* accuracy over speed) might have affected results.

It is becoming increasingly popular to assert that nature-inspired designs have beneficial health outcomes, yet few studies have empirically tested these designs to validate such claims. Here, we aimed to establish a relationship between interactions with our nature-inspired surface and several measures related to mental wellbeing. Overall, the level of statistical significance did not confirm a relationship between the robot's ocean wave movement and stress reduction, perceived restoration, or sustained attention. Future HRI researchers should provide longer interactions with novel soft robotic systems designed for human wellbeing to account for the "novelty effect," which suggests that we have different reactions to novel things when we are exposed to them for the first time [14]. Longer or repeated interactions would allow users to acclimate to novel robotic systems and help people move past initial experiences of discomfort.

The soft, compliant quality of silicone, used to fabricate many soft robots, is often touted as being a human-friendly material in comparison to rigid industrial robots. Yet, researchers developing soft robots for human interaction should be mindful that users may find a sticky texture off-putting. We recommend developers of soft robots for human interaction use materials that have a desirable level of squishiness while minimizing stickiness. More research is needed on user perceptions of soft robots to establish design guidelines that encourage positive reactions to tangible qualities. This study provides a starting point towards that goal.

There were several limitations to this study. First, it would have been preferable to utilize an objective physiological stress measure (e.g., heart rate variability [19], cortisol levels [25], or galvanic skin response [44]) to validate the self-reported measure. Future work will aim to incorporate a physiological stress marker to better understand the effects of the surface during both the nature-inspired movement and guided breathing exercises. The findings of our study serve as an early validation for soft robots as effective breathing guides for relaxation; yet we acknowledge that if people were aware breathing exercises are meant to be relaxing, it might have influenced self-reported ratings.

Another limitation was that the interventions were tested between-groups, which prevented qualitative comparisons of the behaviors of the system. A within-groups study would have better enabled us to understand comparisons of the two behaviors, since in this study there was no way to assess if one of the behaviors was preferred. Future studies might consider a more qualitative approach to understand which behaviors are preferred by users and determine what qualities make them preferable.

This work begins to establish that soft robotic surfaces have the potential to support emotion regulation and wellbeing. This study provided a comparison of two novel interactions designed to support mental wellbeing: a nature-inspired design to capture involuntary attention, and an active behavioral intervention through guided breathing. We found the active behavioral intervention was more effective. Our future work will study if our robot's softly fascinating ocean behavior should be improved to effectively reduce stress, or if longer interaction times might be sufficient to promote restoration and mitigate initial experiences of surprise or discomfort. As more of us come to live and work in smaller spaces in urban environments, this research reveals the promise of embedded robotic systems in confined interior spaces to support the mental wellbeing of inhabitants.

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